Overview of Pulse Jet Mixer/Hybrid Mixing System Development to Support the Hanford Waste Treatment Plant

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ABSTRACT

The U.S. Department of Energy (DOE) Office of River Protection’s Waste Treatment Plant (WTP) will process and treat radioactive waste that is stored in underground tanks at the Hanford Site. Pulse jet mixer (PJM) technology was selected for mixing the contents of many of the process vessels. Several of the tanks are expected to contain concentrated slurries that exhibit a non-Newtonian rheology—and the understanding required to apply this technology to mobilize the non-Newtonian slurries was not mature. Consequently, an experimental testing effort was undertaken to investigate PJM performance in several scaled versions of WTP vessels and to develop mixing system configurations that met WTP requirements. This effort evolved into a large, multifaceted test program involving many different test facilities. Elements of the test program included theoretical analysis, development and characterization of simulants, development of instrumentation and measurement techniques, hundreds of tests at various scales in numerous test stands, and data analysis and application. This program provided the technical basis for the selection of pulse jet mixers along with air spargers and steady jets generated by recirculation pumps to provide mixing systems for several of the vessels with non-Newtonian slurries. This paper provides an overview of the testing program and a summary of the key technical results that formed the technical basis of the final mixing system configurations to be used in the WTP.

INTRODUCTION

Background

The U.S. Department of Energy (DOE) Office of River Protection’s Waste Treatment Plant (WTP) is being designed and built to pretreat and then vitrify a large portion of the wastes in Hanford’s 177 underground waste storage tanks. The WTP consists of three primary facilities: pretreatment, low-activity waste (LAW) vitrification, and high-level waste (HLW) vitrification. The pretreatment facility receives waste feed from the Hanford tank farms and separates it into 1) a high-volume, low-activity, liquid stream stripped of most solids and radionuclides and 2) a much smaller-volume HLW slurry containing most of the solids and most of the radioactivity.

The process streams significant to this paper are the HLW streams in the pretreatment facility. These concentrated waste slurries are expected to exhibit non-Newtonian rheology, which can be represented by a simple Bingham plastic model. With this model the slurries are characterized by yield stress and a consistency factor. The presence of yield stress means that a certain amount of excess shear must be applied to maintain material motion. These slurries also develop gel-like properties when they are at rest for a period of time. They behave like very weak solids, a behavior that is characterized by shear strength that is typically greater than the yield stress. When an applied force exceeds the shear strength, the gel structure fails, and the slurry acts like a fluid and begins to flow.

Mixing Requirements

One of the primary concerns with non-Newtonian slurries is their propensity to retain flammable gases. Radioactive waste generates hydrogen and other gases by the processes of radiolysis and thermolysis; hydrogen is the primary flammable gas of concern. These gases will generally bubble out of fluids with Newtonian rheology. However, concentrated slurries with a significant yield stress or shear strength will trap gas bubbles in situ and can allow buildup of 20 to 40 vol% total retained gas in a stagnant state [1]. A sudden release of this gas could form a flammable gas mixture in the headspace of the tank and/or the plant ventilation system. Thus the mixing system must be able to shear the waste contents adequately to allow the gas to be released more gradually in a safe and controlled manner.

The tank contents must be mixed adequately for several reasons beyond ensuring controlled release of flammable gases. Reasons include maintaining a reasonable degree of homogeneity in process vessels to ensure representative sampling, limiting solids settling and stratification, improving heat transfer, and mixing of various process solutions that are typically added to the top of the vessel contents.

Based on an assessment of the plant flow sheet and rheological data from actual tank wastes, seven tanks were projected to contain non-Newtonian slurries: two ultrafiltration process (UFP) vessels, two HLW lag storage (LS) vessels, a HLW blend tank, and two HLW concentrate receipt vessels (CRVs), which have been eliminated from the WTP design. The LS vessels and the blend tank are very similar in size and geometry and were generally treated as being the same for testing purposes.

Mixing Technologies

A combination of PJMs and air spargers was selected for mixing the WTP vessels containing slurries exhibiting non-Newtonian rheology. These technologies have been selected for use in so-called "black cell" regions of the WTP, where maintenance capability will not be available for the operating life of the WTP. Both of the technologies were selected in part because they have no moving parts that require maintenance. The UFP vessel design already contained recirculation pumps to provide feed to the filtration system, so mixing with steady jets has also been incorporated for some modes of operation.

PJM mixing technology involves a pulse tube coupled with a jet nozzle (Fig. 1; top left). The motive force is supplied by air entering at the top of the pulse tube. The supplied air is cycled through pressure, vent, and vacuum phases to create three operating modes for the pulse tube: 1) the drive mode, when pressure is applied to discharge the contents of the PJM tube at high velocity through the nozzle; 2) the vent mode, when the drive air is vented to the atmosphere; and 3) the refill mode, when vacuum is applied to refill the pulse tube. The PJM system uses these operating modes to produce a sequence of drive cycles that provide mixing in the vessel. PJM operating parameters—number of PJMs, applied pressure, nozzle exit velocity, nozzle diameter, and drive time—along with the rheological properties of the fluid being mixed contribute to the effectiveness of mixing within the vessel.

Air sparging involves forcing air out the bottom of tubes inserted into the vessel contents with the outlet typically placed near the bottom of the vessel (Fig. 1; top right). Tilton et al. [2] describe the fluid mechanics of air sparging systems in non-Newtonian fluids as having two primary flow regions. In the first region, fluid flows with the bubbles as they rise. This is referred to as the "region of bubbles" (ROB). Outside the ROB, the fluid flow is reversed and is, on average, opposite the direction of bubble rise. This region is referred to as the "zone of influence" (ZOI). Farther outside the ZOI is a region of fluid that is

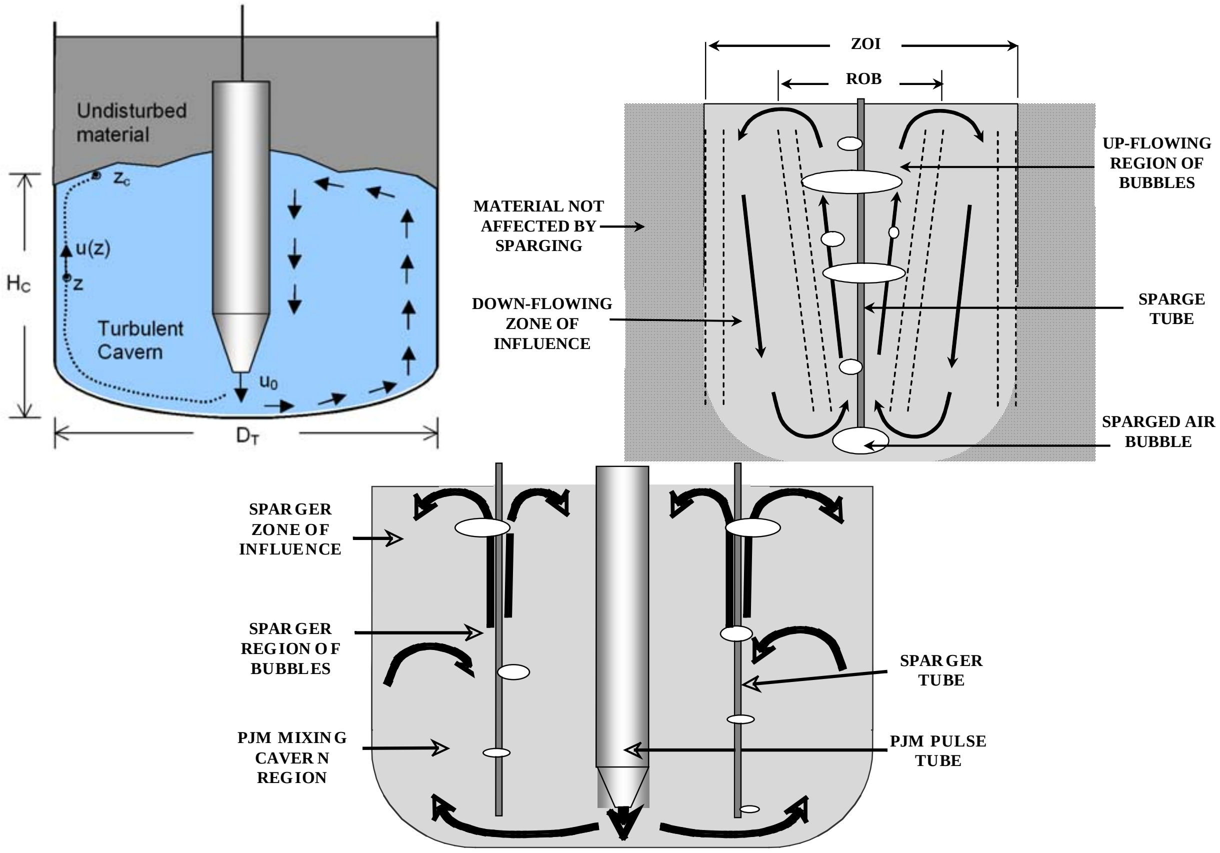

Fig. 1. Illustration of PJM mixing cavern (top left), air sparge mixing (top right), PJM/hybrid mixing concept (bottom)

unaffected by the spargers. The fluid flow regime is typically turbulent in the ROB and laminar in the ZOI. Each of these regions is separated by boundary layers that form the transition between the various regions and flow regimes.

By combining PJMs with air sparging to form a hybrid system the entire tank contents can be effectively mixed (Fig. 1 bottom). The PJMs are effective at mixing the lower regions of the tank. If the sparge tubes are submerged in the PJM mixing cavern, material will move between the lower and upper regions and the tank contents will be completely mixed.

Need for an Experimental Program

PJM technology had been used successfully in the past for mixing Newtonian fluids in radioactive environments. However, applying the technology to non-Newtonian slurries with a relatively high yield stress was new with the WTP, and an adequate supporting technical basis was not available. Initial efforts to rate the mixing system designs used a computational fluid dynamics (CFD) approach, but this was found to be beyond the state-of-the-art for existing codes. The major challenges included modeling yield stress materials, defining minimum velocities that accurately differentiated between moving and stationary regions, and modeling turbulent and laminar regions resulting from unsteady-state PJM operation. Similarly, an adequate technical basis for mixing with air sparging was not available. Accordingly, an integrated scaled testing approach was developed and implemented for the WTP vessels expected to contain non-Newtonian slurries.

The program essentially evolved into three phases. Phase I was the initial program to perform scaled testing of PJM-only systems and included development of simulants, development of methods to assess mixing behavior, testing to validate the PJM scaling approach for mixing and gas retention and release (GR&R) and tests in scaled prototypic WTP vessels. In Phase II, the program was expanded to include mixing with air spargers and steady jets provided by recirculation pumps. The addition of sparging required modifications to the scaled testing approach because sparge mixing does not scale easily. Instead, large-scale tests were conducted with single and multiple sparge tube arrays. In Phase III, tests were performed in a half-scale replica of the LS vessel to demonstrate various operational scenarios involving intermittent operation of the PJMs and air spargers.

Simulant Selection

Simulants were used for all of the testing due to the high cost and safety issues associated with using actual wastes in the quantities required for the PJM mixing program. Accordingly, two nonhazardous, relatively inexpensive simulants were developed and used for the majority of the testing, Laponite and kaolin-bentonite clay [3]. The simulants were selected based on limited actual waste slurry rheology measurements that indicate the WTP non-Newtonian waste stream can be represented by a Bingham plastic rheology model. The WTP specified bounding values are 30 Pa for yield stress (τ_y) and 30 cP for consistency (κ) for the Bingham plastic parameters. Other important physical parameters for the simulants are density and shear strength.

Laponite is a synthetic smectite clay mineral consisting of nanoscale crystals in the form of platelets that make a transparent solution when dispersed in water due to their small particle size. A range of rheological properties can be obtained by varying the concentration slightly. The shear strength ranged from 30 to 120 Pa with a yield stress that ranged from 0-10 Pa and a consistency in the range of 10 to 20 cP. The Laponite concentration was typically about 2 wt%, and the density of the resulting solution was slightly greater than that of water. Laponite was used primarily to represent the gelled-state conditions encountered by PJMs upon restart from idle periods. As such, shear strength was considered the important yield parameter. This simulant was extraordinarily useful for testing because it allowed direct visual observation of the mixing behavior.

A simulant developed by Rassat et al. [4] for Hanford tank retrieval studies was 80% kaolin and 20% bentonite powder mixed to various solids concentrations in water. At the proper solids concentration, this simulant has Bingham plastic properties near the target 30-Pa yield stress and 30-cP consistency. Additionally, unmobilized simulant developed a shear strength over about 12 hours that was 1.5 to 2 times the yield stress. Typical density was about 1200 kg/m^3. The rheological properties of the kaolin-bentonite clay simulant were characterized extensively for solids loadings in the 20 to 30 wt% range [3]. Unlike the Laponite, this simulant maintained the pertinent rheological properties when sheared and was therefore the simulant of choice for quantitative testing.

A limited amount of testing was completed with precipitated hydroxide simulants that mimic the chemical, rheological, and physical properties of selected pretreated waste samples. This simulant was used during the simulant development effort to bench mark the behavior of the clay and Laponite simulants. Extensive use of this type of simulant was precluded by high procurement costs and the hazardous characteristics of the materials.

SUPPORTING THEORY AND SCALE-UP

Small-scale testing is a common approach used successfully in many areas of applied fluid dynamics. The approach is successful because system performance usually depends on certain nondimensional groupings of physical parameters and, if these parameter groupings can be preserved at different geometric scales, the essential behavior of the system will be the same. This principle is referred to as similarity in the theory of fluid dynamics engineering. In complex fluid dynamic problems there can be many nondimensional parameter groups; however, often the essential behavior of the phenomenon is dominated by only a few key groups. In this situation, small-scale testing can produce results that are very close to large-scale behavior.

Pulse Jet Mixers

The scaling theory developed to describe PJM mixing of non-Newtonian fluids is based on turbulent steady jet theory that was modified to account for the periodic nature of the jets produced by the PJMs [5]. Based on rheological measurements of pretreated tank waste samples, the Bingham yield stress model was selected that represents the non-Newtonian fluid with a yield stress, τ_y, and a consistency factor, κ. A gelled slurry also exhibits shear strength, τ_s, that must be exceeded before the slurry begins to move. The PJM mixing theory was based on the concept of a mixing "cavern," which is a region near the PJM nozzles where the yielded slurry experiences turbulent flow that is bounded by unmobilized, gelled slurry. Gas retention and release scaling theory assumes gas is retained as bubbles that rise through the slurry in a well-mixed region but are fixed when mixing ceases[6]. Gas release occurs when the bubbles rise to the surface of the mixed vessel contents.

The non-Newtonian test program used geometric scaling in which the geometric scale factor was defined by $s = L_L / L_S$, where L_L is any characteristic linear dimension of the large-scale system (e.g., tank or nozzle diameter). At small scale, every linear dimension, L_S, was reduced or scaled by s. Thus, the small-scale test was a geometric miniature of the large system, with all areas scaled according to $A_S = A_L / s^2$, and all volumes scaled according to $V_S = V_L / s^3$.

When testing at small scale, one must determine how to scale velocity (i.e., PJM drive velocity, u_0). One choice is to scale velocity by the scale factor. This is problematic, however, because it tends to reduce the Reynolds number by $1/s^2$ and introduce further difficulties with the scaling of time. A better choice is to keep jet velocity constant at both scales ($u_{0_S} = u_{0_L}$).

For steady jet mixing, time does not come into play. However, PJM operation is a periodic process, so the scaling of time must be addressed. If velocity is held constant and geometry scaled, it follows that all imposed time scales must be reduced at small scale. Similarly, to keep the jet discharge velocity the same while scaling pulse volume geometrically, pulse time will be reduced by the scale factor according to $t_{DS} = t_{DL} / s$. Hence the PJM drive, refill, and cycle times are all reduced by s at small scale.

Scale factors up to about 10 are considered acceptable in typical fluid mixing tests; that is, much of the important physics can be captured at small scale. For the non-Newtonian test program, the design of scaled prototypic vessels was limited to conservative scale factors in the range of 4 to 5 due to the immaturity of the technology and the importance of the outcome. Testing to demonstrate the scaling laws was performed with scaling factors as high as 9.

Several important nondimensional groups were derived to characterize PJM mixing and gas retention and release processes. These groups and the associated scaling laws are summarized as follows:

Yield Reynolds number: $$Re_\tau = \frac{\rho u_0^2}{\tau}$$

Here ρ is the density, u_0 is the PJM discharge velocity, and τ is the relevant rheological stress parameter (either shear strength, τ_S, for a gelled slurry or yield stress, τ_y, for a slurry with Bingham-type behavior). Physically, the yield Reynolds number is the ratio of the jet dynamic stress to the non-Newtonian resistive stress of the slurry. This ratio directly affects the size of the mixing cavern. The yield Reynolds number will be the same at both large and small scales as long as the same simulant is used.

Jet Reynolds number: $$\mathrm{Re}_0 = \frac{\rho u_0 d_0}{\kappa}$$

Here d_0 is the PJM nozzle diameter and κ is the consistency of the slurry. The jet Reynolds number is the ratio of jet dynamic stress to viscous stress. It affects the degree of turbulence in the mixed region as well as transitional flow regimes associated with nonsteady mixing. It also affects cavern height. Because the yield Reynolds number was held constant, the jet Reynolds number was reduced at smaller scale. This resulted in a conservative testing approach because testing at reduced jet Reynolds numbers results in generally reduced mixing phenomena such as cavern height, magnitude of velocity, and degree of turbulence. The quality of mixing is therefore expected to improve at the large scale.

Strouhal number: $$S_0 = \frac{t_D u_0}{d_0}$$

The Strouhal number is the ratio of PJM drive time to the jet flow time scale. It affects the degree to which the jet approaches steady behavior. In the limit of steady jet flows, the Strouhal number becomes infinite, and the effects of pulsation are no longer present. For small Strouhal numbers, the mixing behavior is highly dominated by pulsation effects. If the drive time is reduced by the scale factor at small scale, the Strouhal number is held constant, and the essential nonsteady behavior of the mixing process is preserved.

Bubble rise time: $$\tau_R = \frac{V_s}{AU_R} = \frac{H}{U_R}$$

The bubble rise time, τ_R, is the time constant of the gas-release process in the well-mixed slurry bubble migration model. Here, the vessel fill level, H, equals the gas free slurry volume, V_s, divided by the area of the slurry surface, A. Because the bubble rise velocity, U_R, is roughly constant with scale, the bubble rise time is reduced in proportion to the vessel fill level, H. Hence at small scale it is reduced in proportion to the geometric scale factor.

The bubble rise time can be nondimensionalized by any characteristic time scale as follows:

Gas holdup number: $$N_\alpha = \frac{g_v V_s}{AU_R} = \frac{g_v H}{U_R} = g_v \tau_R$$

The gas holdup number represents the ratio of gas generated to gas leaving by virtue of bubble rise. It is equal to the theoretical holdup (volume of retained gas per volume of slurry) predicted by the bubble migration theory. If the specific volumetric gas generation rate, g_v, is increased by the geometric scale factor in the small-scale tests, the gas holdup, and therefore the gas holdup number, remains the same at large and small scale.

Gas release number:

$$N_R = \frac{t_C U_R}{H} = \frac{t_C}{\tau_R}$$

The ratio of PJM cycle time, t_C, or any relevant system time, to bubble rise time is defined as the gas release number. It directly affects gas release rates and other transients. The gas release number is preserved at small scale.

Air Sparging

The scaled testing approach developed for PJM mixing required some modification for air sparging [7]. The rising bubbles and the associated fluid interaction of the surrounding slurry exhibit nonlinear scale behavior, and a test program needed to develop nonlinear sparge mixing scale laws was impractical. Therefore, large-scale mixing tests were used to develop design guidelines for air sparging. First, the ZOI for a single sparge tube with nearly full-scale submergence was determined as a function of air flow rate. The ZOI (or some fraction of it to allow for overlap of mixing zones) is used as the distance between sparge tubes for multiple sparge tube arrays. This distance, together with the diameter of the vessel, determines the total number of sparge tubes. The scaling methodology for testing air sparge systems in reduced-scale tests involves maintaining the same superficial velocity and sparge number density as the full-scale design. Results of this scaling approach should be somewhat conservative because full-scale vessels have a greater sparge submergence depth, and more effective mixing can be expected for a given sparge mixing zone.

EXPERIMENTAL

Nine different test stands were constructed for all phases of the scaled testing (Table I). Initially, a single pulse tube was used in the development of simulants and to demonstrate cavern formation with PJMs. Three geometrically scaled vessels containing 4 PJMs in a square array were used for demonstrating the scale-up of PJM mixing behavior. Three scaled prototype vessels represented the UFP, LS, blend, and CRV plant vessels with scale factors ranging from 4 to 5. The actual plant LS and blend vessels are not exactly the same size and geometry, but were judged similar enough that a single LS prototype was a suitable representation for both. The scaled prototypes consisted of clear acrylic tanks with internals that could be reconfigured into many different mixing configurations. A half-scale replica of the LS vessel was used to demonstrate plant operating modes. Air sparging was investigated in a large cone bottom tank, initially with a single sparge tube and later with an array of 9 sparge tubes.

Tests performed in these test stands included cavern size and breakthrough (where the top of the cavern reaches the surface), mixing, sparging (introducing air bubbles at low level through multiple points), and gas retention/release. Mixing tests investigated mixing effectiveness, time to mix, solids suspension, and slurry velocity distribution. Sparging tests included determination of the size of the ROB and ZOI, aerosol generation, and velocity distributions.

Several methods were developed and implemented for assessing the effectiveness of the various mixing configurations and the time to mix. These methods involved the addition of various colored dyes, chemical tracers (e.g., sodium chloride)[13], passive integrated transponder (PIT) tags[7,9], and neutrally buoyant polymeric beads. The spatial and temporal distribution of these materials was monitored to assess the effectiveness of the mixing configurations. The monitoring techniques included grab and core sampling followed by chemical analysis [9,13], in situ monitoring with ion selective electrodes (ISEs), and antennas for detecting the PIT tags [7,9]. Ultrasonic Doppler velocity probes were used to determine the boundaries of mixed regions as well as to characterize velocities in the mixing regions [7,10].

Table I. Summary of Mixing Test Vessels and Applications

Vessel [ref]	Internals	Description	Scale	Approximate Volume L, (gal)
APEL Single PJM [8]	1 PJM	Single pulse tube in clear acrylic vessel	NA	950 (250)
Large-scale tank (336) [5]	4 PJMs	Four pulse tubes in stainless steel vessel	1	38,000 (10,000)
APEL(a) ¼ scale 4 PJM [5]	4 PJMs	Four pulse tubes in clear acrylic vessel	1:4.53 scale of 4 PJM Large-scale tank	950 (250)
SRNL(b) 1/9th scale 4 PJM [5,11]	4 PJMs	Four pulse tubes in clear acrylic vessel	1/9 scale of 336 4 PJM Large-scale tank	110 (30)
UFP scaled prototype [9,10]	Variable PJMs, spargers, recirculation pump	Scaled prototype representing UFP vessel	1:4.94 scale of full-scale UFP vessel	1,320 (350)
LS scaled prototype [9,10]	Variable PJMs, spargers, recirculation pumps	Scaled prototype representing LS and blend vessels	1:4.29 scale of full-scale LS vessel	3,800 (1,000)
CRV scaled prototype [12]	Variable PJMs, spargers, recirculation pump	Scaled prototype representing CRV	¼ scale of full-scale CRV	870 (230)
HSLS vessel	8 PJM cluster (7 around 1), 7 spargers	Half-scale LS (HSLS) vessel	½ scale of full-scale LS vessel	38,000 (10,000)
Cone bottom tank [7]	1 or 9 Spargers	Spargers in tank with cone shaped bottom	Similar to Large-scale tank	38,000 (10,000)

(a) Applied Process Engineering Laboratory
(b) Savannah River National Laboratory

Hydrogen peroxide decomposition was used to simulate uniform, constant gas generation in plant waste slurries [6,14]. Laponite simulant required addition of manganese dioxide catalyst to induce the decomposition. The clay simulant was sufficiently catalytic without additives. GR&R tests were planned carefully because hydrogen peroxide has a relatively high decomposition rate and must be mixed uniformly in the simulant to produce a uniform gas generation rate. However, hydrogen peroxide can be placed into only those regions that participate in mixing. The retained gas volume was determined by measuring the change in the simulant surface level relative to the degassed volume. Methods used to monitor the simulant levels included ultrasonic-type sensors, micropower impulse radar sensors, radio frequency admittance sensors, laser level sensors and manual measurements with tape measures.

EXPERIMENTAL VALIDATION OF SCALE-UP

PJM Mixing

The PJM scaled testing strategy was validated by testing geometrically similar 4 PJM mixing systems at three different scales, large, ~1/4, and ~1/9 scale. The data were compared nondimensionally to demonstrate the validity of testing prototypic PJM mixing systems at small scales. The complete scaling results including cavern tests over a range of aspect ratios, surface breakthrough measurements in clay and Laponite, and upwell velocity measurements in clay are presented in reference [5]. An example of the scaling results is shown in Fig. 2, where the nondimensional cavern heights in Laponite are plotted versus the yield Reynolds number. In addition several surface breakthrough points are included. Data for

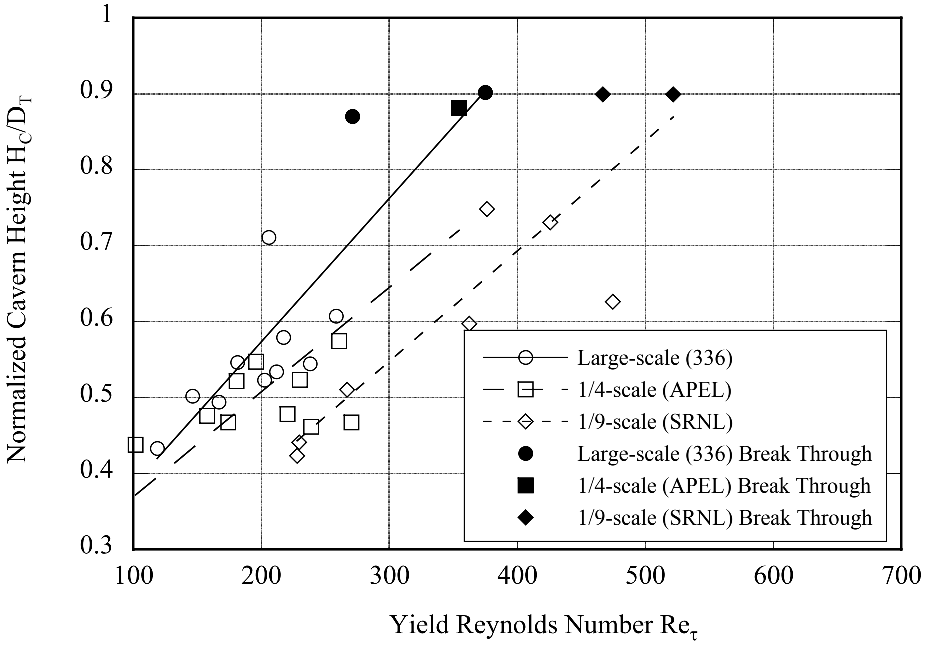

Fig. 2. Nondimensional cavern height (H_C/D_T) versus yield Reynolds number for Laponite; yield Reynolds number based on peak average PJM velocity; data limited to nondimensional fill level of $H/D_T = 0.9$

the three scale vessels are plotted separately, and linear regressions are also shown on the plot to aid in scale comparison. The data show that nondimensional cavern height increases with increasing yield Reynolds number. While some scatter exists in the data, the linear regression curves demonstrate that cavern heights are generally greatest in the largest vessel (336). This result is attributed to the fact that the jet Reynolds number increased with scale. Surface breakthrough velocity tests performed in both clay and Laponite also showed that the yield Reynolds number associated with surface breakthrough increased with the test scale factor. Upwell velocity measurements indicated that normalized velocities generally decreased with yield Reynolds number. While it was difficult to conclusively observe jet Reynolds number effects, the data suggest that upwell velocities are a weak, decreasing function of jet Reynolds number.

The scaling theory and experimental test results demonstrated that the mixing performance of PJM systems in non-Newtonian slurries can be conservatively assessed at small scale. The yield Reynolds number, which determines cavern formation due to non-Newtonian fluid behavior, was held essentially the same at small and large scale by employing a simulant with bounding rheological properties and using full-scale PJM velocities. The Strouhal number, which takes into account nonsteady PJM operation, was held the same at small and large scale by reducing the PJM cycle times by the geometric scale factor. The jet Reynolds number, which determines the flow regime (laminar or turbulent), the degree of turbulence, and the magnitude of mixing velocities, increases with the geometric scale factor when the rheological properties and PJM velocities are the same at both scales. Small scale tests are therefore conservative because large-scale mixing will always occur at higher jet Reynolds number and hence have a higher degree of turbulence.

Gas Retention and Release

The holdup scaling law derived from the well-mixed bubble migration model states that the holdup at steady state is equal to the volumetric gas generation rate multiplied by the gas release time constant, $\tau_R = H/U_R$, where U_R is the bubble rise velocity at the surface, and H is the slurry depth [6]. This means that, because the bubble rise velocity is roughly constant, the gas generation rate in a small-scale system should be increased by the scale factor to achieve the same holdup.

An example of some of the holdup test results is shown in Fig. 3 for some of the scaled tests that used a similar simulant rheology. The gas generation rates, at least between 336 and APEL, were in the correct proportion according to the length scale. As a result, the holdups are in the same range though the approach to steady state occurred at different rates. Results from other holdup tests and gas release tests in references [6] and [14] indicated greater uncertainty and fluctuations.

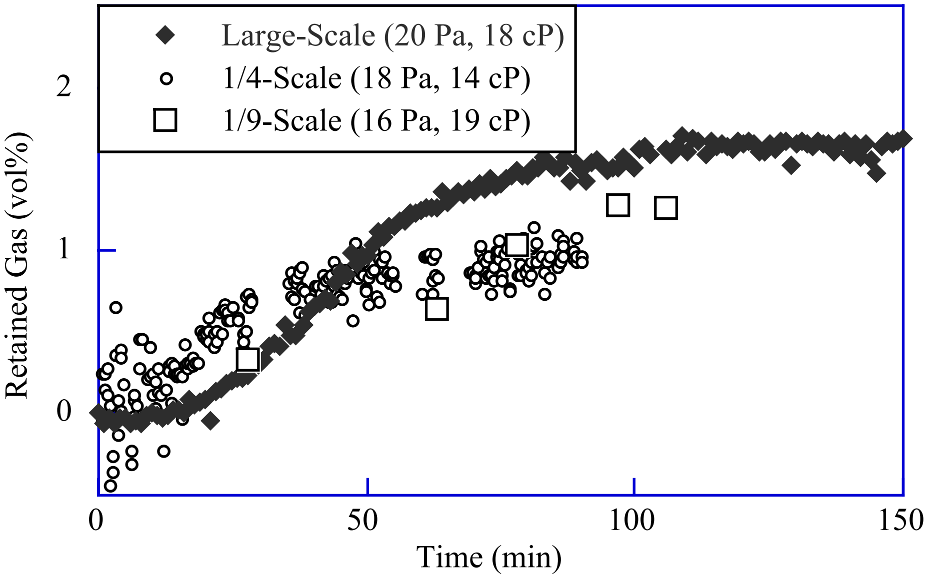

Fig. 3. Retained gas holdup test results in three scaled 4 PJM systems – Similar Rheology. Values in parentheses refer to the simulant yield stress and the consistency.

While uncertainty and fluctuations in the gas volume fraction during holdup tests makes comparison difficult, the holdup scaling law was qualitatively verified by test results from the three 4PJM systems. Though the results of scaled release tests were less conclusive, the simple gas and hydrogen peroxide mass conservation model predicted gas volume fractions that matched data from three-stage tests including holdup, accumulation, and the initial gas release periods. This result supports the gas bubble migration model as the fundamental description of the GR&R process.

Air Sparging

Single sparge tube performance data for ROB and ZOI provided the basis for specifying multiple sparge tube arrays for PJM/hybrid mixing systems. A power law correlation of the ROB and ZOI diameters at the simulant surface to the actual volumetric air flow rate at the sparge nozzle gives

$$D_{ROB} = 11Q_S^{0.34} \qquad \text{(Eq. 1)}$$

$$D_{ZOI} = 34Q_S^{0.34} \qquad \text{(Eq. 2)}$$

where D_{ROB} is the ROB diameter (in.), D_{ZOI} is the ZOI diameter (in.), and Q_S is the actual volumetric flow rate of the air at the sparge tube nozzle (ft^3/min) [7]. These data were collected over submergence depths that ranged from 1.7 to 3 m and results indicated that the ROB and ZOI diameters were a weak but increasing function of submergence depth.

The results from the single sparge tube tests were used to provide design guidelines for the multiple-sparge tube arrays. A conservative approach was used in which the sparge tubes were placed such that the ZOI from one sparge tube met the ROB from an adjacent sparge tube. This resulted in overlapping mixing zones to ensure that the entire tank contents were mixed. An additional conservatism results from the fact that the ROB and ZOI diameters will be somewhat larger at full scale due to increased submergence depth. As a general rule, there is a trade-off between the number of sparge tubes and total air requirement. As the number of sparge tubes is reduced, the air flow rate per sparge tube is increased such that the total airflow requirement is increased. Conversely, the total air flow can be reduced by increasing the number of spargers.

SCALED PROTOTYPE TESTING RESULTS

In Phase I of the test program several different PJM configurations were investigated [9]. The initial scaled tests demonstrated that the baseline pulse jet designs did not mix the non-Newtonian slurries to WTP requirements. The baseline PJM configurations consisted of pulse tubes placed around the outer portion of the tank creating a central upwell of the fluid. While these designs generally mixed the center of the tank, the upper portions near the tank walls remained stagnant.

Several PJM design features were varied to develop alternative configurations with better mixing performance. A list of the design variables and a summary of the findings are provided below:

- **The PJM cluster configuration** was found to be ideal when combined with the complementary flow patterns from air sparging and/or recirculation pumps and was implemented in Phase II testing.
- **Outward-angled PJM nozzles** improved mixing and were implemented in Phase II testing.
- **Increased nozzle velocity** improved mixing but decreased drive time and increased air demand. Nozzle velocities up to 12 m/s were implemented in Phase II testing.
- **Larger pulse tubes** improved mixing but increased air demand.
- **Larger-diameter pulse tube nozzles** improved mixing but greatly increased air demand.
- **Additional pulse tubes** placed at higher levels increased mixing in some regions but blocked the flow of the central upwell and increased air demand.
- **Multiple nozzles** for each pulse tube promoted regional mixing but this concept was rejected because of concerns with abrasive wear and fabrication difficulties.
- **Asychronous PJM operations** in which pulse tubes were activated at different times were not found to be effective.
- **Recirculation pumping** to provide steady jets was found to be effective and was implemented in Phase II testing.

Near the end of Phase I, an alternative "PJM-only" configuration was developed that mixed the vessels containing non-Newtonian slurries. These designs included additional pulse tubes, some at higher levels in the tank; increased nozzle velocity; and multiple nozzles. Complete mixing of the vessel contents was demonstrated by testing in scaled prototypes. However, the alternative PJM-only mixing systems were not acceptable because of their effect on the WTP facility designs and greatly increased compressed air consumption. Accordingly, Phase II of the program investigated PJM hybrid mixing systems with spargers and recirculation pumps added to minimize the impact to overall project cost and schedule. The PJMs were generally arranged in a central cluster configuration and used angled nozzles operating at a velocity up to 12 m/s. This design retained the baseline number of PJMs and the baseline nozzle size to limit demand on the air supply. The sparge systems and recirculation jets operated continuously.

Phase II testing demonstrated that PJM hybrid systems mixed non-Newtonian slurries in accordance with WTP requirements and provided safe flammable gas retention and control [10,12,14]. However, an engineering evaluation indicated that a recirculation pump was infeasible in the LS vessel and that full-time sparging would exceed the allowable vent system air capacity by a factor of 3. This difficulty was solved by introducing intermittent sparging to release retained gas after a quiescent period. The tests were conducted in a large-scale vessel with a nine-sparge tube array and clearly released most of the retained gas in about 5 minutes and all of the gas in 10–15 minutes, which showed that intermittent, full-flow sparging was feasible [7]. One-third-flow tests released gas much more slowly, indicating that continuous low-flow sparging might be adequate but would provide a reduced degree of mixing. Based on these successful sparger gas release results, the recirculation pumps were deleted from the LS and blend vessel designs.

The final PJM designs consist of pulse tubes in a central cluster configuration with a number of pulse tubes arrayed around a central tube [15]. The nozzles on the perimeter pulse tubes are angled radially outward at a 45° angle while the nozzle on the center tube points straight down. The pulse tubes are enclosed with a shroud to exclude wastes from the zones in between the pulse tubes that are difficult to mix. The cluster configuration provides good mixing for the lower portions of the vessel. Sparge tubes are placed around the PJM cluster to promote mixing in the upper regions of the vessel. For the UFP vessels, a steady jet provided by a recirculation pump is also available.

HALF-SCALE CONFIRMATORY TESTING

While Phase II testing covered most of the issues associated with management and scale up of mixing and flammable gas retention, a confirmatory demonstration of a large, correctly scaled hybrid mixing system was determined to be necessary [16]. This large-scale demonstration became Phase III of the test program. Testing was performed in a half-scale vessel representing the plant LS vessel during normal operations, post-design basis event (post-DBE) operations, and near term accident response (NTAR) operations. The normal operational mode consisted of continuous mixing with the PJMs and intermittent operation of the air spargers. The post-DBE operational mode consisted of intermittent operation of the PJMs and the air spargers. This mode of operation would be used in case of a design basis event such as an earthquake that leads to a loss of normal power to the plant. The near-term accident response operational mode consisted of intermittent operation of the air spargers. This mode of operation could be used in the event of a partial loss of air to the pulse jet mixers. In each test a repeating periodic state was achieved with moderate fluctuations of the maximum and minimum cyclic retained gas volume fractions. Mixing was reestablished early in each mixing cycle, and the retained gas accumulated during the off cycle was released with no measurable long-term buildup. Tests showed that full-flow, sparger-only (no PJMs) operation mixed more than 60% of the simulant volume with an unmixed heel of approximately 35%, including the PJM pulse tube volume. Mixing with both full-flow sparging and PJMs operating at half-stroke provided essentially 100% mixing of the vessel contents.

Phase III tests demonstrated that the selected hybrid design provided mixing and flammable gas control that meets WTP requirements during the normal and post-DBE operating scenarios. The larger unmixed volume associated with NTAR (sparging-only operation) would limit the time during which this scenario could be used to avoid excessive gas accumulation. Phase III was completed by applying the test results via a mass balance model to the plant-scale LS and blend vessels and extending the scale-up methodology to the plant-scale UFP vessels. The scaling laws for gas holdup and release were embodied in a gas inventory model that was fit to the HSLS data in a Monte Carlo uncertainty analysis to create probability distributions for gas release rate constants representing four mixing modes: PJMs and full sparging, PJMs and idle sparging, full sparging only, and idle sparging only. An example of a comparison of the model predictions to the data from the post-DBE test is shown in Fig. 4. The accumulated one-quarter and half-scale test data showed that gas release constants vary with both slurry yield stress and the product of volumetric gas generation rate and simulant depth, g_vH. A methodology was developed to account for these variations in the four parameters and apply them via the mass balance model to predict plant-scale GR&R behavior. The result includes both the uncertainty in the reduced data and the uncertainty in the scaling process itself. This process was also extended to scale up the one quarter-scale UFP test data.

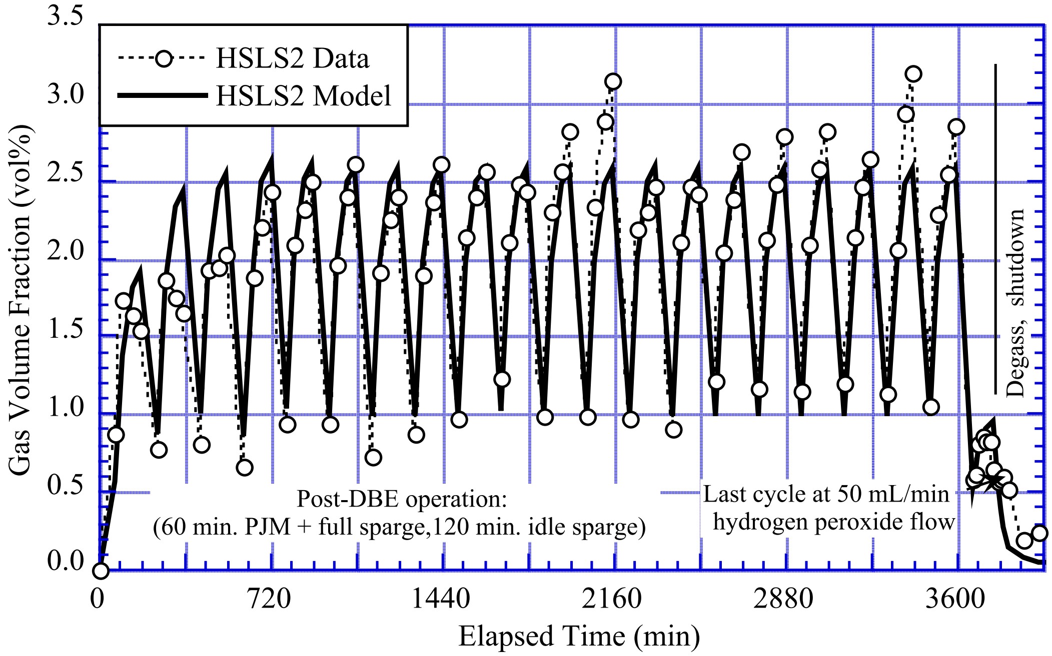

Fig. 4. Comparison of gas inventory model prediction for Post-DBE test

SUMMARY AND CONCLUSIONS

The WTP non-Newtonian PJM Test Program was planned and executed to provide a significant design margin for the mixing systems [17]. Conservative approaches were taken at each stage of the program. The kaolin-bentonite clay simulant was conservative because its Bingham plastic behavior bounds actual waste rheology, which exhibits shear-thinning behavior (i.e., the consistency is reduced with higher shear rates). Additionally, the yield stress of the simulant used in the scaled tests generally exceeded the design-basis upper bound of 30 Pa. The scaled test approach identifies three key nondimensional parameters that govern PJM mixing behavior. Two of these were preserved during testing (Strouhal and yield Reynolds numbers), and the third (jet Reynolds number) was smaller in the small-scale tests. This introduced another degree of conservatism because mixing performance is reduced at lower jet Reynolds numbers. This effect was confirmed by mixing tests that clearly demonstrated increased cavern height and fluid velocity with increasing vessel scale. Testing with sparge systems was also conservative. Tests were performed in vessels that were approximately one-half the full-scale vessel depth. The sparge ZOI increases somewhat with submergence depth, and the overall energy input increases nonlinearly with submergence depth. Therefore, mixing performance of sparge systems will be improved in plant-scale vessels. Additionally, sparge tube spacing involved significant ZOI overlap, and synergism between adjacent sparge mixing zones was not credited. The removal of hydrogen by mechanisms other than bubble migration (e.g., stripping by the sparge air or from the slurry surface) should be relatively larger (compared with bubble rise) at the lower generation rates found in the plant. This and the increased effectiveness of sparger mixing at full scale imply that the measured holdup in the small-scale tests with oxygen is higher than the WTP will experience. These factors, as well as others documented in the supporting test reports, ensure a significant degree of conservatism in the test results on which the WTP will base its designs.

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