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C. W. Stewart
P. A Meyer
M. S. Fountain
C. E. Guzman-Leong
S. A. Hartley-McBride
J. L. Huckaby
B. E. Wells

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Test Specification	24590-WTP-TSP-RT-05-0001 ^(a)
Test Plan	WSRC-TR-2005-00127 ^(a)
Test Exceptions	24590-PTF-TEF-RT-05-00016 ^(a)
R&T Focus Area	Pretreatment & Vitrification
Test Scoping Statement(s)	S-200 and B-100

(a) These documents were issued to define testing performed by Savannah River National Laboratory. Battelle – Pacific Northwest Division analyzed the data.



Battelle – Pacific Northwest Division
Richland, Washington, 99352

Completeness of Testing

This report summarizes the results of analysis of the data obtained by Savannah River National Laboratory as specified by the Test Specifications and Test Plans listed on the inside title page. The analyses and the report, which used data from, but did not involve laboratory testing, followed the quality assurance requirements outlined in Pacific Northwest Division's Waste Treatment Plant Support Project Quality Assurance Requirements and Description Manual.

The descriptions provided in this report are an accurate account of both the conduct of the work and the data analyses performed. A summary of the analysis results is reported. Also reported are any unusual or anomalous occurrences that are different from expected results. The analysis results and this report have been reviewed and verified.

Approved:

Gordon H. Beeman, Manager
WTP R&T Support Project

Date

Testing Summary

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 tanks at the Hanford Site. Pulse jet mixers (PJMs) along with air spargers and steady jets generated by recirculation pumps have been selected to mix the high-level waste (HLW) slurries in several tanks: the HLW lag storage (LS) vessels, the HLW blend vessel, and the ultrafiltration feed process (UFP) vessels. These mixing technologies are collectively called PJM/hybrid mixing systems.

This report addresses the reduction and analyses performed by Battelle – Pacific Northwest Division (PNWD) on data obtained from gas retention and release tests conducted in a small mixing vessel at Savannah River National Laboratory (SRNL) to determine the effect of a selected anti-foam agent (AFA) on gas retention and release behavior. These tests investigated bubbles representing the gases generated within radioactive waste but did not study the large sparged air bubbles used to enhance mixing in hybrid systems. Because the SRNL test mixing system is quite different from the PJM/hybrid mixing system, the results are not directly applicable to plant behavior.

The SRNL test vessel was equipped with mechanical mixing vanes to mobilize non-Newtonian simulants, auxiliary systems to inject air and hydrogen peroxide, and instrumentation and data acquisition systems to operate the system and monitor gas volume fraction. The tests used water and several simulants with non-Newtonian rheological properties representative of actual waste slurries. Simulants included Carbopol, kaolin/bentonite clay, and precipitated hydroxide slurry (AZ simulant) with chemical composition similar to actual Hanford Tank 241-AZ-101 waste (Eibling et al. 2003).

The PNWD effort is a continuation of gas retention and release work under Scoping Statement B-100 that was published in reports WTP-RPT-127 (Meyer et al. 2005) and WTP-RPT-132 (Bontha et al. 2005). Both of these reports recommended further investigation of the effects of AFA on gas retention. The specific scope is defined in WTP baseline change request (BCR) BCR-BNI-153 (June 8, 2006) for support to Bechtel National Inc. (BNI) Research and Technology (R&T) on non-Newtonian PJM testing. This BCR provided for ongoing technical consultation and support of testing at SNRL, including pre-analysis and test planning, data analysis/interpretation/application, draft and final reporting on the results of the data analysis. The actual testing activity was performed by SRNL under Scoping Statement S-200 and Test Exception 24590-WTP-TEF-RT-04-00012. Because of this division of work, many of the required topics below do not apply to PNWD work and are so noted.

Test Objectives

This section is not applicable. Testing was performed by SRNL.

Test Exceptions

This section is not applicable. Testing was performed by SRNL.

Results and Performance Against Success Criteria

This section is not applicable. Testing was performed by SRNL.

Quality Requirements

PNWD's Quality Assurance Program is based on requirements defined in U.S. Department of Energy (DOE) Order 414.1A, Quality Assurance, and 10 CFR 830, Energy/Nuclear Safety Management, Subpart A—Quality Assurance Requirements (a.k.a. the Quality Rule). PNWD has chosen to implement the requirements of DOE Order 414.1A and 10 CFR 830 Subpart A by integrating them into the Laboratory's management systems and daily operating processes. The procedures necessary to implement the requirements are documented through PNWD's Standards-Based Management System.

PNWD implements the DOE River Protection Project (RPP) WTP quality requirements by performing work in accordance with the PNWD WTP Support Program (SP) quality assurance project plan approved by the RPP-WTP Quality Assurance (QA) organization. This work was performed to the quality requirements of NQA-1-1989 Part I, Basic and Supplementary Requirements, NQA-2a-1990 Part 2.7 and DOE/RW-0333P Rev. 13, Quality Assurance Requirements and Description. These quality requirements are implemented through PNWD's WTPSP Quality Assurance Requirements and Description Manual. The analytical requirements are implemented through WTPSP's Statement of Work (WTPSP-SOW-005) with the Radiochemical Processing Laboratory Analytical Service Operations. Implementation of DOE/RW-0333P Rev. 13, Quality Assurance Requirements and Description, was not required for this work.

This report is based on data obtained from testing activities at SRNL. The PNWD WTPSP assumed that the data from these experiments transmitted by SRNL has been fully reviewed and documented in accordance with a BNI-reviewed and -approved QA Program at SRNL. PNWD did not perform any testing, but only analyzed data supplied by SRNL. At PNWD, the WTPSP Quality Assurance Program was applied to calculations performed on these data, reports of the results and conclusions derived.

PNWD addresses internal verification and validation activities by conducting an independent technical review of the final data report in accordance with PNWD procedure QA-RPP-WTP-604. This review verifies that the reported results are traceable, that inferences and conclusions are soundly based, and that the reported work satisfies the Test Plan objectives. This review procedure is part of PNWD's WTPSP Quality Assurance Requirements and Description Manual.

Test Conditions

SRNL followed the general test matrix specified in the test exception (Table S.1) in principle. However, as testing progressed and experience was gained, the matrix was expanded to include 391 additional tests (total of 401), though not all were actually performed. Thus, the final test matrix bears little comparison to Table S.1. Tests using air injection to simulate in situ gas generation generally supplanted hydrogen peroxide decomposition because it proved to be much faster and easier to apply.

Table S.1. Test Matrix from Test Exception 24590-PTF-TEF-RT-05-00016

Test No.	Gas Holdup	Test No.	Gas Release
1a	Water	1b	Same as 1a
2a	Water + Antifoam Agent	2b	Same as 2a
3a	Carbopol (~ 30 Pa)	1b	Same as 3a
4a	Carbopol (~ 30 Pa) + Antifoam Agent	4b	Same as 4a
5a	Clay (~ 12 Pa; 11 cP)	4b	Same as 5a
6a	Clay (~ 12 Pa; 11 cP) + Antifoam Agent	6b	Same as 6a
7a	Clay (~ 30 Pa; 30 cP)	7b	Same as 7a
8a	Clay (~ 30 Pa; 30 cP) + Antifoam Agent	8b	Same as 8a
9a	AZ-101 Simulant (~ 12 Pa; 11 cP)	9b	Same as 9a
10a	AZ-101 Simulant (~ 12 Pa; 11 cP) + Antifoam Agent	10b	Same as 10a

Not all of the tests that were performed were used in the analysis. The Carbopol tests, for example, were for visualization purposes only. Also, tests with clay simulant plus salt and AFA were not analyzed because the calculation of the components of the F_W factor, F_S and F_{AFA} , do not require those data (see Section 1 of this report). On the other hand, tests with water and water with salt and AFA added were analyzed to compare with prior bubble column tests and to assess the consistency of the data over the widest range of simulants. A few tests were not used because the results were anomalous or were compromised in some way. The data analyzed for which results are presented in this report are summarized in Table S.2. A detailed listing of the conditions and results of each test is provided in the appendix.

Table S.2. Data Analyzed to Meet Objectives

Simulant	Yield Strength (Pa)	Superficial Velocity (mm/s)	Agitator rpm	No. of Tests	No. of Tests Using Air Injection	No. of Tests Using H ₂ O ₂	No. of Tests Using AFA
AZ	11–12	0.05–7.7	650	17	15	2	None
AZ	13–14	0.01–7.8	650	47	41	6	21 (4 H ₂ O ₂)
AZ	28–30	0.026–7.9	940–970	15	13	2	7 (1 H ₂ O ₂)
AZ	2–29 ^(a)	0.05, 0.9	400–970	17	17	None	All
Clay	9–11	0.035–7.8	525	19	16	3	None
Clay	13	0.034–0.12	525	12	12	None	None
Clay	16	0.061–0.11	525	2	0	2	None
Clay	22	3.6–15	400	4	4	None	None
Clay	22	3.6–15	700	4	4	None	None
Water	NA	3.5–15	400–700	20	20	None	8
Water + salt	NA	3.5–15	550–900	12	12	None	8

(a) Special test series varying simulant yield stress by sequential dilution with AZ supernatant.

Simulant Use

The simulant used by SRNL was selected based on actual waste slurry measurements^(a) that indicate the WTP non-Newtonian waste stream can be represented by a Bingham plastic rheological model, which is represented by

$$\tau = \kappa\gamma + \tau_y \quad (\text{S.1})$$

where

τ = shear stress (Pa)

κ = consistency factor (Pa-s)

γ = strain rate or shear rate (1/s)

τ_y = Bingham yield stress (Pa), the assumed minimum stress required to initiate fluid movement as determined by a flow curve obtained by fitting rheological data with a Bingham plastic model.

The non-Newtonian waste stream upper bounding rheological values of $\tau_y = 30$ Pa and $\kappa = 30$ cP were identified based on limited data from actual waste slurries that can be represented by a Bingham plastic rheological model (Poloski et al. 2004). These values form the basis for the simulant used in this testing.

This task used a simulant chemically similar to radioactive waste in Hanford Tank 241-AZ-101, as developed by Eibling et al. (2003), that is referred to as “AZ simulant” or “AZ” in this report. The recipe for this simulant results in a slurry with a Bingham yield stress of 13 Pa. A thicker version with 28–30 Pa yield stress was produced by allowing the slurry to settle and decanting a calculated volume of supernatant. Other simulants were also used, including water, salt water, Carbopol, and a 20/80% mixture of kaolin/bentonite clay with rheological properties similar to the AZ simulant to provide a basis for assessing the effect of chemistry.

Results of Data Analysis

Data were analyzed from tests in the SRNL mixing vessel using water, water with salt and AFA, clay simulant, and AZ simulant with and without AFA. The gas volume fractions, α , derived from the test data all followed a power law, $\alpha = AU_s^B$, increasing with superficial velocity, U_s .^(b) Both the coefficient A and exponent B varied with simulant type, yield stress, and agitator rpm, though the variation in B was much less. In addition:

- Gas volume fractions increased approximately in proportion to agitator rpm.
- Gas volume fractions did not appear to vary significantly with simulant yield stress in absence of AFA. Changes with yield stress were masked by the effect of agitator rpm because higher rpm was necessary to mix stiffer simulants.

(a) The development and selection of non-Newtonian waste simulants for use in WTP PJM testing are summarized in Poloski et al. (2004).

(b) The superficial velocity is equal to the volumetric rate of gas introduction (i.e., gas generation) divided by the vessel cross-sectional area.

- Gas volume fractions were higher in AZ simulant than in clay and much higher in AZ simulant with AFA than without.
 - o The effect of AFA in raising the gas volume fraction increased markedly with decreasing yield stress, dominating the counter-effect of decreasing agitator rpm required to mixing thinner slurry. This result indicates that 30 Pa is not the bounding yield stress for gas retention.
 - o The trend of increasing gas volume fraction with decreasing yield stress in simulants with AFA is weaker at lower superficial velocity.

Values for the simulant factor, F_S , the AFA factor, F_{AFA} , and the combined waste factor, F_W (which is the product of F_S and F_{AFA}) were derived directly from SRNL mixing vessel data for simulants with 10- to 13-Pa yield stress. The factors could also be estimated for simulants with 30-Pa yield stress. These factors generally increase exponentially with decreasing superficial velocity (see Figures 5.22 and 5.23 in this report).

For 10- to 13-Pa simulants in the SRNL vessel, the factors are defined as follows:

$$F_S(13 \text{ Pa}) = 1.582 U_s^{-0.077}$$

$$F_{AFA}(13 \text{ Pa}) = 2.958 U_s^{-0.106}$$

$$F_W(13 \text{ Pa}) = 4.706 U_s^{-0.177}$$

For 30-Pa simulants, the factors are estimated as follows:

$$F_S(30 \text{ Pa}) = 1.21$$

$$F_{AFA}(30 \text{ Pa}) = 1.580 U_s^{-0.064}$$

$$F_W(30 \text{ Pa}) = 1.927 U_s^{-0.064}$$

At a superficial velocity of 0.01 mm/s, $F_W(13 \text{ Pa})$ is ~10.7 and $F_W(30 \text{ Pa})$ is ~2.5.

The power law relationship between the bubble rise velocity and gas volume fraction indicated by the SRNL data inspired a revised gas release model that substitutes this power relationship for the original assumption of a constant bubble rise velocity. The model fits essentially all the SRNL release data, data from ~1/4-scale PJM hybrid systems, and data from sparge-induced release tests in the PNWD cone-bottom tank equally well with consistent parameter values (see Section 5.4). This model implicitly bases gas release parameters on the corresponding steady-state values. Thus, by definition, gas release behavior is affected by AFA, simulant rheology, and other factors in the same way as steady-state holdup.

Discrepancies and Follow-on Tests

No discrepancies are noted. The follow-on tests described below are recommended.

The strength of the AFA effect on gas retention confirmed in the SRNL tests and the unexpected effect of AFA in increasing the holdup with decreasing yield stress have broad implications in plant operation, especially concerning sparger operation. It is likely that the AFA would reduce the size of sparged bubbles or increase their tendency to break up, thereby increasing sparger holdup by a potentially large factor. The net effect of this change on mixing effectiveness and gas release is unclear. A series of tests with AZ simulant with and without AFA in a vessel of sufficient size to allow study of large sparge bubbles would reveal any potential problems.

Because these tests confirmed that AFA greatly increases gas retention and slows gas release, it is important to estimate the consequences of these effects on full-scale plant operations. Because the SRNL vessel mixing system was very different from plant PJM/hybrid systems, the SRNL data do not provide the necessary technical basis for these predictions. A similar series of tests in a larger-scale prototype PJM/hybrid-mixed vessel using clay, AZ simulant (or similar chemical simulant) and AZ simulant with AFA over a range of yield stress and gas generation rates is recommended to provide this basis. The sparger holdup tests recommended above, as well as sparger mass-transfer tests, could also be performed in this vessel under the same test program.

The results of the above recommended prototype PJM/hybrid tests, along with the SRNL data, will provide a much better and more detailed definition of the F_W factor and the variation of bubble rise velocity with yield stress than is currently used in the gas retention and release scale-up model given by Bontha et al. (2005). The new gas release model described in Section 5.4 is consistent with the data and provides a better description of gas release. The current scale-up model should be updated to incorporate these new data and improved models.

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Acronyms and Abbreviations

AFA	anti-foam agent
AZ	nonradioactive chemical simulant representing the waste in Hanford Tank 214-AZ-101
BCR	baseline change request
BNI	Bechtel National, Inc.
DOE	U.S. Department of Energy
GR&R	gas retention and release
H ₂ O ₂	hydrogen peroxide
HLW	high-level waste
HSLs	half-scale lag storage
LS	lag storage
PNWD	Battelle – Pacific Northwest Division
PJM	pulse jet mixer
QA	quality assurance
ROB	region of bubbles
RPP	River Protection Project
SRNL	Savannah River National Laboratory
UFP	ultrafiltration feed process
WTP	Waste Treatment Plant
WTPSP	Waste Treatment Plant Support Project
ZOI	zone of influence

Nomenclature

α	gas volume fraction
α_0	initial gas volume fraction
$\alpha_{\min}, \alpha_{\max}$	minimum and maximum gas volume fractions occurring during cyclic mixing
α_{ss}	steady-state gas volume fraction
$\Delta\rho_{ps}$	measured difference between actual and ideal density of hydrogen peroxide solution (g/mL)
γ	strain rate (1/s)
κ	consistency factor in the Bingham plastic model (Pa-s)
σ	standard deviation

ρ_m	density of slurry plus hydrogen peroxide in a mixing volume (g/L)
ρ_{ps}	density of hydrogen peroxide solution (g/L)
ρ_w	density of water (g/L)
τ	shear stress (Pa)
τ	time constant (s)
τ_R	gas release time constant (s)
τ_s	shear strength (Pa)
τ_y	yield stress in the Bingham plastic model (Pa)
v	variance
A	coefficient of power function AU_s^B
A	vessel cross-sectional area (m^2 or L/mm)
B	exponent in power function AU_s^B
C_p	molar concentration of hydrogen peroxide (mole/L)
E_a	activation energy (J/mole)
F_1, F_2, F_3	fractions of retained gas volume that follow release time constants τ_1, τ_2, τ_3
F_{AFA}	bubble rise reduction factor comparing chemical simulant with and without AFA
F_R	bubble rise reduction factor comparing chemical simulant with AFA to radioactive waste with AFA
F_S	bubble rise reduction factor comparing clay simulant to chemical simulant without AFA
F_W	bubble rise reduction factor comparing clay simulant to radioactive waste with AFA
g_v	volumetric gas generation rate (1/s)
h	measured simulant level (mm)
H	effective slurry depth (m or mm)
k_0	reaction rate constant at reference temperature $T_0 = 298K$ (1/s)
k_e	mass transfer coefficient for surface evaporation (m/s)
k_p	reaction rate constant (1/s)
m_e	mass of water evaporated (g)
m_p	mass of unreacted hydrogen peroxide in the simulant (g)
m_w	mass of water created by hydrogen peroxide decomposition and added with the hydrogen peroxide solution (g)
M_p	molecular weight of hydrogen peroxide (34 g/mole)
N	number of data points
p_a	ambient atmospheric pressure (Pa)

p_g	pressure of the gas in the simulant (Pa)
p_{vs}	water vapor pressure (Pa)
Q_g	volumetric rate of air injection (L/s)
Q_{ps}	volumetric rate of injection of hydrogen peroxide solution (L/s)
R	gas constant (8.3145 J/mole-K)
RH	relative humidity (%)
R_p	decomposition reaction rate (mole/L-s)
S_{test}	vessel scale factor for a test (length scale of a test/length scale of plant vessel)
t	time (s)
T	temperature (K)
T_a	ambient air temperature (K)
T_s	simulant temperature
U_R	bubble rise velocity (mm/s)
U_{R0}	initial bubble rise velocity (mm/s)
U_{RSS}	steady-state bubble rise speed (mm/s)
U_S	superficial velocity (mm/s)
v	T-statistic
V_c	volume loss due to splatter or cakeout on vessel walls (L)
V_e	volume of water lost by evaporation (L)
V_g	volume of gas in the simulant (L)
V_m	fictitious mixing volume to represent observed time lag in the effect of hydrogen peroxide injection (L)
V_p	volume of unreacted hydrogen peroxide (L)
V_{sim}	volume of simulant excluding gas (L)
V_w	volume of water produced by hydrogen peroxide decomposition and added with the solution (L)
x_m	mass fraction of hydrogen peroxide into a fictitious mixing volume
x_p	mass fraction of hydrogen peroxide in injected solution

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1.0 Introduction

The 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. Some of the WTP process streams are waste slurries containing relatively high concentrations of solids that are expected to exhibit non-Newtonian rheological behavior where some shear must be applied before the material begins to move or flow.

Seven tanks were projected to contain non-Newtonian slurries. Mixing of these complex fluids must be sufficient to satisfy process requirements. Frequent complete mixing is also required to prevent hazardous volumes of flammable gases generated by radioactivity and chemical reactions from building up in layers of immobile settled solids.

Pulse-jet mixer (PJM) technology is planned for mixing most vessels in the WTP because PJMs have no moving mechanical parts that require maintenance. PJM technology had been used successfully in the past for mixing Newtonian fluids in radioactive environments; however, application of the technology to non-Newtonian slurries was new with the WTP, and an adequate supporting technical basis was not available. Accordingly, an integrated scaled testing approach was developed and implemented for the WTP vessels expected to contain non-Newtonian slurries (Meyer et al. 2005).

A robust scaling theory was developed to describe PJM mixing of non-Newtonian fluids (Bamberger et al. 2005). Based on rheological measurements of pretreated tank waste samples, the Bingham yield stress model was selected to represent the non-Newtonian waste streams using a yield stress, τ_y , and a consistency factor, κ (Poloski et al. 2004). Gelled slurry, an immobile solid, also exhibits shear strength, τ_s , which must be exceeded before it begins to flow. The PJM mixing theory was based on the concept of intermittent mixing within the PJM "cavern," a region near the PJM nozzles where the yielded slurry experiences turbulent flow that is bounded by immobile, gelled slurry.

To mix the region above the PJM cavern, air spargers were added to form the current "hybrid" mixing system. Correlations were developed for the size of the upwelling region of bubbles (ROB) and the downward flow in the wider zone of influence (ZOI) due to sparging (Poloski et al. 2005). Adequate mixing is ensured if sparge tubes are arranged so there is adequate overlap of the individual sparging-induced mixing regions. The hybrid mixing system concept is illustrated in Figure 1.1.

Hybrid mixing is not completely uniform or continuous. The PJM pulses produce jets that mix the slurry only once every few minutes. Spargers may not operate continuously. Gas retention and release scaling theory in a non-Newtonian slurry assumes that gas exists as discrete bubbles that rise through the slurry in a mixed (i.e., mobilized and flowing) region but are fixed when mixing ceases. The retained gas volume fraction, $\alpha(t)$, is determined by the following expression (Russell et al. 2005):

$$\alpha(t) = \alpha_0 e^{-\frac{U_R}{H}t} + g_v \frac{H}{U_R} \left(1 - e^{-\frac{U_R}{H}t} \right) \quad (1.1)$$

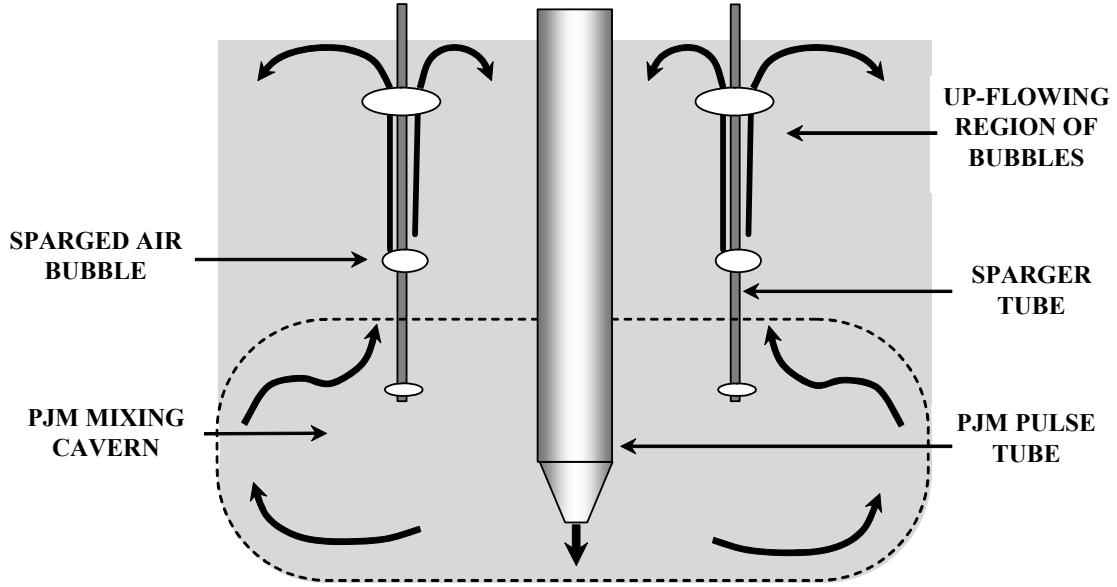


Figure 1.1. Illustration of Hybrid PJM/Sparger Mixing Concept

where

α_0 = initial gas volume fraction (volume of gas/total slurry + gas volume)

U_R = average or effective bubble rise velocity at the surface (m/s)

H = effective slurry depth (m), equal to the total slurry volume divided by the vessel cross-sectional area at the surface.

g_v = volumetric gas generation rate (1/s), (volume of gas generated/unit volume of slurry/unit time).

The effect of mixing on gas retention and release is defined by the time constant H/U_R , where U_R includes the combined effects of intermittency and nonuniformity. The higher the bubble rise speed or the lower the slurry depth, the faster gas is released and the lower the retained gas volume fraction is. If mixing continues for a long time, Eq. (1.1) reduces to a steady-state form:

$$\alpha_{ss} = g_v \frac{H}{U_R} \quad (1.2)$$

Gas accumulates during periods when the mixing system is not operating, the slurry becomes a solid, and U_R is zero. In this condition, Eq. (1.1) reduces to

$$\alpha(t) = \alpha_0 + g_v t \quad (1.3)$$

If only part of the mixing system is operating (e.g., PJMs are on and spargers are off during normal operation), the effective U_R is not zero but is reduced to represent nonuniform or less-effective uniform mixing. Therefore, in cyclic operation, a repeating quasi-steady cycle occurs where the maximum gas volume fraction, α_{max} , at the end of the off (or reduced mixing) period is described by Eq. (1.3) or (1.1) with a reduced U_R and α_0 set to the minimum gas volume fraction, α_{min} . This minimum gas volume fraction occurs at the end of a mixing period and is defined by Eq. (1.1) with α_0 set to α_{max} from the

preceding reduced mixing period. If the mixing period lasts for several time constants, $\tau = H/U_R$, then $\alpha_{\min}$ can be approximated by Eq. (1.2).

A large-scale test was performed to confirm that the mixing and gas retention/release scaling theories hold under these cyclic conditions and to demonstrate that full mixing was reestablished and accumulated gas released each cycle. The test represented the plant lag storage (LS) vessel at half scale. Tests included normal operations with continuous PJM operation and intermittent sparging, post-design-basis event operations with intermittent operation of both PJMs and spargers, and a near-term accident response scenario with intermittent sparging only (Bontha et al. 2005).

A simple gas inventory model based on the above scaling laws was applied to the cyclic mixing test data to establish probability distributions representing the effective values of the bubble rise speed, U_R , for each mode of the cyclic operation (i.e., PJMs + full spargers, PJMs only, spargers only, etc.). An example of the half-scale test data compared to the data reduction model is shown in Figure 1.2 (taken from Bontha et al. 2005). The scale-up process modified these derived parameters to account for differences in physical scale, rheological properties, gas generation rates, and fluid type using a Monte Carlo simulation to correctly include variability in the test data, measurement uncertainty, and uncertainty in the scale-up process itself.

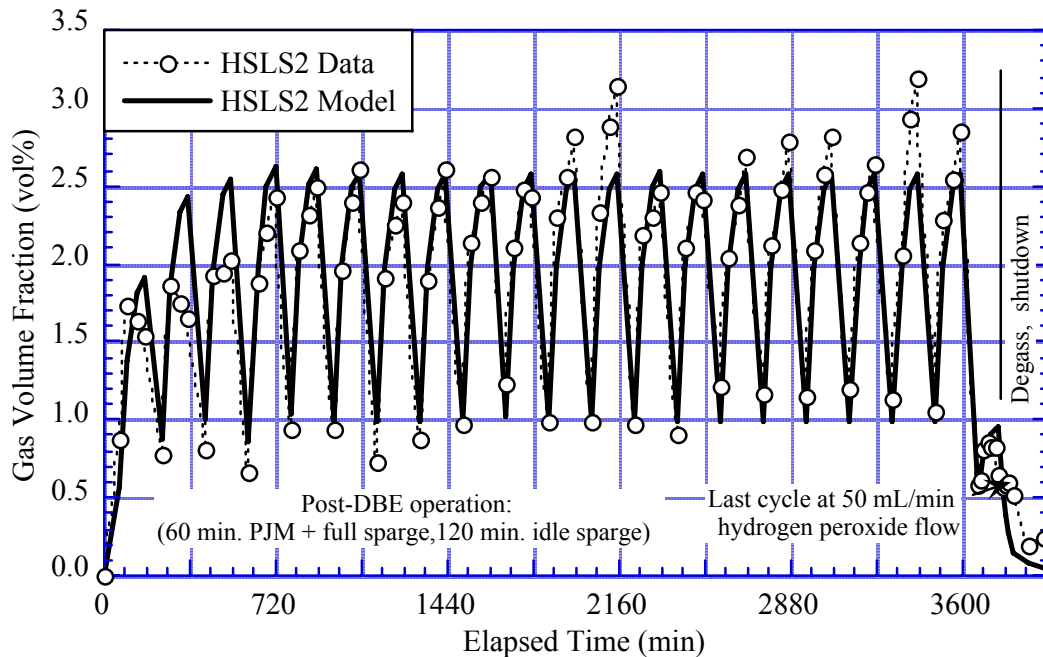


Figure 1.2. Comparison of Gas Inventory Prediction with Half-Scale Test Data

The largest source of uncertainty in the scale-up process is the difference between the behavior of the clay simulant used in the test and the radioactive waste slurry in the plant, including the chosen anti-foam agent (AFA). A waste factor, $F_w > 1$, expresses this difference as the ratio of the bubble rise speed in clay

simulant to that in waste with AFA under the same conditions.^(a) Ignoring the second-order effects, the resulting scale-up expression is

$$\left(\frac{U_R}{H}\right)_{\text{plant}} = \left(\frac{U_R}{H}\right)_{\text{test}} \frac{S_{\text{test}}}{F_W} \quad (1.4)$$

where S_{test} is the scale factor of the test (e.g., 0.5 for the 1/2-scale test).

The F_W factor is recognized to be a product of several subfactors. The first, F_S , is the ratio of the bubble rise speed in clay to that in a nonradioactive chemical simulant representing the waste in Hanford Tank AZ-101. The next subfactor, F_{AFA} , is the ratio of bubble rise speed in AZ simulant to that in the same simulant containing AFA and the last, F_R , is the ratio of bubble rise speeds in AZ simulant with AFA to plant radioactive waste slurry with AFA. Thus, F_W is given by

$$F_W = \left(\frac{U_{R-\text{clay}}}{U_{R-\text{AZ}}}\right) \left(\frac{U_{R-\text{AZ}}}{U_{R-\text{AZ+AFA}}}\right) \left(\frac{U_{R-\text{AZ+AFA}}}{U_{R-\text{waste+AFA}}}\right) = F_S F_{\text{AFA}} F_R \quad (1.5)$$

To evaluate the ratios making up F_W , data are needed from gas retention and release tests in clay, AZ simulant (or other appropriate chemical simulant), and AZ simulant with AFA, all with the same rheological properties. At the time of the half-scale test, the only data available to quantify the effect of AFA were obtained from small bubble-column tests (Russell et al. 2005). These results indicated that F_{AFA} might be as high as 10, but the data were conflicting and controversial. These same tests also showed that F_S was approximately 1.0. Because it is impossible to perform tests in radioactive waste, and AZ simulant was designed specifically to represent radioactive waste from Hanford Tank 241-AZ-101, F_R was also assumed to be 1.0 by consensus since no gas retention test data in actual waste are available to evaluate it.

The two main concerns with using the bubble column data were that 1) the bubbles representing the retained gas also provided the mixing, and 2) the bubbles were generated at a frit at the base of the column, a process that might be much more strongly affected by an AFA than bubbles generated in situ. These concerns and the high uncertainty in value of F_W from the bubble column data prompted the following discrepancy in the overview report of the PJM test program (Meyer et al. 2005):

While the current test data using a clay simulant provide an adequate basis to account for physical scale-up to plant operation, the difference in gas retention and release (GR&R) behavior between clay with gas generated by hydrogen peroxide decomposition and radioactive waste slurry containing anti-foaming agent with gas generated by a radiothermal process is not known. Small-scale GR&R tests using clay and AZ-101 chemical simulant with and without an anti-foaming agent are planned to quantify the difference.

This discrepancy eventually led to a test program at Savannah River National Laboratory (SRNL) to quantify the effect of AFA more precisely. The tests were performed in the existing SRNL 1/9-scale

(a) Because the gas volume fraction is inversely proportional to the bubble rise speed via Eq. (1.2), the ratio may also be expressed as the gas volume in waste with AFA to that in clay simulant.

4-PJM test stand with a mechanical agitator replacing the PJMs to ensure complete, continuous mixing of the simulant. Tests were conducted with water, kaolin/bentonite clay simulant, and AZ-101 chemical simulant with and without AFA and with several sets of rheological properties. Thus, the results provide information on the magnitude and dependencies of both F_{AFA} and F_S as applies to mixing conditions in this vessel. In planning these tests, it was recognized that future tests in a larger vessel with a prototypic mixing system might be required, depending on the magnitude of these factors.

This report describes the reduction and analysis of the data from the SRNL tests and presents the results. Section 3 briefly describes the test apparatus and conduct of the tests.^(a) The data reduction model is presented in Section 4, and the results are given in Section 5. Conclusions on the value and uncertainty in F_w and the implications for scaling analysis are presented in Section 6. References are listed in Section 7, and test conditions and analysis results are listed in the appendix.

(a) Guerrero HN and MD Fowley. 2006. *Testing to Determine the Effect of Antifoam Agent on Gas Holdup and Release Rate from non-Newtonian Slurries* (Draft). SRNL, Aikin, South Carolina.

2.0 Quality Requirements

PNWD's Quality Assurance Program is based on requirements defined in U.S. Department of Energy (DOE) Order 414.1A, Quality Assurance, and 10 CFR 830, Energy/Nuclear Safety Management, Subpart A—Quality Assurance Requirements (a.k.a. the Quality Rule). PNWD has chosen to implement the requirements of DOE Order 414.1A and 10 CFR 830 Subpart A by integrating them into the Laboratory's management systems and daily operating processes. The procedures necessary to implement the requirements are documented through PNWD's Standards-Based Management System.

PNWD implements the RPP-WTP quality requirements by performing work in accordance with the PNWD WTPSP quality assurance project plan approved by the RPP-WTP Quality Assurance (QA) organization. This work was performed to the quality requirements of NQA-1-1989 Part I, Basic and Supplementary Requirements, NQA-2a-1990 Part 2.7 and DOE/RW-0333P Rev. 13, Quality Assurance Requirements and Description. These quality requirements are implemented through PNWD's WTPSP Quality Assurance Requirements and Description Manual. The analytical requirements are implemented through WTPSP's Statement of Work (WTPSP-SOW-005) with the Radiochemical Processing Laboratory Analytical Service Operations. Implementation of DOE/RW-0333P Rev. 13, Quality Assurance Requirements and Description, was not required for this work.

This report is based on data obtained from testing activities at SRNL. PNWD WTPSP assumed that the data from these experiments transmitted by SRNL has been fully reviewed and documented in accordance with a BNI reviewed and approved QA program at SRNL. PNWD did not perform any testing but only analyzed data supplied by SRNL. At PNWD the WTPSP QA program was applied to calculations performed on these data, reports of the results and conclusions derived.

PNWD addresses internal verification and validation activities by conducting an independent technical review of the final data report in accordance with PNWD procedure QA-RPP-WTP-604. This review verifies that the reported results are traceable, that inferences and conclusions are soundly based, and that the reported work satisfies the Test Plan objectives. This review procedure is part of PNWD's WTPSP Quality Assurance Requirements and Description Manual.

3.0 Test System and Method

The tests were performed at the Engineering Development Laboratory at SRNL. This section describes the test apparatus and test procedures developed by SRNL.^(a)

3.1 Test Stand

The primary concern in the PNWD bubble column tests (Russell et al. 2005) was that the same bubbles studied for gas holdup also mobilized the non-Newtonian simulant. To allay this concern, a mechanical agitator system was installed in the SRNL tank to provide radial and axial mixing independent of the introduced gas bubbles. Use of the originally installed 4-PJM system was considered initially, but the difficulty in measuring small level changes in an inherently fluctuating system and the relatively poor mixing provided by this nonprototypic system led to choosing the mechanical agitator. This system was deemed adequate for the primary purpose, investigating the effect of AFA understanding that future tests in a prototypic mixing system might be necessary.

The test stand consisted of a 152-L (40-gal), elliptical-bottom tank, a mechanical agitation system, two separate systems for generating bubbles in the simulant (air injection and hydrogen peroxide injection), devices to measure the height of the simulant in the vessel, and several ancillary support systems. These components are shown in Figure 3.1.

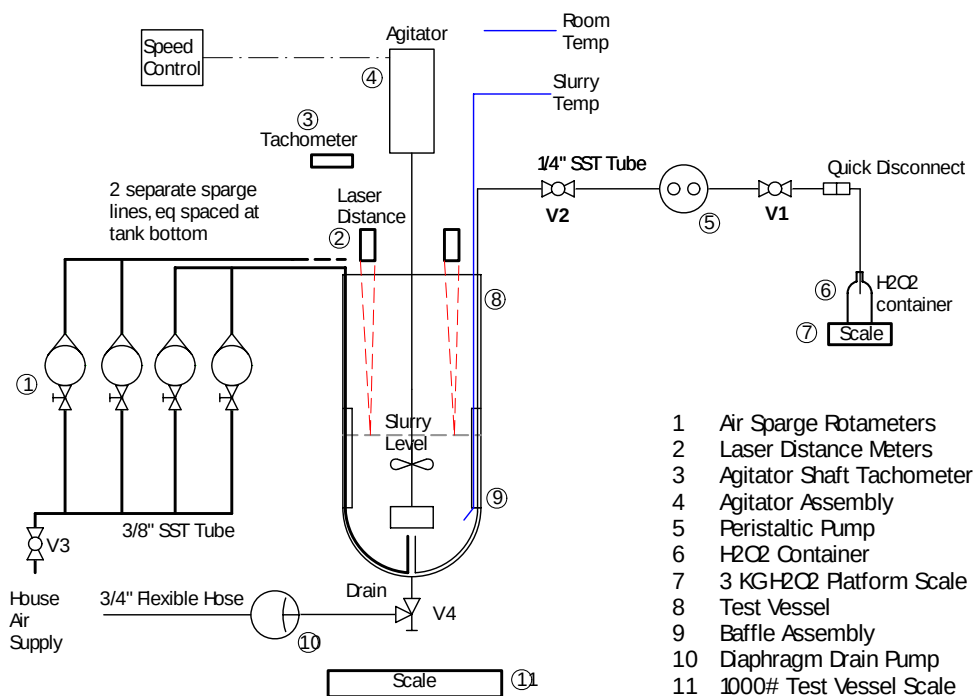


Figure 3.1. Test Stand Schematic

(a) Guerrero HN and MD Fowley. 2006. *Testing to Determine the Effect of Antifoam Agent on Gas Holdup and Release Rate from non-Newtonian Slurries* (Draft). SRNL, Aikin, South Carolina.

The vessel has an inner diameter of 17.25 in. (43.8 cm), clear acrylic sides, and a stainless steel elliptical bottom fabricated from an 18-in. schedule 40 pipe cap. The height of the side wall is 38.5 in. (97.8 cm), and the overall height from the bottom center is 43 in. (109.2 cm). Four equally spaced vertical baffles were installed flush with the top of the elliptical bottom section and spaced 0.1 in. (2.5 mm) from the wall. The baffles are 22 in. (55.9 cm) long and 1.5 in. (3.8 cm) wide (baffle width/tank diameter $\sim 1/12$).

The test vessel rested on a platform scale so that mass changes due to evaporation, sampling, and chemical additions could be measured. Simulant temperature was measured continuously with a thermocouple immersed in the slurry. Equipment, wiring, and tubing attached to the test vessel were minimized to maintain an accurate weight reading.

3.1.1 Mixing System

The impeller system and baffles in the test vessel were selected to provide thorough mixing of a non-Newtonian fluid with a yield stress up to 30 Pa at a tip speed of ~ 5 m/s (1000 ft/min) at ~ 700 rpm. The agitators consisted of an upper 5.25-in.- (13.3-cm-) diameter axial mixing impeller and a lower 5.25-in. (13.3-cm) radial flow mixing impeller. The lower radial impeller, specifically designed to break up gas bubbles, was installed with the lower edge of the cylindrical section ~ 5 in. (12.7 cm) above the tank bottom. The upper axial impeller, placed about one impeller diameter above the lower impeller, drove flow upward. A photograph of the agitators and baffles is shown in Figure 3.2.



Figure 3.2. Photograph of Water-Filled Vessel and Agitators

3.1.2 Gas Introduction System

Gas bubbles were either introduced by direct air injection or generated in situ by decomposition of hydrogen peroxide into oxygen gas and water. While hydrogen peroxide decomposition most closely represented in situ radiolytic and thermolytic gas generation in the plant, tests using air injection were much faster to run. Because both types of tests provided similar results (Section 5), most tests employed direct air injection.

When direct air injection was used, the air was injected through two sets of rotameters (one set for higher flows of 2.5 to 21 scfm and another for lower flows of 2 to 522 mL/min) via tubes routed down the tank wall along opposite baffles to approximately 1 in. below the center of the lower impeller. The impellers were designed to break up the bubbles issuing from the tube into smaller bubbles and disperse them throughout the simulant.

When hydrogen peroxide decomposition was used, a nominal 30-wt% hydrogen peroxide (H_2O_2) solution was injected into the vessel with a peristaltic pump through a 1/4-in. stainless steel tube routed down the tank wall along a baffle to position the outlet approximately 1 in. below the center of the lower impeller. The hydrogen peroxide solution was supplied from a 2-L polypropylene bottle placed on a 3-kg platform scale. The solution flow rate was calculated from the weight loss recorded during pumping.

3.2 Simulants

The non-Newtonian waste stream upper bounding rheological parameters of $t_y = 30$ Pa and $\kappa = 30$ cP were identified based on limited data from actual waste slurries that can be represented by a Bingham plastic rheological model (Poloski et al. 2004). These values provide the basis for the simulant used for this testing.

The AZ simulant is designed to be chemically similar to radioactive waste in Hanford Tank 241-AZ-101, as developed by Eibling et al. (2003). It has a pH of approximately 12.5 with 20 wt% solids. The liquid fraction consists mainly of sodium salts with a total sodium concentration of 9.2 g/L. The overall bulk composition is given in Table 3.1. As prepared from the recipe, this simulant has yield stress of 13 Pa. A thicker version with 30-Pa yield stress was produced by allowing the slurry to settle and decanting a calculated volume of supernatant. A series of tests with sequentially lower yield stress down to 2 Pa was performed by successively back-diluting the 30-Pa simulant with the decanted supernatant.

The clay simulant was a 20/80% kaolin/bentonite mixture with water added to achieve rheological properties similar to the AZ simulant. Holdup tests were performed in clay simulants with yield stresses of 9–10, 13, 22, and 28 Pa. However, the 28-Pa data could not be used. The thick clay was apparently not sufficiently mixed because successively higher air injection rates gave anomalously lower gas volume fractions. In other tests, extremely high uncertainty in the simulant level change made the results unusable. Early tests where salt and AFA were added to the clay were not analyzed because these data were not used in defining F_w .

Table 3.1. Composition of AZ Simulant

Constituent	Concentration (mg/L)	Constituent	Concentration (mg/L)
Silver	3	Aluminum	30,980
Boron	100	Barium	470
Oxalate	210	Calcium	2,400
Cadmium	4,500	Cerium	1,620
Chloride	170	Cobalt	40
Carbonate	9,370	Chromium	760
Cesium	34	Copper	185
Fluoride	66	Iron	62,750
Potassium	790	Lanthanum	1,800
Magnesium	500	Molybdenum	21
Sodium	11,040	Neodymium	1,330
Nickel	3,100	Nitrite	780
Nitrate	15,500	Phosphorus	764
Lead	545	Rhodium	160
Ruthenium	500	Silicon	4,050
Sulfate	660	Strontium	1,060
Zirconium	20,170		

Other simulants were also used to visualize the bubble production and release process and to compare these test results with prior work. The simulants included water, salt water, and Carbopol, an acrylic polymer that forms a translucent suspension of hydrated spheres in water. Tests were performed with and without AFA added to each of these three simulants. The Carbopol tests were intended for visualization, and the numerical data were not analyzed. The appendix to this report lists each test for which results were used in the analyses and the results obtained.

3.3 Simulant Level Measurement

Changes in simulant level in the test vessel in response to gas introduction were the primary data obtained from the tests. Because relatively low gas introduction rates were used, the measurement system had to distinguish very small level differences. This was made difficult by the natural disturbance of the simulant surface resulting from agitation and breaking of larger bubbles at the surface. Accordingly, the surface level was monitored using two methods: four equally spaced tapes affixed to the outside of the clear acrylic wall and one to four laser range finders focused on the simulant surface from approximately 60 cm above it. The tape measurements were used during static periods when setting the initial simulant volume or adjusting the volume after sampling. The laser range finders measured the rapidly fluctuating surface during agitation and gas injection.

The height of the simulant in the test vessel was related to volume by repeatedly adding a measured mass of water to various levels, as indicated by the tape measure. The volume of added water was calculated from the density determined from its measured temperature. This calibration was required because a significant portion of the vessel interior was occupied by hardware of complicated geometry.

The lasers were attached to the agitator support, which was not connected to the test vessel. During shakedown only one laser was used, but nonuniform fluctuations in the surface level indicated that additional lasers would provide more accurate level data. Accordingly, another laser was added and later two more as they became available. The four lasers used for most of the tests defined more of the simulant surface and provided the best resolution of small level differences. The laser system could resolve level differences on the order of ~ 1 mm, representing gas volumes on the order of 0.5 vol% or less.

The laser range finders reported the distance from their front aperture to the target. Determination of an absolute simulant level therefore required knowing the distance of laser reference point to the bottom of the tank. However, because the critical data for the test were the changes in simulant level due to gas and because the lasers were often dismounted and remounted during a test to replace depleted batteries, a relative distance was used instead. For data analysis, a reference level was calculated as the aggregated reading (see Section 4.4.1) of the four lasers for a period immediately prior to introducing gas with the agitators running at test speed. The gas volume fraction was calculated based on the increase in level from this initial reference level.

It was necessary to use a series of floats during water tests because the lasers either did not register or frequently gave erroneous readings when reflecting off a transparent surface.

3.4 Ancillary Systems and Procedures

Various activities were carried out either away from the test area or with special equipment not used during the testing itself. This section describes those typically used.

3.4.1 Simulant Addition and Removal

All test solutions except water and the aqueous salt solution required extensive preparation prior to testing. Preparation of kaolin/bentonite clay simulant required a long period of vigorous agitation to obtain consistent and uniform rheological properties. The AZ simulant was prepared following a detailed recipe requiring several complicated chemical additions and volume reductions by boiling. These activities were completed in separate mixing vessels with dedicated simulant transfer systems.

Test simulants were removed from the bottom of the vessel using a diaphragm pump connected to the drain and either reclaimed or sent to waste containers. Care was taken when reclaiming AZ simulant to ensure separation of the batches with and without AFA and to reduce loss in the drain system.

3.4.2 AFA Addition

The AFA required thinning with water to promote pouring and reduce the loss from adhesion to the pouring container. The target AFA concentration of 350 mg/L in the test is also the target concentration for the WTP process tanks. The volume of AFA to achieve this target concentration was derived from the initial volume of simulant determined with the tape measure. The AFA and thinning water were added to the simulant surface with the agitators operating. During tests using AFA, any additions (e.g., water, simulant, supernatant) were adjusted to contain the target AFA concentration.

3.4.3 Catalyst Addition

Manganese dioxide catalyst was added to the clay simulant for the hydrogen peroxide tests to control the rate of bubble production. A concentration of 100 ppm of manganese dioxide was found to provide sufficient delay for the hydrogen peroxide to be thoroughly dispersed throughout the simulant before many bubbles began to form. No separate catalyst was needed with the HLW chemical simulant.

3.4.4 Hydrogen Peroxide Solution Density

The concentration of the hydrogen peroxide in the test solution was verified by a density measurement prior to each test. The solution was weighed at a constant temperature of 20°C using a densitometer whose accuracy was checked each time with filtered, deionized water. The typical solution had a pretest density of 1.1166–1.118 g/mL, indicating a concentration of 31.1–31.5 wt% H_2O_2 (see Section 4).

3.5 Experimental Method

A typical test began by recording a static zero level on the tape (and lasers) with agitators off. Next, the agitator was restarted and, after stabilization, a dynamic zero point recorded on the lasers. Gas holdup (and sometimes gas release) testing began at that point. Gas holdup and release testing with air injection involved a sequence of timed events; for instance, air injection with agitation lasted five minutes followed by two minutes with both agitation and air injection off, then five minutes of agitation without air injection for gas release. Tests were started on the minute as closely as practical for easier time sequencing. Many air injection tests could be conducted in a day. One of the longer air injection series is illustrated by the simulant level versus time plot in Figure 3.3. Each peak or plateau represents a different test (12 tests are shown).

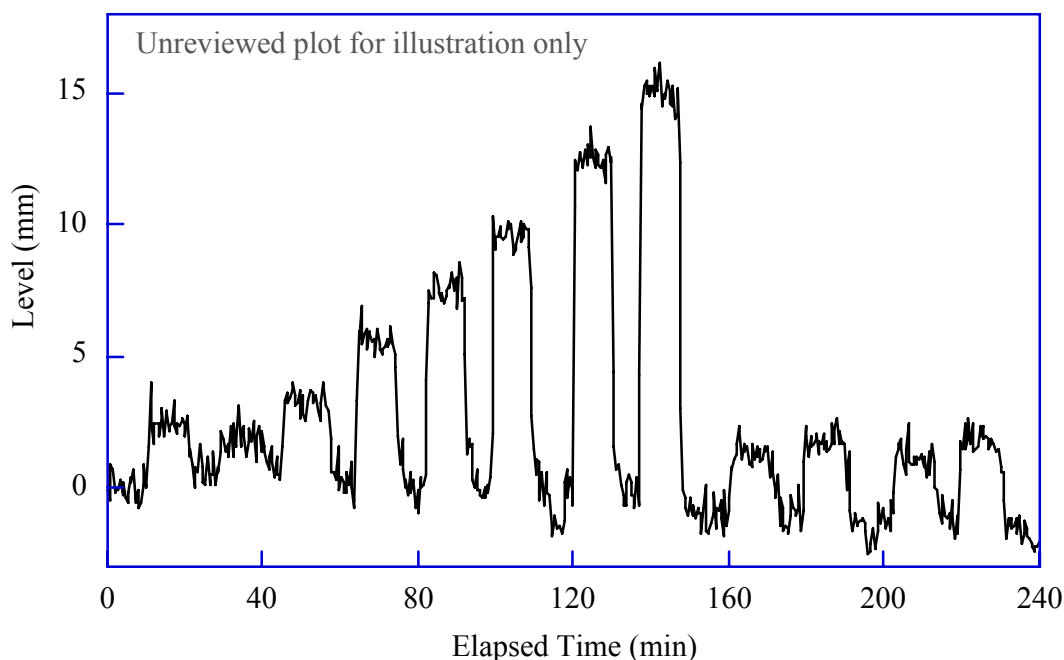


Figure 3.3. Air Injection Test Series Illustration, Level Versus Time

Gas holdup testing with hydrogen peroxide injection was more complicated. Hydrogen peroxide injection was started after a period of agitation to fully mix the simulant. The level would begin rising 5 to 15 minutes after injection began, when the decomposition reaction had saturated the solution with dissolved oxygen and bubbles began forming. The level then increased asymptotically as gas generation increased, eventually reaching a relatively constant rise rate corresponding to the rate of water production from hydrogen peroxide decomposition. This steady or linear level rise indicated that the gas bubbles were being released at the same rate they were being generated by hydrogen peroxide decomposition and that the corresponding production of water had become constant. This linear rise was allowed to continue for at least 20 minutes to ensure that the gas holdup was sufficiently captured in the data. The progress of a typical hydrogen peroxide test is illustrated by the level versus time plot in Figure 3.4. After a test, the residual hydrogen peroxide in the vessel was allowed to decompose (typically overnight), and the resulting gas accumulation was released by starting the agitator.

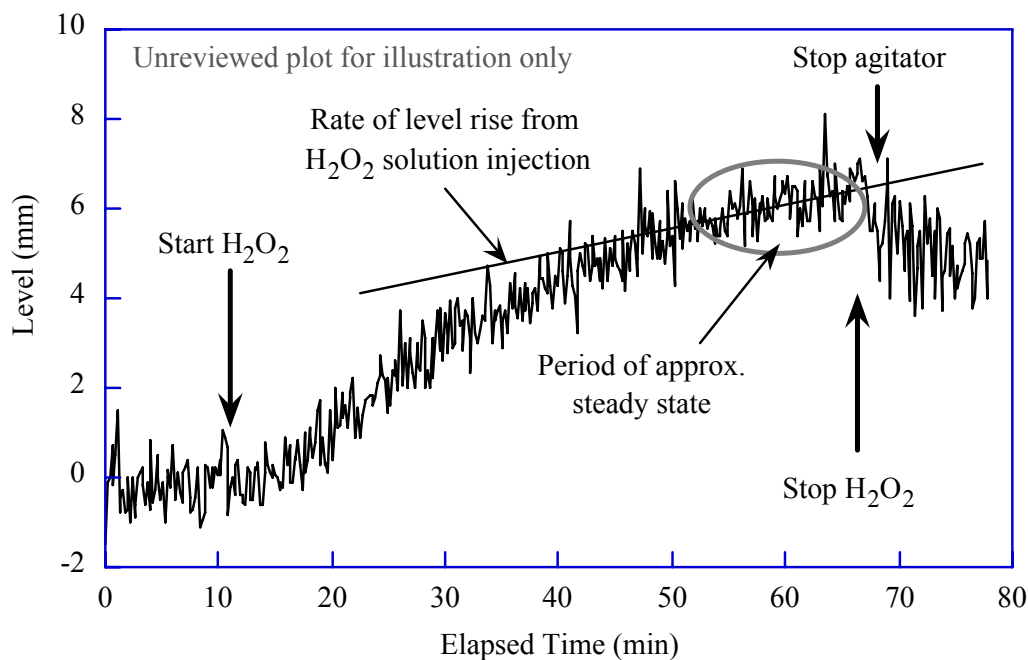


Figure 3.4. Hydrogen Peroxide Test Illustration; Level Versus Time

3.5.1 Mixing

Because the rheological properties of the simulants varied widely and the agitator speed was infinitely variable, it was important to achieve a consistent state of mixing to produce consistent holdup data. Mixing was deemed sufficient when the majority of the simulant was in motion, as judged visually by the amount of surface motion or turnover (material on the surface being pulled below) and the degree of movement along the clear acrylic walls. Once the agitator speed for sufficient mixing was established (by consensus of all test personnel present), that speed was used for all tests with that simulant at that rheological condition.

Sufficient mixing was fairly easy to recognize with water, the salt solution, and the thin clay or HLW simulants (yield stress under 20 Pa), where an rpm of 400 to 700 (550–962 ft/min tip speed) would

produce sufficient mixing. But determining sufficient mixing became somewhat difficult with the thicker simulants (yield stress over 20 Pa). Motion along the wall could be seen easily at reasonable agitator speeds, but excessive agitator speed was sometimes required to move the simulant surface in dead or slow zones around the baffles. Unfortunately, excessive agitator speed created large undulations in the surface and caused large fluctuations in the laser readings. In these cases, a compromise speed was set that minimized dead zones as well as surface undulations. Typically, agitator speeds of 700 to 1000 rpm (962–1374 ft/min tip speed) produced the desired mixing for the thicker simulants.

3.5.2 Sampling and Simulant Adjustment

Samples of the simulant were required during testing to measure and track changes in rheological properties due to evaporation, water dilution from hydrogen peroxide decomposition, or various additions to the test solution. A polypropylene coliwasa was used for small samples, and occasionally a 500-mL grab sampler was used for large samples.^(a) The small samples were typically placed in 125- or 500-mL polypropylene bottles. Samples were generally taken before and after a test or series of tests (multiple air injection tests could be conducted in one day) but sometimes in the middle of a long test series.

3.6 Test Summary

Results from 169 tests are presented in this report. Of these, 15 used hydrogen peroxide to generate gas and the rest used direct air injection. There were 32 tests in water, 41 in clay simulant, and 96 tests in AZ simulant. The analyzed tests are summarized in Table 3.2. A detailed listing of the conditions and analysis results for each test is provided in the appendix.

Table 3.2. Summary of Tests Analyzed in This Report

Simulant	Yield strength (Pa)	Superficial velocity (mm/s)	Agitator RPM	No. of Tests	No. tests using air injection	No. tests using H ₂ O ₂	No. tests using AFA
AZ	11–12	0.05–7.7	650	17	15	2	None
AZ	13–14	0.01–7.8	650	47	41	6	21 (4 H ₂ O ₂)
AZ	28–30	0.026–7.9	940–970	15	13	2	7 (1 H ₂ O ₂)
AZ	2–29 ^(a)	0.05, 0.9	400–970	17	17	None	All
Clay	9–11	0.035–7.8	525	19	16	3	None
Clay	13	0.034–0.12	525	12	12	None	None
Clay	16	0.061–0.11	525	2	0	2	None
Clay	22	3.6–15	400	4	4	None	None
Clay	22	3.6–15	700	4	4	None	None
Water	NA	3.5–15	400–700	20	20	None	8
Water + salt	NA	3.5–15	550–900	12	12	None	8

(a) Special test series varying simulant yield stress by sequential dilution with AZ supernatant.

(a) A coliwasa is a device for sampling sludge or semi-solid material consisting of a tube with piston inside. The tube is inserted into the material with the piston held fixed to collect the sample. The piston is then pushed into the tube to eject the sample into a container.

4.0 Holdup Test Data Reduction Model

The model described herein calculates the gas volume fraction from simulant level measurements, accounting for simulant loss by evaporation and splatter as well as addition of hydrogen peroxide and its decomposition if applicable. Two types of tests are considered: 1) those where gas bubbles are generated in the simulant by decomposition of hydrogen peroxide that is injected at a constant rate and 2) those where gas bubbles are injected directly into the simulant. In both types of tests, agitator vanes near the bottom of the vessel mix the simulant and break up the bubbles. Test results are presented for water, kaolin/bentonite clay, and a salt slurry that represents the chemistry of Hanford HLW.

The gas volume fraction, α , is defined as the ratio of the volume of gas in the simulant, V_g , to the volume of simulant, V_{sim} , plus the gas as given by Eq. (4.1):(a)

$$\alpha(t) = \frac{V_g(t)}{V_{sim}(t) + V_g(t)} = 1 - \frac{V_{sim}(t)}{V_{sim}(t) + V_g(t)} \quad (4.1)$$

The total volume of simulant, including gas, is given as a linear function of measured simulant level, $h(t)$, initial simulant level, $h(0)$, tank area, A , and the initial simulant volume, $V_{sim}(0)$. The total volume of simulant plus accumulated gas can therefore be expressed as a function of time:

$$V_{sim}(t) + V_g(t) = V_{sim}(0) + A[h(t) - h(0)] \quad (4.2)$$

To partition the total volume into simulant and gas, the transient simulant volume is assumed to consist of the initial solid and liquid volume plus the cumulative additions and subtractions defined as

- $V_c(t)$ estimated loss due to solid/liquid splash deposits or “cakeout” on vessel walls and associated hardware
- $V_p(t)$ unreacted hydrogen peroxide (zero for air injection tests)
- $V_w(t)$ water produced by hydrogen peroxide decomposition plus water added with the injected hydrogen peroxide solution (also zero for air injection tests)
- $V_e(t)$ water loss by evaporation from the simulant surface and as vapor released with bubbles.

In earlier tests, only the effects of hydrogen peroxide injection (with $V_p + V_w$ assumed equal to the total hydrogen peroxide solution injection rate) were considered, and evaporation was neglected. However, because the current tests had to resolve level differences of a few millimeters, and the smaller surface-to-volume ratio would make evaporation and cakeout more important, they were explicitly included in reducing the data from the SRNL tests. In tests lasting several hours, the evaporation loss was on the order of 0.8 mm. Cakeout estimates were on the same order.

(a) Similarly, the holdup, η , is defined as the ratio of gas volume to simulant volume so that $\alpha = \frac{1}{1 + \eta}$.

Assuming that the initial simulant volume contains no gas, the transient non-gas simulant volume can be estimated by

$$V_{\text{sim}}(t) = V_{\text{sim}}(0) + V_p(t) + V_w(t) - V_e(t) - V_c(t) \quad (4.3)$$

Theory and data are available to calculate reasonably accurate estimates for V_p , V_w , and V_e that can be validated or calibrated empirically. The cakeout loss, V_c , however, can only be roughly estimated. Anecdotal information on cakeout is given in the SRNL test logs^(a) when the simulant coating on the vessel walls is first observed and occasionally scraped off. Bubbles breaking the surface account for most observations of cakeout in high-flow rate air injection tests. For some of these tests, changes in the measured simulant level at zero flow between runs can be used to help determine an appropriate estimate for cakeout. Cakeout was not generally observed in tests using hydrogen peroxide because gas generation rates were low.

Substituting Eq. (4.2) and (4.3) into Eq. (4.1) produces the final expression relating the gas volume fraction in the simulant to changes in simulant surface level:

$$\alpha(t) = 1 - \frac{V_{\text{sim}}(0) + V_p(t) + V_w(t) - V_e(t) - V_c(t)}{V_{\text{sim}}(0) + A[h(t) - h(0)]} \quad (4.4)$$

The gas volume fraction is correlated with the volumetric gas generation rate per unit volume of gas-free simulant, g_v , simulant volume, V_{sim} , surface area, A , and bubble rise speed, U_R , according to a slightly modified version of the fundamental gas release Eq. (1.1). Over an interval t_1 to t_2 , where the gas generation rate, bubble rise speed, and gas-free simulant volume can be considered constant, the gas release model is expressed by Eq. (4.5):^(b)

$$\alpha(t_2) = \alpha(t_1) e^{-\frac{AU_R}{V_{\text{sim}}(t_2)}(t_2 - t_1)} + g_v(t_2) \frac{V_{\text{sim}}(t_2)}{AU_R} \left(1 - e^{-\frac{AU_R}{V_{\text{sim}}(t_2)}(t_2 - t_1)} \right) \quad (4.5)$$

For air injection tests, a steady state is assumed so that $\alpha = g_v V_{\text{sim}} / (AU_R)$. In hydrogen peroxide tests, the full form of Eq. (4.5), along with a mass balance on the added hydrogen peroxide solution, is fit to the data to determine U_R .

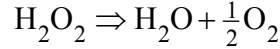
The balance of this section derives expressions for V_p , V_w , and V_e and methods for obtaining U_R and g_v from Eq. (4.5) using the sets of $\alpha(t)$ calculated from test data. Section 4.1 applies to tests using hydrogen peroxide to generate gas, and Section 4.2 covers air injection tests. Section 4.3 gives the curve fits for water properties as a function of temperature and for the density of hydrogen peroxide solutions versus peroxide mass fraction and temperature. Uncertainty analysis methods and significance tests are described in Section 4.4.

(a) E-mail attachment, Gas Release Test Logs R5a.xls, from M. Fowley to CW Stewart, July 17, 2006. Subject: Test Log.

(b) The solution is, in fact, carried out in a series of time steps of approximately one minute or less, over which these quantities are essentially constant.

4.1 Tests Generating Gas by Hydrogen Peroxide Decomposition

Hydrogen peroxide is injected into the simulant as a solution of ~31 wt% hydrogen peroxide in water. The hydrogen peroxide decomposes into water and oxygen to generate gas bubbles in situ. Though decomposition of hydrogen peroxide is fairly complex and involves several intermediate reactions, the end result can be expressed by the following reaction:



One mole of water and one-half mole of oxygen gas are produced by decomposition of one mole of hydrogen peroxide. The oxygen is generated in solution in the liquid, so some time is required before liquid supersaturates with oxygen sufficiently to create gas bubbles or diffuse into existing gas bubbles to cause an increase in volume. The contributions of other dissolved gases to bubble volume are ignored so that the total gas generation rate is assumed equal to the production rate of oxygen gas by decomposition of hydrogen peroxide with a correction to account for water vapor saturating the bubbles.

4.1.1 Hydrogen Peroxide Decomposition Reaction Rate

The hydrogen peroxide reaction rate can be represented by a simple first-order model where the rate is proportional to the molar concentration, C_p , of hydrogen peroxide in the simulant. That is,

$$R_p = k_p(T_s)C_p = \frac{k_p(T_s)}{M_p V_{\text{sim}}(t)} m_p(t) \quad (4.6)$$

where

- R_p = decomposition rate of hydrogen peroxide (mole/L-s)
- $k_p(T_s)$ = reaction rate constant (1/s), function of temperature, T_s (K)
- C_p = hydrogen peroxide concentration in liquid (mole/L)
- M_p = molecular weight of hydrogen peroxide (34 g/mole)
- m_p = mass of unreacted hydrogen peroxide in the simulant (g).

According to the decomposition reaction, the molar rate of production of water, R_w , is equal to R_p , and the molar oxygen generation rate is equal to $1/2 R_p$.

We assume an Arrhenius dependence of the rate constant on temperature so that

$$k_p(T_s) = k_0 e^{\frac{E_a}{R} \left(\frac{1}{T_0} - \frac{1}{T_s} \right)} \quad (4.7)$$

where

$$k_0 = k_p(T_0), \text{ with } T_0 = 298\text{K}$$

E_a = activation energy (40,000 J/mole assumed, can range from 20,000–75,000 J/mole depending on the catalysts present)^(a)
 R = gas constant (8.31451 J/mole-K)
 T_s = simulant temperature (K).

Eq. (4.7) indicates that a 10K temperature increase causes the reaction rate to approximately double. For simplicity, the hydrogen peroxide decomposition reaction rate constant will be denoted by k_p in the derivations that follow rather than writing the full Eq. (4.7).

4.1.2 Mass Balance of Hydrogen Peroxide in the Simulant

The rate of change of mass of hydrogen peroxide, m_p , in the simulant is equal to the mass injection rate less the mass decomposition rate. However, actual gas generation occurs only after a time lag due to hydrogen peroxide mixing and oxygen saturation. The time lag can be roughly modeled by partitioning out a small fictitious volume of simulant, V_m , where mixing occurs only as shown in Figure 4.1.^(b) The mixing partition receives the injected hydrogen peroxide solution directly and passes the volume-averaged mixture with density ρ_m and hydrogen peroxide mass fraction x_m to the rest of the vessel at the same volumetric flow rate.

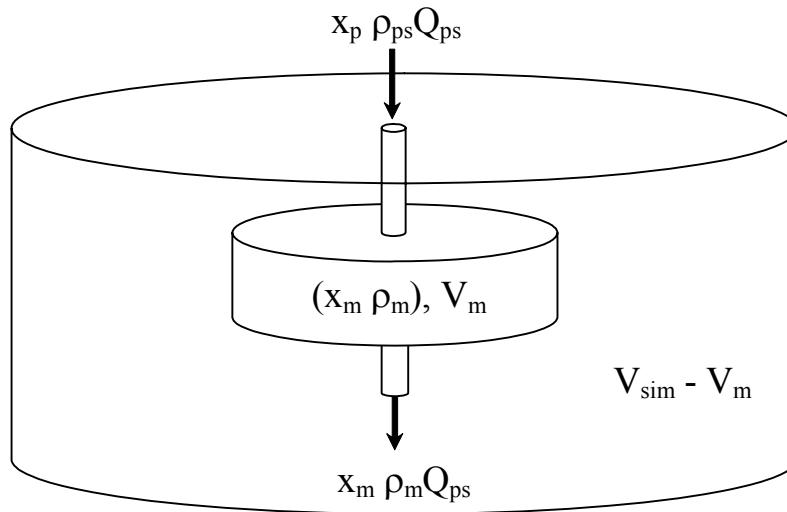


Figure 4.1. Mixing Partition Concept

The solution to a transient mass balance on the mass of hydrogen peroxide in the mixing partition is given by Eq. (4.8):

(a) See, for example, Hasan et al. (1999). The exact value of E_a is not important because the value of k_0 determined by a least squares fit also, in effect, adjusts E_a .

(b) The mixing volume time lag construction is applied only to the hydrogen peroxide mass balance. It is not used for water addition with the hydrogen peroxide solution.

$$(x_m \rho_m)(t) = x_p \rho_{ps} \left(1 - e^{-\frac{Q_{ps}}{V_m} t} \right) \quad (4.8)$$

where

x_p = mass fraction of hydrogen peroxide in the injection solution

ρ_{ps} = density of hydrogen peroxide solution (g/L = kg/m³)

Q_{ps} = volumetric injection rate of hydrogen peroxide solution (L/s)

V_m = mixing volume (L).^(a)

Assuming V_m is small,^(b) the mass balance on hydrogen peroxide in the simulant outside the mixing partition is given by

$$\frac{dm_p}{dt} = x_m \rho_m Q_{ps} - M_p V_{sim}(t) R_p \quad (4.9)$$

Substituting Eq. (4.6) for R_p and Eq. (4.8) for $(x_m \rho_m)$ yields

$$\frac{dm_p}{dt} + k_p m_p = x_p \rho_{ps} Q_{ps} \left(1 - e^{-\frac{Q_{ps}}{V_m} t} \right) \quad (4.10)$$

Integrating Eq. (4.10) from time t_1 to t_2 , gives the following expression for the mass of hydrogen peroxide in the simulant:

$$m_p(t_2) = m_p(t_1) e^{-k_p(t_2-t_1)} + \frac{x_p \rho_{ps} Q_{ps}}{k_p} \left[1 - e^{-k_p(t_2-t_1)} \left(1 - \frac{e^{-\frac{Q_{ps}}{V_m} t_1}}{1 - \frac{Q_{ps}}{k_p V_m}} \right) - \frac{e^{-\frac{Q_{ps}}{V_m} t_2}}{1 - \frac{Q_{ps}}{k_p V_m}} \right] \quad (4.11)$$

Assuming that hydrogen peroxide conserves its density in solution, the volume of hydrogen peroxide in the simulant is calculated from the result of Eq. (4.11):

$$V_p(t) = \frac{m_p(t)}{\rho_p} \quad (4.12)$$

(a) The mixing volume is determined by a least squares fit of the combined hydrogen peroxide decomposition and gas retention model to test data.

(b) Values of V_m obtained from curve fits are less than 0.2% of V_{sim} .

4.1.3 Mass Balance on Water Added via Hydrogen Peroxide

The added water includes both the water injected with hydrogen peroxide solution and the water created during decomposition of hydrogen peroxide. Given that the molar rate of water generation equals the rate of hydrogen peroxide decomposition, the mass balance of added water, corresponding to Eq. (4.10), can be written as follows:

$$\frac{dm_w}{dt} = \frac{M_w}{M_p} k_p m_p(t_2) + (1 - x_p) \rho_{ps} Q_{ps} \quad (4.13)$$

Assuming that m_p is approximately constant over a time period t_1 to t_2 and integrating gives

$$m_w(t_2) = m_w(t_1) + \left[\frac{M_w}{M_p} k_p m_p(t_2) + (1 - x_p) \rho_{ps} Q_{ps} \right] (t_2 - t_1) \quad (4.14)$$

The volume of added water in the simulant is calculated from Eq. (4.14) as

$$V_w(t) = \frac{m_w(t)}{\rho_w} \quad (4.15)$$

4.1.4 Mass Loss by Evaporation

The liquid fraction in the simulant is subject to water loss by evaporation via two pathways: 1) direct evaporation from the simulant surface (enhanced by mixing of the simulant and forced air flow over the surface) and, 2) evaporation into gas bubbles transiting through the simulant. The driving force for evaporation from the surface is the difference between the partial pressures of water vapor in the simulant and in the ambient air being blown over the vessel.^(a) The rate of mass loss by evaporation from the surface can be represented by

$$\left. \frac{dm_e}{dt} \right|_{\text{surf}} = M_w k_e A \frac{p_{vs}(T_s) - (0.01RH)p_{vs}(T_a)}{RT_s} \quad (4.16)$$

where

- m_e = mass of water evaporated (g)
- k_e = empirical mass transfer coefficient (m/s)
- A = area of the vessel liquid surface (m^2)
- p_{vs} = water vapor pressure (Pa)
- T_s = simulant temperature (K)
- RH = ambient relative humidity (%)
- T_a = ambient air at temperature T_a (K).

(a) The effect on water vapor pressure of the relatively low salt concentration in tests with AZ simulant, or where salt was added to water to mimic the concentration of AZ simulant, is ignored.

For ambient conditions existing around the test vessel,^(a) the mass transfer coefficient is calculated as 0.0239 m/s using the correlation described by Guo and Roache (2003). The relative humidity was not recorded but is assumed relatively constant at 76.5%.^(b)

We assume that the gas bubbles generated by hydrogen peroxide decomposition are continuously in thermal equilibrium with the surrounding liquid as they rise and thus contain water vapor at a pressure of $p_{vs}(T_s)$. At typical test temperatures this partial pressure may cause a measurable mass loss over the hour or more of test time. The resulting rate of water loss from bubbles breaking at the simulant surface is given by

$$\left. \frac{dm_e}{dt} \right|_{\text{bubb}} = M_w \frac{p_{vs}(T_s)}{RT_s} U_R \alpha A \quad (4.17)$$

Adding Eq. (4.16) and (4.17), again assuming that α and the vapor pressure are constant between t_1 and t_2 , and integrating provides the following expression for the cumulative total mass loss from evaporation:

$$m_e(t_2) = m_e(t_1) + \frac{M_w A(t_2 - t_1)}{RT_s} \left\{ k_e [p_{vs}(T_s) - (0.01RH)p_{vs}(T_a)] + p_{vs}(T_s) \alpha(t_1) U_R \right\} \quad (4.18)$$

The calculation of water vapor pressure as a function of temperature is described in Section 4.3. The corresponding volume loss is equal to the mass loss, Eq. (4.18), divided by the density of water.

$$V_e(t) = \frac{m_e(t)}{\rho_w} \quad (4.19)$$

4.1.5 Determining Bubble Rise Speed

The bubble rise speed is calculated by fitting the simulant level corresponding to the gas volume fraction from the gas release model, Eq. (4.5), to the measured simulant level, including the corrections of Eq. (4.12), (4.15), and (4.19) for volume gains and losses. The volumetric gas generation rate, g_v , in Eq. (4.5) is calculated as half the molar decomposition rate of hydrogen peroxide (Eq. 4.6) plus the volume of saturated water vapor as follows:

$$g_v(t) = \frac{k_p}{2M_p V_{\text{sim}}(t)} \frac{RT_s}{p_g} m_p(t) \left[1 + \frac{p_{vs}(T_s)}{p_g} \right] \quad (4.20)$$

(a) The test environment is described in an email from Hector Guerrero, SRNL, July 24, 2006, "Test environment question," as being directly in the draft of an air conditioner unit at a constant temperature of 22°C. See CCP-WTPSP-110 for the details of the calculation.

(b) The relative humidity in the laboratory near the test vessel was measured at 76.5% after testing was completed. The result was reported in an email from Hector Guerrero, SRNL, August 9, 2006.

where p_g is the average pressure in the gas bubbles calculated as the hydrostatic pressure at simulant mid-depth based on the current local atmospheric pressure recorded for each test.^(a) The mass of hydrogen peroxide present in the simulant, $m_p(t)$, in Eq. (4.20) is calculated using Eq. (4.11).

The fit is performed by adjusting the bubble rise speed, U_R , in Eq. (4.5), the time lag partition volume, V_m , and the hydrogen peroxide reaction rate constant, k_p ,^(b) in Eq. (4.11) to minimize the sum of the squares of the difference between the level difference associated with the gas volume fractions calculated using Eq. (4.5) and the measured level difference at each data point in a test. The level difference is calculated from the modeled gas volume fraction by

$$[h(t) - h(0)] = \frac{V_{\text{sim}}(t)}{A[1 - \alpha(t)]} - h(0) \quad (4.21)$$

If the test is carried out for a sufficient time to approach a steady state, say t_{ss} , the bubble rise rate can be determined algebraically. At large times, the gas release, Eq. (4.5), and hydrogen peroxide mass balance, Eq. (4.11), reduce, respectively, to the following:

$$\alpha_{ss} = g_v(t_{ss}) \frac{V_{\text{sim}}(t_{ss})}{AU_R} \quad (4.22)$$

$$m_{pss} = \frac{x_p \rho_{ps} Q_{ps}}{k_p} \quad (4.23)$$

Combining Eq. (4.22) and (4.23) using Eq. (4.20) and solving for U_R gives

$$U_R = \frac{x_p \rho_{ps} Q_{ps}}{2M_p A} \frac{RT_s}{p_g} \frac{1}{\alpha_{ss}} \left[1 + \frac{p_{vs}(T_s)}{p_g} \right] \quad (4.24)$$

In correlating the bubble rise speed, gas volume fraction, and gas generation rate, the latter is generally expressed as the superficial velocity. The superficial velocity, U_S , is the total gas generation rate divided by the gas release area, which can be calculated from g_v as

$$U_S = \frac{g_v(t_{ss}) V_{\text{sim}}(t_{ss})}{A} = \frac{x_p \rho_{ps} Q_{ps}}{2M_p A} \frac{RT_s}{p_g} \left[1 + \frac{p_{vs}(T_s)}{p_g} \right] \quad (4.25)$$

(a) The small increase in bubble internal pressure due to surface tension is ignored. For a 1-mm-diameter spherical bubble, this pressure is less than 300 Pa.

(b) Using the Arrhenius equation (Eq. 4.7) to account for temperature dependence, the reference reaction rate, k_0 , is actually adjusted in the fit.

4.2 Tests Generating Gas by Air Injection

Though generating gas within the simulant by hydrogen peroxide decomposition better represents in situ radiolytic and thermolytic gas generation in nuclear waste, it is much more convenient to inject gas directly into the simulant. Gas is injected at a constant rate, Q_g (L/s at local pressure and temperature), through small tubes under the mixing impeller, which is designed to break up the bubbles of injected gas to approach the size distribution of those generated in situ.

Using direct air injection greatly simplifies the data reduction calculation. The volume corrections $V_p(t)$ and $V_w(t)$ for the presence of hydrogen peroxide and water addition from its decomposition, respectively, are both zero. Also, each air injection test can easily be carried to a steady state so that the involved process of fitting a transient model to transient data is not necessary. If a least squares fit is performed to extract bubble rise speeds from gas release transients, for example, it only involves Eq. (4.5). The hydrogen peroxide mass balance is not used.

4.2.1 Evaporation Loss

Evaporation from the simulant surface follows Eq. (4.16) equally for direct air injection or hydrogen peroxide tests. Mass transfer to bubbles is expressed similarly to Eq. (4.17), expressing the gas generation rate with Q_g . Summing both contributions, the resulting evaporation expression is

$$\frac{dm_e}{dt} = \frac{M_w}{RT_s} \{k_e A [p_{vs}(T_s) - (0.01RH)p_{vs}(T_a)] + p_{vs}(T_s)Q_g\} \quad (4.26)$$

The evaporative volume loss is obtained by integrating Eq. (4.26) over the period t_1 to t_2 and dividing by the density of liquid water to give

$$V_e(t_2) = V_e(t_1) + \frac{M_w(t_2 - t_1)}{\rho_w RT_s} \{k_e A [p_{vs}(T_s) - (0.01RH)p_{vs}(T_a)] + p_{vs}(T_s)Q_g\} \quad (4.27)$$

4.2.2 Determining Bubble Rise Speed

Without the complexity of hydrogen peroxide, the expression for volume fraction in the simulant in terms of simulant surface level, Eq. (4.4), reduces to

$$\alpha(t) = 1 - \frac{V_{sim}(0) - V_e(t) - V_c(t)}{V_{sim}(0) + A[h(t) - h(0)]} \quad (4.28)$$

The superficial velocity for direct air injection tests, including corrections for the local pressure of gas injection (calculated at tank bottom by SRNL, corrected to mid-depth) and for water vapor in the bubbles, is given by

$$U_S = \frac{Q_g}{A} \left(2 - \frac{p_a}{p_g} \right) \left[1 + \frac{p_{vs}(T_s)}{p_g} \right] \quad (4.29)$$

The bubble rise speed is computed by

$$U_R = \frac{Q_g}{A\alpha_{ss}} \left(2 - \frac{p_a}{p_g} \right) \left[1 + \frac{p_{vs}(T_s)}{p_g} \right] = \frac{U_S}{\alpha_{ss}} \quad (4.30)$$

where α_{ss} is the steady-state gas volume fraction determined by Eq. (4.28).

4.3 Properties of Water and Hydrogen Peroxide

Because the simulant temperature can vary significantly over a test period, we need expressions for the density and vapor pressure of water as a function of temperature to calculate the decrease in level due to evaporation. These expressions are given in Section 4.3.1. Also, the strength of the hydrogen peroxide solution used to generate gas was determined before each test by measuring its density at a constant temperature of 20°C. To apply the model described in Section 4.1, we need to know the density of hydrogen peroxide solution as a function of the mass fraction, as given in Section 4.3.2.

4.3.1 Water Density and Vapor Pressure

Data giving water density and vapor pressure as a functions of temperature (CRC 1991) were fit over the range of interest for these tests. The data are given in Table 4.1, and the fits are plotted with the data in Figure 4.2. The fit for temperatures in the range 283–333K (~50°–140°F) is

$$\rho_w(T) = 703.772 + 2.2179T - 0.004141T^2 \quad (R^2 \ 0.9998) \quad (4.31)$$

Table 4.1. Water Density and Vapor Pressure Data

Temperature (K)	Density (g/L)	Vapor Pressure (Pa)
283	999.70	1,228.1
293	998.21	2,338.8
303	995.65	4,245.5
313	992.22	7,381.4
323	988.00	12,344.0
333	983.20	19,932.0

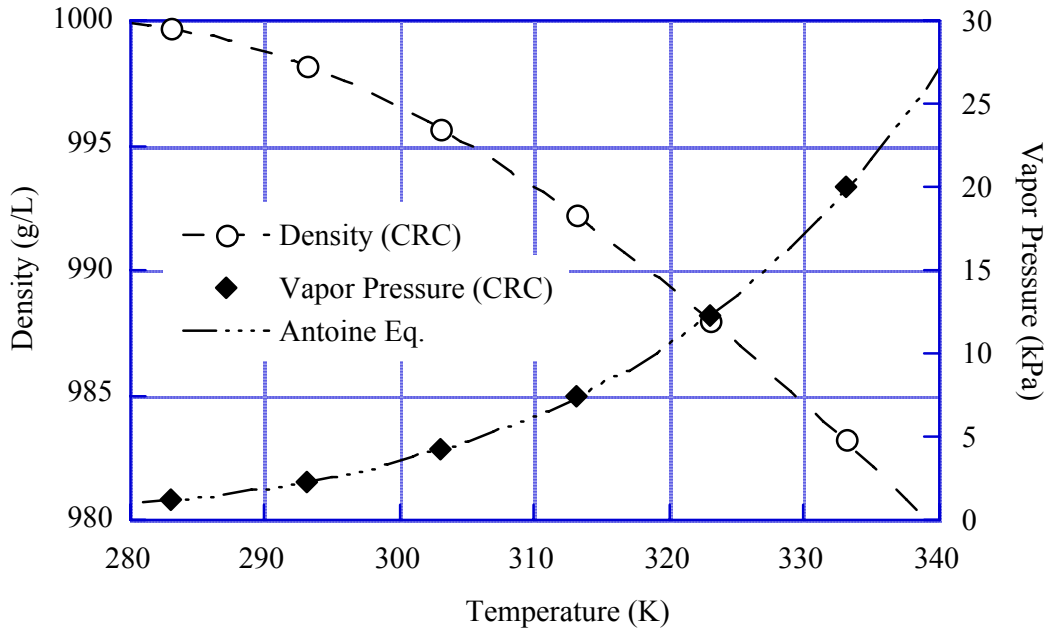


Figure 4.2. Water Density and Vapor Pressure Versus Temperature

Water vapor pressure (kPa) for $284 < T < 441\text{K}$ is given by the Antoine equation with constants for water given in Reid et al. (1977) as follows:^(a)

$$p_v(T) = \exp \left[18.3036 - \frac{3816.44}{T - 46.13} \right] \quad (4.32)$$

The water vapor pressure, Eq. (4.32), is also plotted with the CRC data in Figure 4.2.

4.3.2 Density of Hydrogen Peroxide Solutions

The density of an aqueous hydrogen peroxide solution is expressed as a function of the mass fraction of hydrogen peroxide and temperature by

$$\rho_{ps}(x_p, T) = \left[\frac{x_p}{\rho_p(T)} + \frac{1-x_p}{\rho_w(T)} \right]^{-1} + \Delta\rho_{ps}(x_p, T) \quad (4.33)$$

(a) In the chemical waste simulant, the presence of dissolved salts reduces the water vapor pressure in proportion to the mole fraction of water in the liquid according to Raoult's law (Reid et al. 1977). However, the relatively low density of the bulk simulant (~1.2 g/mL), including solids and the low concentration of dissolved sodium given in the simulant "recipe," indicate that the reduction would be small, and it is therefore ignored.

where $\Delta\rho_{ps}$ is the difference between the actual and ideal solution density, the latter expressed by the term in brackets. Measurements of $\Delta\rho_{ps}$ are available at 0° and 20°C (Phibbs and Giguere 1950). A curve fit ($R^2 = 0.99998$) for the mass fraction of hydrogen peroxide versus measured solution density at 20°C is

$$x_p = -436.969 + 622.145\rho_{ps} - 208.69\rho_{ps}^2 + 24.1636\rho_{ps}^3 \quad (4.34)$$

The 20°C data of Phibbs and Giguere (1950) are listed in Table 4.2, and the curve fit is shown in Figure 4.3. The 20°C value of density is used for the incoming hydrogen peroxide solution because the temperature of the room where the tests were performed is said to average around 22°C. For computing the volume of unreacted hydrogen peroxide in the system, the 20°C value (1.4502 g/mL) is also used, even though the simulant temperature may be much higher, because the volume is small compared with that of added water.

Table 4.2. Density of Hydrogen Peroxide Solutions at 20°C

wt% H ₂ O ₂	Ideal Density (g/mL)	Measured Difference (g/ml) $\Delta\rho_{ps}$	Measured Density (g/ml) (Eq. 4.35)
0	0.9982	0.0000	0.9982
9.05	1.0272	0.0030	1.0302
20.02	1.0647	0.0072	1.0718
33.6	1.1150	0.0121	1.1271
43.2	1.1535	0.0128	1.1664
56.6	1.2120	0.0149	1.2269
73.7	1.2959	0.0108	1.3067
91.6	1.3971	0.0041	1.4012
100	1.4502	0.0000	1.4502

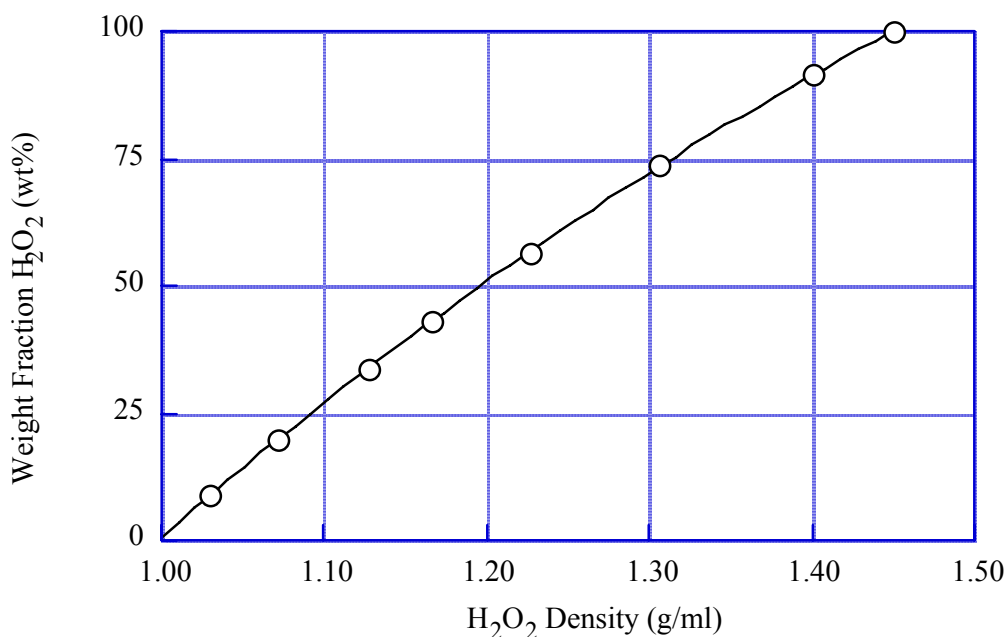


Figure 4.3. Mass Fraction of H₂O₂ Versus Solution Density at 20°C

4.4 Uncertainty Estimates and Significance Test

Whether gas is injected directly or generated in situ via hydrogen peroxide decomposition, the gas volume fraction is calculated from the difference between current and initial simulant levels. The degree to which this level difference may represent the actual volume of gas present is quantified by the uncertainty and the significance of the difference between the two levels. These measures are especially important for these tests, where level differences of a few millimeters must be resolved while the level fluctuates randomly over a range of several centimeters.

4.4.1 Estimating the Uncertainty in Level

The level difference is calculated from the raw 1-second level data from four (one or two in earlier tests) laser range finders. These raw data are aggregated over periods of 2 to 3 minutes for air injection tests and 5 to 10 minutes in hydrogen peroxide tests. A two-minute period includes around 450 data points (480 maximum less roughly 6% null measurements).

Intermittent simulant splashing and bubbles breaking at the surface creates a small population of random level measurements high above the bulk of the data. An example of raw level data recorded from four lasers during an air injection run is shown in Figure 4.4. For data analysis purposes, it is necessary to aggregate the level data that best represents the state of gas retention in the simulant, shown as the dark band 3–5 mm in width on Figure 4.4. The sparse collection of dots extending above the band represents random splashes or waves on the simulant surface which are not a measure of gas retention. To capture the best representation, the raw data comprising the aggregating period were fit to a normal distribution.

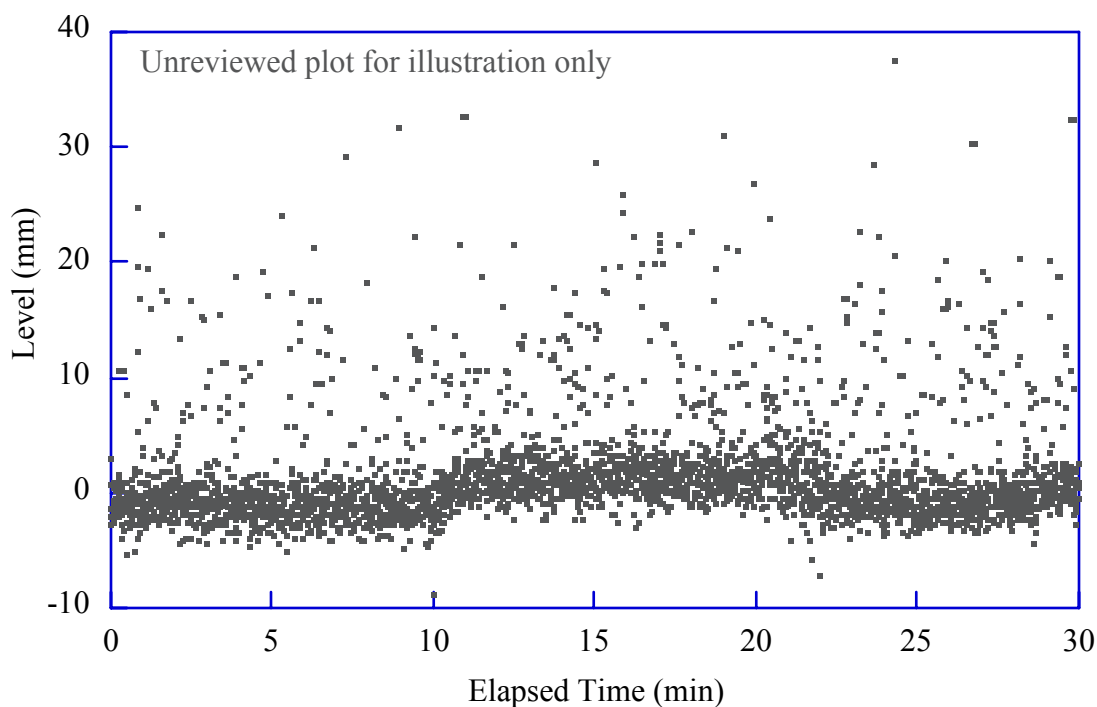


Figure 4.4. Illustration of Laser Level Data

The median (50th percentile) of the raw data was used as the best measure of central tendency (rather than the mean, which is biased toward the extreme data; in this case, the random splashes extending above the band). An estimate of the standard deviation was calculated as half the difference between the median and the 2.5 percentile value of the raw data set (the 2.5–50 percentile interval covers two standard deviations in a normal distribution). This is a common statistical method used to estimate the standard deviation. This method not only captures the best measure of central tendency but provides a more reasonable estimate of the true uncertainty that the simple mean and variance do not provide. Examples of these fits for three tests are shown in Figure 4.5. The simulant type and air injection rate are shown on each frame.

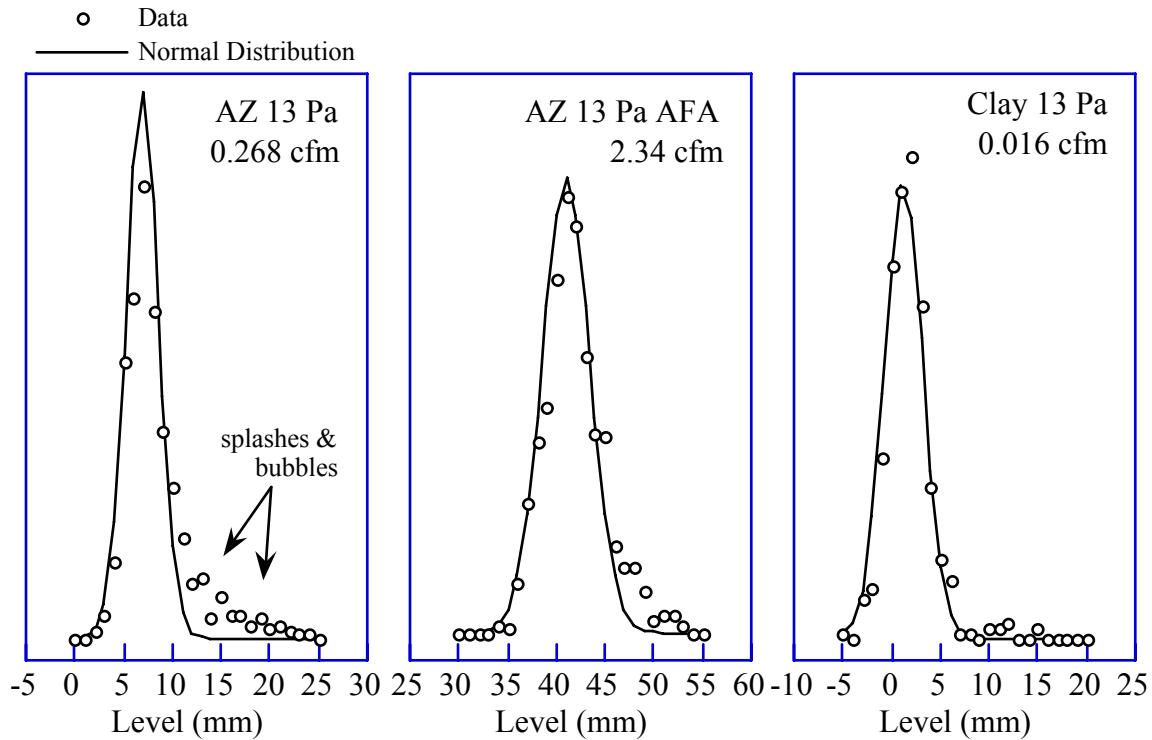


Figure 4.5. Illustrations of Normal Distribution Fits to Level Data

The uncertainty in the level difference computed from the aggregated level values is described by the pooled estimate of the variance, v_{i-0} , of the two aggregated levels. This pooled estimator is simply the average variance weighted by the number of data points (Bain and Englehardt 1989) and is computed by

$$v_{i-0} = \frac{v_i(N_i - 1) + v_0(N_0 - 1)}{N_i + N_0 - 2} \quad (4.35)$$

where the variances are calculated as the square of the standard deviation defined previously, and

- v_i = variance of the i th aggregated level
- v_0 = variance of the initial average level
- N_i = number of data points comprising the i th aggregate
- N_0 = number of data points comprising the initial aggregate.

The standard deviation of the level difference, $\sigma_{\Delta L}$, is the square root of the pooled variance given by Eq. (4.35). The associated uncertainty in the gas volume fraction is computed by propagating the level uncertainty through Eq. (4.4) to give

$$\sigma_{\alpha} = [1 - \alpha(t)]^2 \frac{A}{V_{\text{sim}}(t)} \sigma_{\Delta L} \quad (4.36)$$

The associated uncertainty in the bubble rise speed is obtained similarly by propagating the uncertainty in the gas volume fraction through Eq. (4.30) so that

$$\sigma_{U_R} = \frac{U_R}{\alpha(t)} \sigma_{\alpha} \quad (4.37)$$

4.4.2 Significance Test

The Student's T distribution is used to test for a significant difference in the levels. The T-test is performed by calculating a test statistic, as shown in Eq. (4.38), and using that test statistic to determine whether the two levels are significantly different. High values of the T-statistic indicate a significant difference, while low values (close to zero) indicate no significant difference. The T-statistic, v , for the i th test is given by the following equation (Bain and Engelhardt 1989):

$$v = \frac{h_i - h_0}{\sqrt{v_{i-0} (1/N_0 + 1/N_i)}} \quad (4.38)$$

where

h_i = the aggregated level for the i th test (mm)

h_0 = aggregated initial reference level (mm)

v_{i-0} = pooled variance from Eq. (4.35) (mm^2).

The T distribution, $T(v, N)$,^(a) where N is the number of degrees of freedom, $N = N_0 + N_i - 2$, provides a probability of significance, or p-value, used as a criterion for determining whether the levels are significantly different. Typically, p-values less than 0.05 are considered significantly different. The complement of the p-value, represented by $1 - T(v, N)$, 0.95 for a p-value of 0.05, represents the probability that the level difference is significant. A level difference with significance probability less than 0.95 is considered suspect.

Data sets that are too large can adversely affect the reliability of the test because arbitrarily large values of N_0 and N_i , which appear inverted in the denominator of Eq. (4.38), give arbitrarily large values of the T-statistic. This has the same effect as a smaller pooled variance or larger level difference, either of which increases the probability that the difference is significant and can mask adverse data behavior that might otherwise be detected. The typical 400–700 points in a typical aggregation of level data are more than large enough to obscure potential problems in this way. Therefore, the T-test was performed in

(a) The T distribution is evaluated with the function TDIST in Microsoft Excel®.

a separate calculation using a shorter aggregating period of approximately 0.125 minutes, which resulted in about 70 degrees of freedom.

4.4.3 Uncertainty in Curve Fit Parameters

In Section 5, the measured gas volume fraction, α , and superficial velocity, U_S , are fit with a power law of the form

$$\alpha = AU_S^B \quad (4.39)$$

The standard error in the fit parameters A and B , σ_A and σ_B , can be estimated by converting the power function to a linear function for which expressions for these uncertainties have been developed. Taking the logarithm of Eq. (4.39) yields

$$\ln \alpha = \ln A + B \ln U_S \quad (4.40)$$

Substituting $y = \ln \alpha$, $a = \ln A$, and $x = \ln U_S$ simplifies Eq. (4.40) to the standard linear equation:

$$y = a + Bx \quad (4.41)$$

Assuming that the errors for the log-transformed variables are normally and independently distributed, Eq. (4.41) can be used to predict n fitted values, y_{fi} , that are associated with n pairs of measured values of x_i and y_i . A least-squares fit is performed by adjusting the parameters a and B to minimize the sum of the squared differences between the measured y_i and corresponding predicted y_{fi} values. The standard errors of the resulting parameters a and B for the linear form are given by, respectively (Rencher 2000),

$$\sigma_a = \sqrt{\frac{\sum_{i=1}^n (y_i - y_{fi})^2}{(n-2)} \left[\frac{1}{n} + \frac{\bar{x}^2}{\sum_{i=1}^n (x_i - \bar{x})^2} \right]} \quad (4.42)$$

$$\sigma_B = \sqrt{\frac{\sum_{i=1}^n (y_i - y_{fi})^2}{(n-2) \sum_{i=1}^n (x_i - \bar{x})^2}} \quad (4.43)$$

where $\bar{x}$ is the mean of the set of x_i . Because $a = \ln A$ and $a + \sigma_a = \ln(A + \sigma_A)$, the standard error in A can be approximated as

$$\sigma_A \approx e^{(a + \sigma_a)} - A \quad (4.44)$$

4.4.4 Prediction Interval for Applying Curve Fits

The uncertainty in the individual fit parameters does not describe the overall uncertainty in using the results of a least-squares fit to predict values of the dependent variable. Instead, a *prediction interval* is used based on the T distribution and the variance of the data on which the fit is based. If the linear fit described by Eq. (4.41) is used to predict a future value y_F from a given x_F , the prediction interval for y_F is stated as $y_F \pm \sigma_y$ where σ_y is defined as follows (Rencher 2000):

$$\sigma_y = t_{a,n-2} S \sqrt{1 + \frac{1}{n} + \frac{(x_F - \bar{x})^2}{\sum_{i=1}^n (x_i - \bar{x})^2}} \quad (4.45)$$

where

$t_{a,n-2}$ = value of the inverse T distribution for given 2-tail probability (i.e., α represents a combined “tail” of 0.05 for 95% confidence) and $n-2$ degrees of freedom.^(a)

S = the square root of the variance of the fit expressed as

$$S = \sqrt{\frac{\sum_{i=1}^n (y_i - y_{fi})^2}{(n-2)}} \quad (4.46)$$

Inverting the substitution $y = \ln \alpha$ the prediction interval at a confidence level of $(1-\alpha)$ for the gas volume fraction computed using the power fit $\alpha = AU_S^B$ can be written as

$$e^{y_F - \sigma_y} < \alpha < e^{y_F + \sigma_y} \quad (4.47)$$

where $y_F = \ln A + B \ln U_S$.

In Section 5.5, the bubble rise velocity reduction factors F_S , F_{afa} , and F_W are calculated as the ratios of two curve fits of the form of Eq. (4.39). The resulting fit for F has the form

$$F_{12} = \frac{\alpha_2}{\alpha_1} = \frac{A_2}{A_1} U_S^{(B_2 - B_1)} \quad (4.48)$$

Taking the logarithm and substituting as for Eq. (4.41), the linear analog is

$$y_{12} = a_2 - a_1 + (B_2 - B_1)x \quad (4.49)$$

Eq. (4.49) represents the difference between two linear fits of Eq. (4.41) to n_1 and n_2 data points $(x_{i1}:y_{i1})$ and $(x_{i2}:y_{i2})$, respectively. Assuming B_2 and B_1 are statistically independent, y_1 , y_2 , and y_{12} have

(a) The inverse T distribution is evaluated with the function TINV in Microsoft Excel®.

(reasonably) the same variance, and the x_i measurements are centered, the prediction interval for this combination for a single given x_F can be expressed as $y_{12F} \pm \sigma_{y12}$ where σ_{y12} is defined as

$$\sigma_{y12} = t_{a, n_1+n_2-2} S_{12} \sqrt{1 + \frac{1}{n_1} + \frac{(x_F - \bar{x}_1)^2}{\sum_{i=1}^{n_1} (x_{i1} - \bar{x}_1)^2} + \frac{1}{n_2} + \frac{(x_F - \bar{x}_2)^2}{\sum_{i=1}^{n_2} (x_{i2} - \bar{x}_2)^2}} \quad (4.50)$$

where

t_{a, n_1+n_2-2} = value of inverse T distribution for given 2-tail probability and n_1+n_2-2 degrees of freedom.

S_{12} = the square root of the pooled variance of the two fits defined as

$$S_{12} = \sqrt{\frac{S_1^2 (n_1 - 1) + S_2^2 (n_2 - 1)}{(n_1 + n_2 - 2)}} \quad (4.51)$$

where S_1 and S_2 are defined by Eq. (4.51).

Inverting the substitution $y = \ln \alpha$ the prediction interval at a confidence level of $(1-a)$ for the bubble rise reduction factor computed using the power fit given by Eq. (4.48) is written as

$$e^{y_{12F} - \sigma_{y12}} < F_{12} < e^{y_{12F} + \sigma_{y12}} \quad (4.52)$$

where $y_{12F} = \ln A_2 - \ln A_1 + (B_2 - B_1) \ln U_S$.

5.0 Data Analysis

The purpose of this test program is to provide estimates of the waste bubble rise reduction factor, F_w , based on data obtained from a range of simulants in the SRNL mixing vessel. The data reduction models described in Section 4 were applied to data provided by SRNL. The results of this analysis, primarily sets of steady-state gas volume fraction, superficial velocity, and bubble rise speed with their associated uncertainties for each test run, are presented and interpreted in this section. The first three subsections present gas holdup test results: water tests in Section 5.1, tests in clay simulant in Section 5.2, and AZ HLW simulant tests in Section 5.3. Gas release test analyses are described in Section 5.4, and the overall comparison of effects of simulant and AFA is given in Section 5.5.

Though the results are remarkably consistent over a wide range, it is not possible to compare all tests on exactly the same basis. The SRNL testing program accomplished more than 200 tests over about three months in several simulants using two methods of gas generation. Because the mixing system had not been used before, the test method evolved as system behavior became better understood. As briefly described in Section 3, the primary changes were in the number and positioning of laser range finders for level measurement, the timing and sequence of test events, and the technique for setting agitator speed to obtain a consistent degree of mixing. Because the water and thick clay tests were conducted first, their results are more uncertain than later tests with thin clay and AZ high-level waste simulant.

An early, major change in the test program was to realize the huge range of test conditions required to represent plant operation. The April water tests were performed at superficial gas velocities from 3 to 15 mm/s, comparable to those used in the PNWD bubble column tests, and believed necessary to achieve a level change large enough to measure accurately. However, in reviewing data from the half-scale and hybrid PJM tests (Bontha et al. 2005, Russell et al. 2005), it was clear that superficial velocities three orders of magnitude smaller were necessary to approach plant conditions. The overall range of conditions and the data of the SRNL test program are illustrated in Figure 5.1. At the low end of the range, gas volume fractions were less than 0.5 vol%, requiring resolution of differences in simulant level of only 2-3 mm. This requirement led to the use of four lasers carefully placed to “see” the entire simulant surface and running tests for longer periods to ensure a steady state.

The net effect of these issues is that the later data are most consistent and of highest quality. Fortunately, these include tests in thin clay and HLW simulant with and without AFA—precisely the data needed to evaluate the F_w factor.

5.1 Gas Holdup Tests in Water

The water tests presented in this section were conducted on March 28, April 7, and April 11. Thirty-two tests were performed with air injection at superficial velocities in the 3–15 mm/s range (corresponding to air injection rates of 1–4 acfm), as shown in Table 5.1. No hydrogen peroxide tests in water were analyzed.

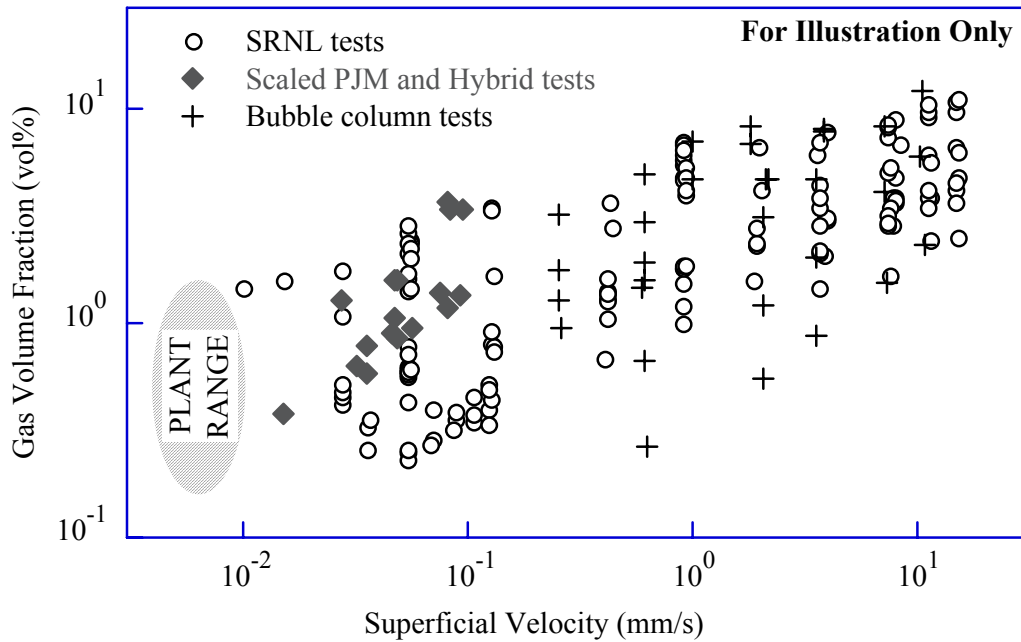


Figure 5.1. Range of Data Obtained in SRNL Tests

Table 5.1. Water Test Summary

Simulant	Agitator RPM	No. of Tests
H ₂ O	400	4 (3.6, 7.6, 11.4, 15 mm/s)
	550	4 “
	700	4 “
H ₂ O + salt	700	4 “
H ₂ O + AFA	400	4 “
	700	4 “
H ₂ O + salt + AFA	550	4 “
	900	4 “

The variation of gas volume fraction and bubble rise speed with superficial velocity and agitator rpm is shown in Figure 5.2. The water tests immediately reveal the trend that extends to all tests regardless of simulant or agitator speed. The gas volume fraction and bubble rise speed both vary linearly with superficial velocity on a log-log plot with remarkable consistency. These data can be fit with an equation of the form

$$\alpha = AU_S^B \quad (5.1)$$

In view of the steady state relation between α , U_R , and U_S given by Eq. (4.30), the following are also true:

$$U_R = \frac{1}{A} U_S^{(1-B)} \quad (5.2)$$

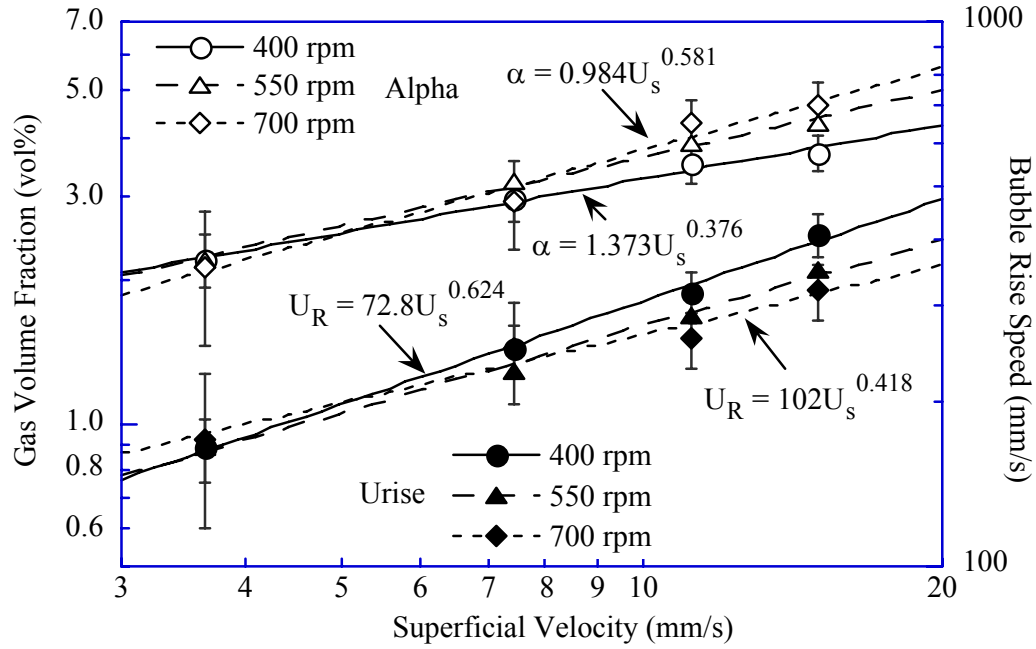


Figure 5.2. Gas Volume Fraction and Bubble Rise Speed Versus Superficial Velocity in Water

$$U_R = \frac{1}{A^{\frac{1}{B}}} \alpha^{\left(\frac{1}{B}-1\right)} \quad (5.3)$$

The close relation of U_R to α is obvious in Figure 5.2. Because presenting both variables is redundant, only α versus U_s will be shown in future plots.

Increasing agitator speed increases the gas volume fraction. Because the lower agitator is specifically designed to break up bubbles, increasing its speed also reduces the average bubble size, hence reducing bubble rise speed and increasing the gas volume fraction. In later tests with non-Newtonian clay and HLW simulants, the agitator speed was increased until simulant surface motion was observed all the way to the wall. While this produced a consistent level of mixing, the combined effects of changing simulant yield stress and agitator speed on the bubble size distribution are difficult to separate.

The results of prior PNWD bubble column holdup tests for water with and without AFA are compared with SRNL water data in Figure 5.3. Both tests show essentially the same behavior for water, but the effect of AFA is much greater in the bubble column. The F_{AFA} factor suggested by the ratio of coefficients of the curve fits is 2.5 for the SRNL data and 6.9 for the bubble column. We suspect that this is due to AFA reducing the size of bubbles formed at the frit at the base of the bubble column. AFA apparently has less effect on the breakup of bubbles by the agitator.

Figure 5.4 shows the effect of salt on the gas volume fraction in water with and without AFA to further illustrate the effect of the agitator in controlling bubble size. The addition of salt, both with and without AFA, reduces the variation of gas volume fraction with superficial velocity. Salt in water is

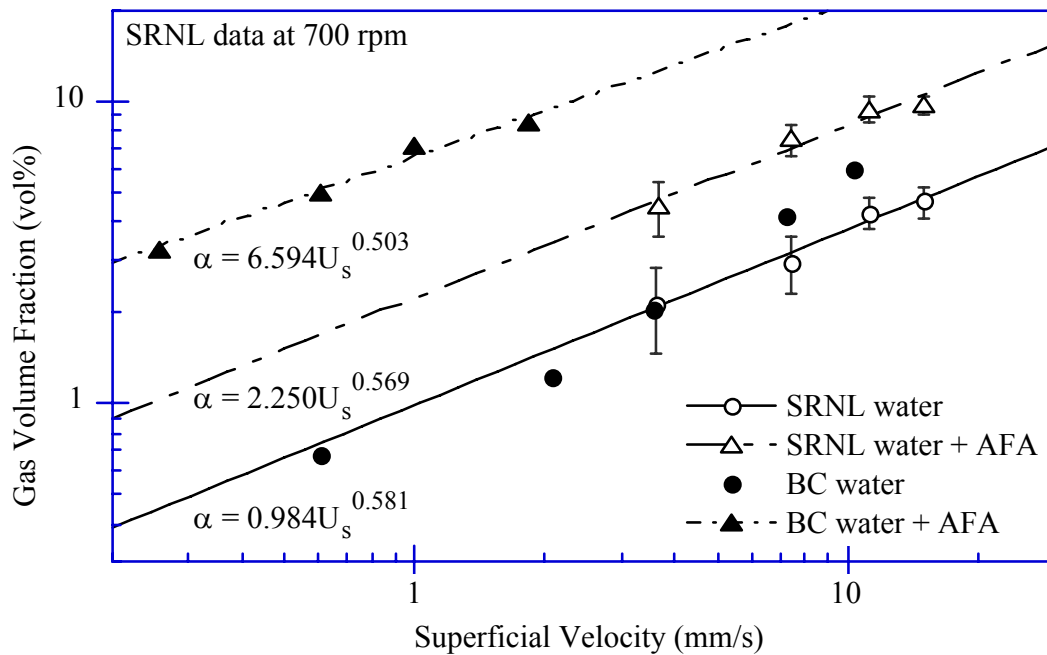


Figure 5.3. Comparison of PNNL Bubble Column and SRNL Holdup Tests in Water

known to alter the bubble interface to reduce or prevent coalescence and breakup. In air injection tests, this would tend to reduce the variation in bubble size with gas injection rate. The relative effect of AFA, which also operates on the bubble interface, is not as strong in the presence of salt.

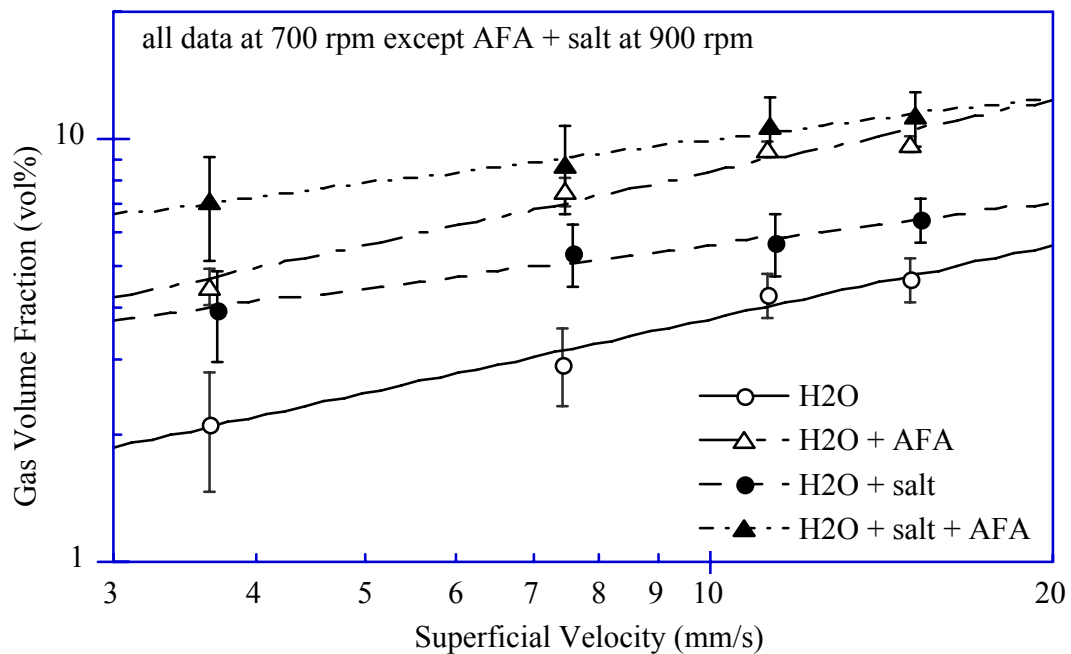


Figure 5.4. Effect of AFA and Salt on Gas Volume Fraction in Water

5.2 Gas Holdup in Clay Simulant

The clay simulant tests described in this section were conducted on March 29, April 27, and May 4, 9–11, and 15. Thirty-five tests were performed with air injection at superficial velocities of 0.03 to 15 mm/s and seven using hydrogen peroxide at 0.06 to 0.24 mm/s. Tests were also performed in thick (28-Pa) clay and in thinner clay with salt and AFA. However, the thick clay data were unusable, and the salt and AFA tests in clay were not used (see Section 3). The clay tests analyzed in this section are summarized in Table 5.2.

Table 5.2. Clay Simulant Test Summary

Yield Stress (Pa)	Agitator rpm	Superficial Velocity (mm/s)	No. of Tests	No. of Tests Using H ₂ O ₂
9–11	525	0.035–7.8	19	3
13	525	0.034–0.12	12	None
16	525	0.061–0.11	2	2
22	400	3.6–15	4	None
22	700	3.6–15	4	None

The gas volume fractions for all the air injection tests in clay (hydrogen peroxide tests are discussed in Section 5.3) are plotted in Figure 5.5 along with those obtained from PJM and hybrid scaled holdup tests (Russell et al. 2005, Bontha et al. 2005). The clay yield stress range is indicated in the plot legend, where LS refers to the ~ 1/4 scale LS hybrid sequence 14 and 15 holdup tests, APEL 4PJM to the ~1/4-scale four-PJM scaling holdup tests, HSLS to the half-scale LS hybrid holdup tests where PJMs and spargers were operating simultaneously, and BC to PNWD bubble column tests.

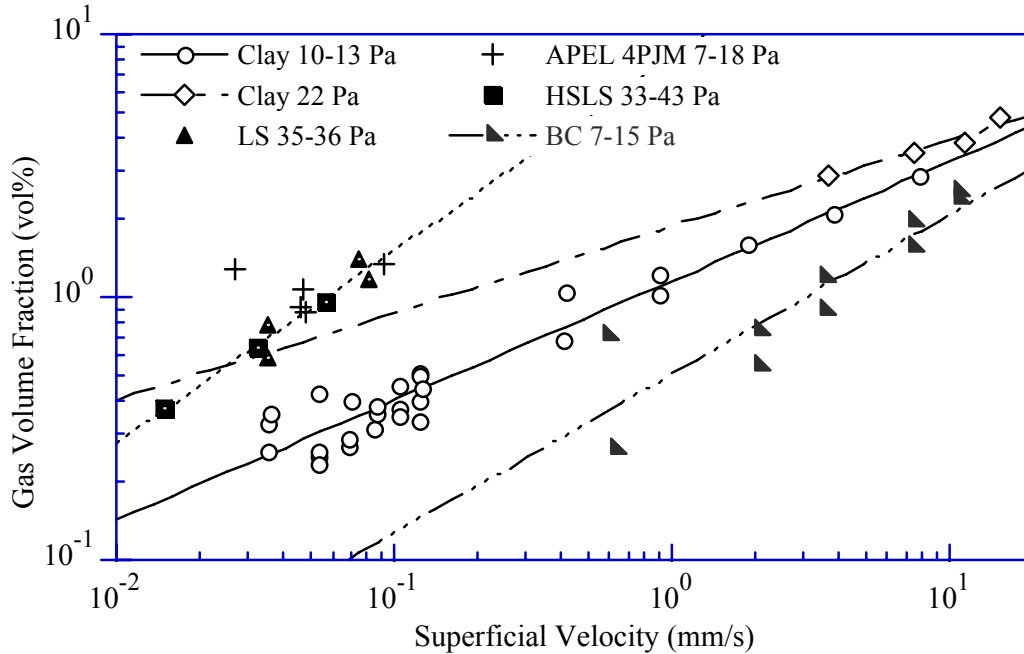


Figure 5.5. Comparison of SRNL Test Results to Half-Scale and PJM Hybrid Tests in Clay

The 10- to 13-Pa clay test results closely follow the same $\alpha = Ae^B$ trend over four orders of magnitude of superficial gas velocity. It is also interesting that the extrapolated trend of the 22-Pa SRNL data passes through or slightly below the large-scale PJM and hybrid data. However, the slope of the $\sim 1/4$ -scale and LS and HSLS trend shown by the dotted line is much different than SRNL data. This implies that SRNL test results are not directly applicable to predict gas retention/release in large PJM hybrid systems. Nevertheless, the SRNL data appear to be a much closer match than the bubble column tests, whose trend and magnitude appear to fall outside the population of both SRNL and scaled PJM and hybrid tests.

Figure 5.5 also implies that the gas volume fraction increases with yield stress. However, this effect is masked by use of different agitator speeds. The gas volume fraction is higher at higher agitator speed in clay as well as in water, apparently because higher rotation speed produces smaller gas bubbles. The gas volume fraction in 22-Pa clay is plotted against superficial velocity for tests at 400 and 700 rpm in Figure 5.6. The ratio of coefficients of the power fits indicates the higher agitator speed increases holdup by more than a factor of 2. Figure 5.7 compares the gas volume fractions from tests at approximately the same superficial velocity but different yield stress and agitator speed. Water data are also plotted at zero yield stress for comparison. Extrapolating between the 400 and 700 rpm values at 22 Pa would indicate little if any change in gas volume fraction with yield stress at either superficial velocity.

5.3 Gas Holdup in HLW Simulant

Described in this section are tests with HLW (AZ) simulant conducted May 16–25 and June 6–9. Seventy-seven tests were performed with air injection at superficial velocities of 0.01–7.9 mm/s and ten

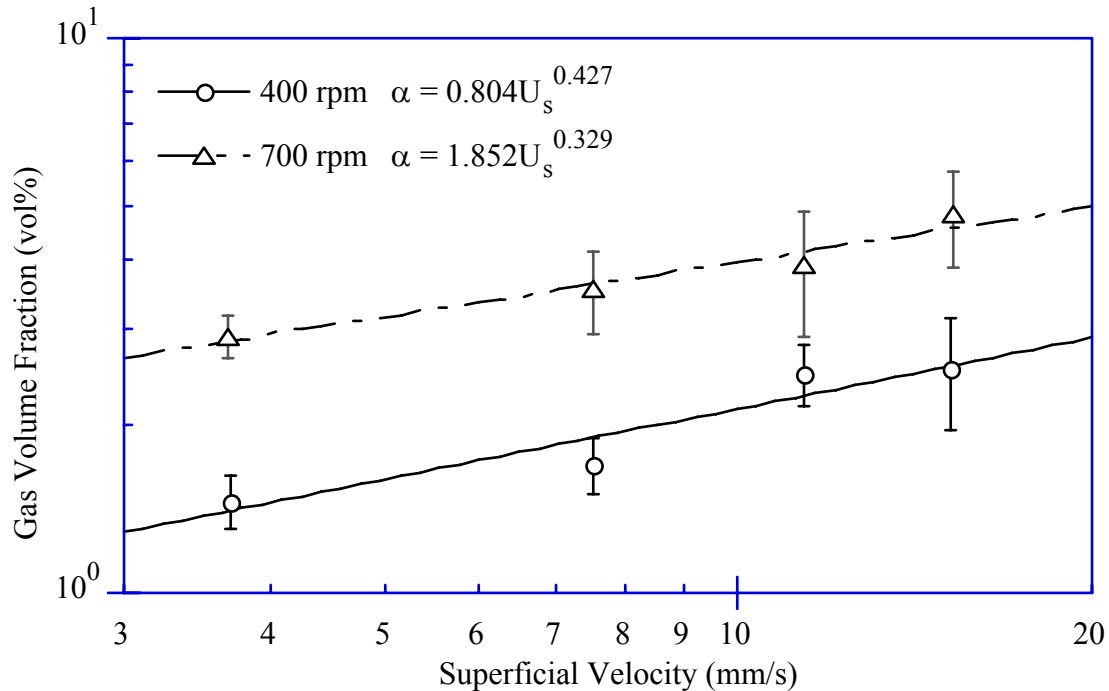


Figure 5.6. Effect of Agitator RPM on Gas Volume Fraction in 22-Pa Clay Simulant

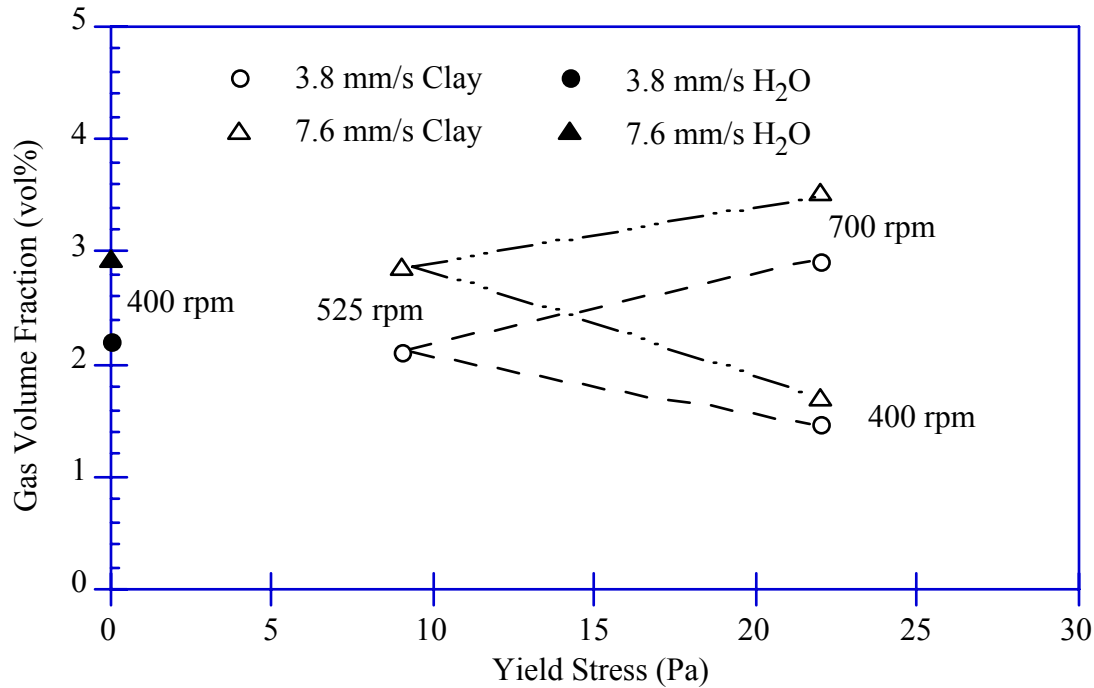


Figure 5.7. Effect of Yield Stress on Gas Volume Fraction in Clay Simulant

with hydrogen peroxide at 0.06–0.13 mm/s. AFA was added in 39 of the air injection tests and five of the hydrogen peroxide tests. The tests analyzed in this section are summarized in Table 5.3.

The test results for air injection tests in AZ simulant without AFA are shown in terms of gas volume fraction versus superficial velocity in Figure 5.8. Without AFA, the gas volume fraction in AZ simulant appears relatively insensitive to yield stress. The increase in gas volume fraction going from 11 to 30 Pa is only 22%, as indicated by the ratio of leading coefficients of the power fits shown in the figure. Also, the exponents for the 13-Pa and 30-Pa fits are essentially identical, indicating that the ratio of the two is constant over about three orders of magnitude of superficial velocity.

The effect of adding AFA to AZ simulant is depicted in Figure 5.9, which compares the variation of gas volume fraction with superficial velocity for air injection tests in AZ simulant with and without AFA. While the trends with superficial velocity are similar, gas fractions are much higher with AFA and the effect stronger at the lower yield stress. The ratio of coefficients of the power fit for 13-Pa AZ simulant

Table 5.3. HLW Simulant Test Summary

Yield Stress (Pa)	Agitator (rpm)	Superficial Velocity (mm/s)	No. of Tests	No. of Tests Using AFA	No. of Tests Using H ₂ O ₂
11–12	650	0.05–7.7	17	None	2
13–14	650	0.01–7.8	47	21 (4 H ₂ O ₂)	6
28–30	940–970	0.026–7.9	15	7 (1 H ₂ O ₂)	2
2–29 ^(a)	400–970	0.05, 0.9	17	All	None

(a) Special test varying simulant yield stress by sequential dilution at two superficial velocities.

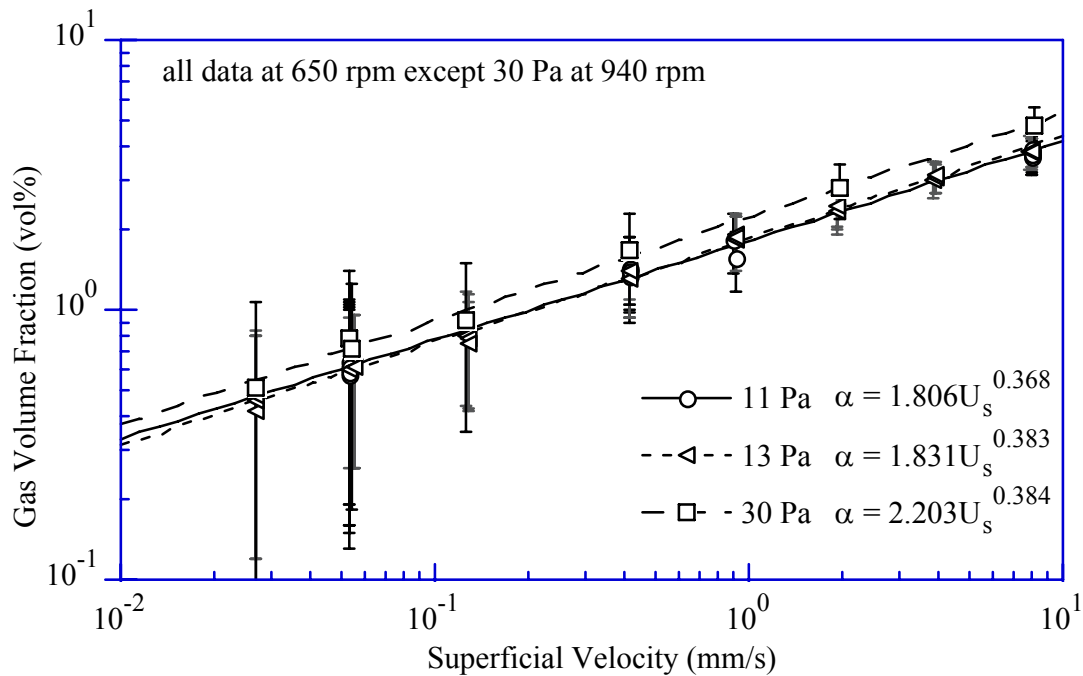


Figure 5.8. Gas Volume Fraction Versus Superficial Velocity in AZ Simulant Without AFA

indicates the gas volume fraction with AFA is almost three times that in tests without AFA. For 30-Pa AZ simulant, the gas volume fraction with AFA is only 1.6 times as high. The smaller exponents on the power fits for AZ simulant with AFA indicate that the ratios increase at lower superficial velocities.

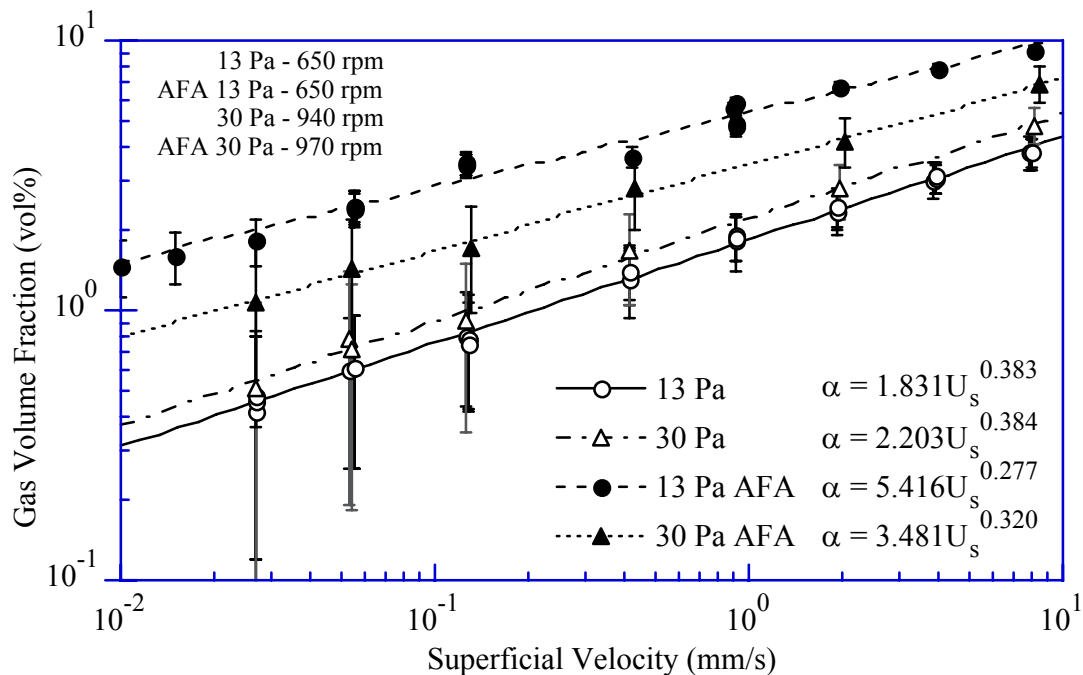


Figure 5.9. Gas Volume Fraction Versus Superficial Velocity in AZ Simulant with AFA

The influence of yield stress was investigated specifically in a special series of tests where 28-Pa AZ simulant with AFA was sequentially diluted with supernatant in steps down to 2 Pa. At each dilution, two air injection holdup tests were performed at different superficial velocities. The resulting gas volume fractions are plotted versus simulant yield stress in Figure 5.10. Gas volume fractions extrapolated from the curve fit for water with salt and AFA added in Figure 5.4 are also plotted at zero yield stress for comparison (realizing that water plus salt is not a rheological equivalent of zero-yield stress AZ simulant). The effect of decreasing the yield stress is to increase the gas volume fraction. This indicates that, with AFA, dilution of solids does not reduce holdup. Unreviewed SRNL data showed a similar phenomenon in clay with AFA added.

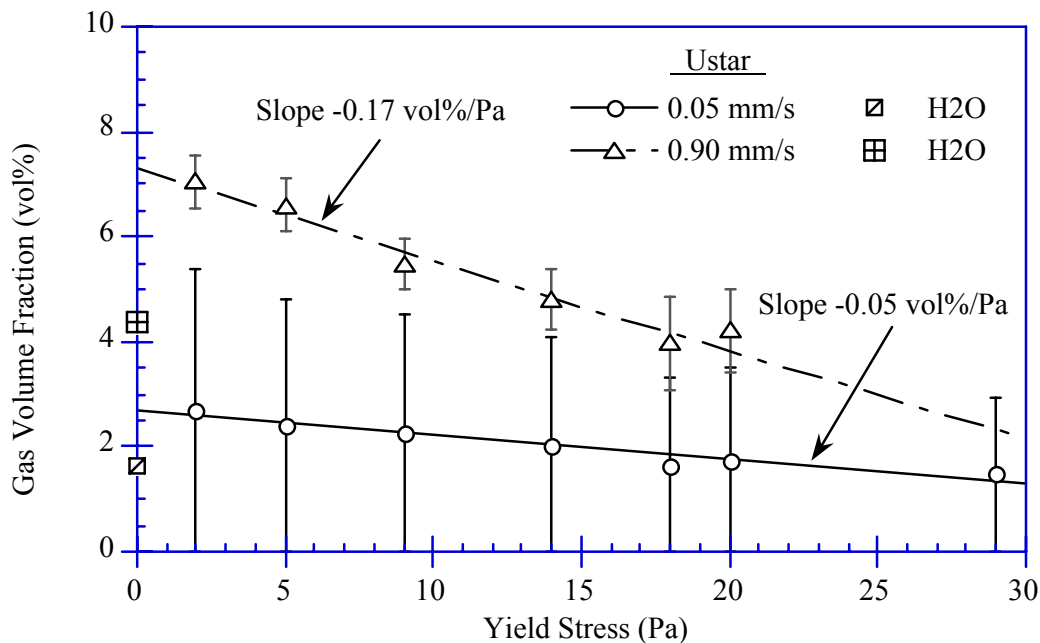


Figure 5.10. Effect of Yield Stress on Gas Volume Fractions in AZ Simulant with AFA

The gas retention behavior of AZ simulant is compared with clay simulant in Figure 5.11. The gas volume fraction is higher in AZ simulant than in clay though the difference is less at higher yield stress (22-Pa clay compared to 30-Pa AZ). At 10–13 Pa yield stress, the gas volume fraction is about 60% higher in the AZ simulant.

Tests using hydrogen peroxide decomposition for gas generation were performed because this method was more likely to represent in situ gas generation in actual waste. Also, except for the bubble column, the prior scaled gas holdup tests in PJM systems also used hydrogen peroxide. The results of both air injection and hydrogen peroxide tests at similar superficial velocities are compared in Figure 5.12 (clay results are shown in this section because few H₂O₂ tests were performed in clay). The gas volume fractions for the 10-Pa clay tests with H₂O₂ are somewhat higher than those from the air injection tests, though the values are similar within their uncertainty. The gas volume fractions for the H₂O₂ tests with AZ simulant are more consistent with those of the corresponding air injection tests. The results of H₂O₂ tests in AZ simulant with and without AFA are shown in Figure 5.13. The gas volume fractions are slightly lower than the air injection values, while the single H₂O₂ test in 30-Pa AZ simulant with AFA falls well within the corresponding air injection data.

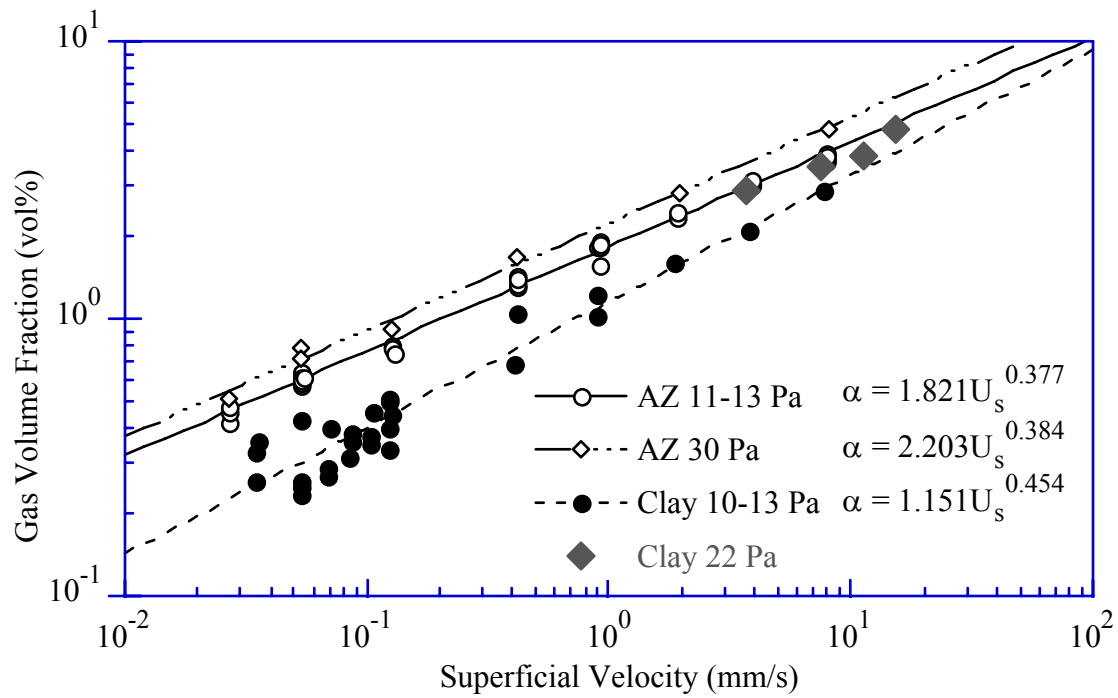


Figure 5.11. Comparison of Gas Volume Fractions in AZ and Clay Simulants

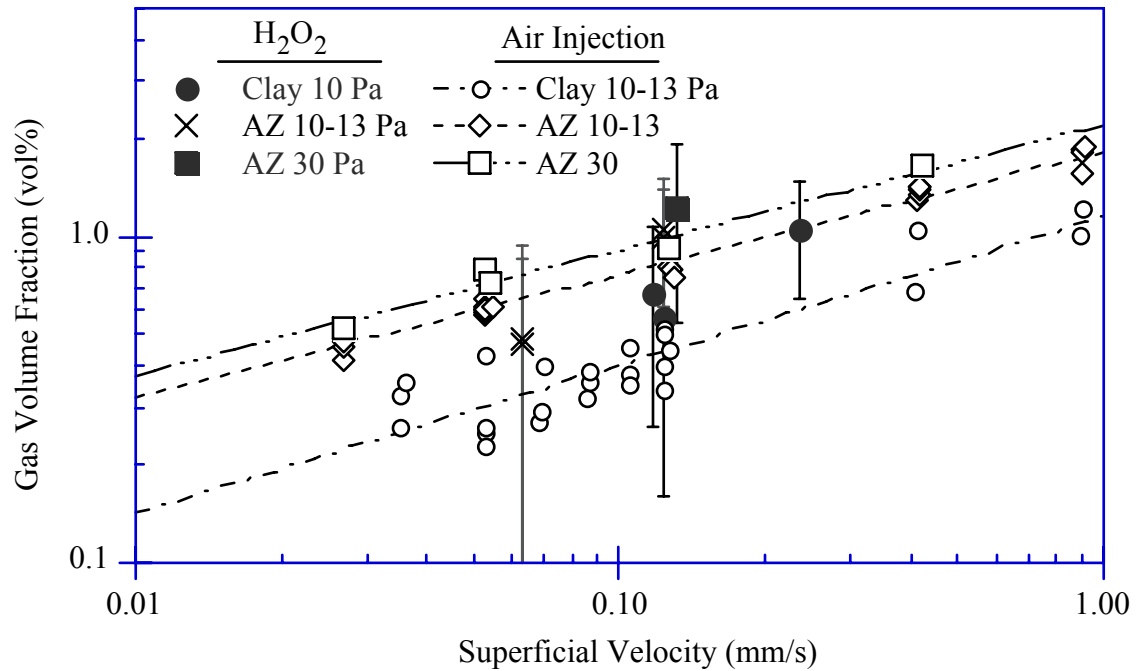


Figure 5.12. Comparison of Air Injection and H_2O_2 Tests in AZ and Clay Simulants

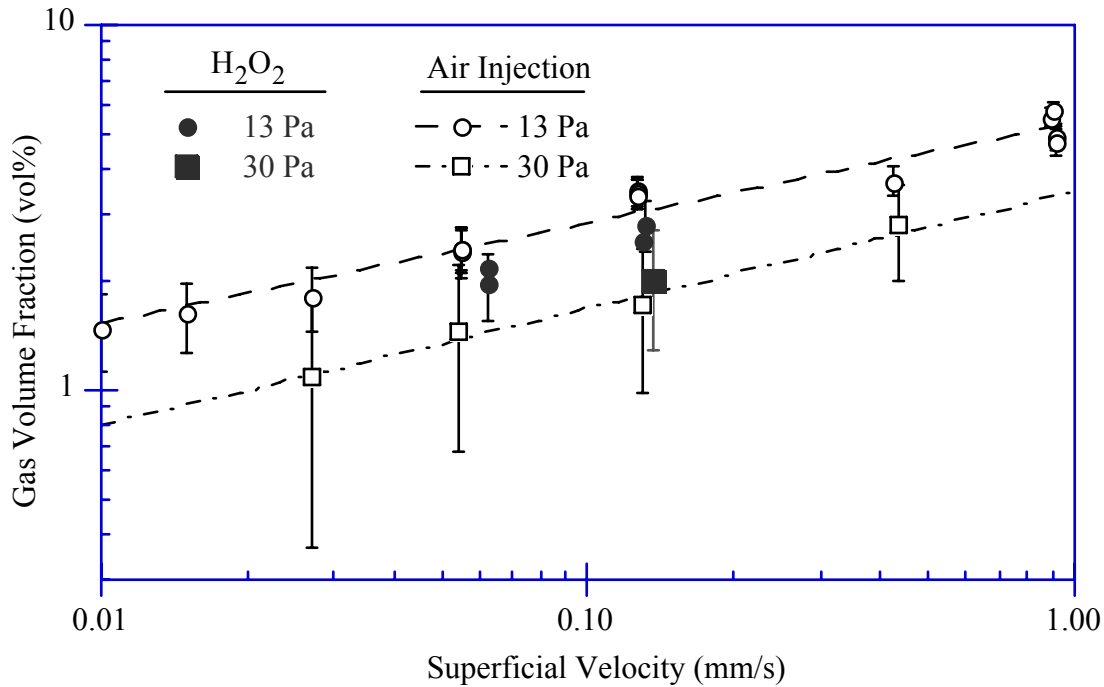


Figure 5.13. Comparison of Air Injection and H₂O₂ Tests in AZ Simulant with AFA

These results imply that the bubble size distribution generated by hydrogen peroxide decomposition, may be different than that of injected bubbles. The hydrogen peroxide bubble size distribution is only modified by the lower agitator, while the injected bubble size distribution is actually created by the lower agitator. However, the H₂O₂ results are not inconsistent with those of air injection and support the latter as a valid test method.

5.4 Transient Gas Release Behavior

The preceding sections discussed the results of holdup tests where steady-state gas volume fractions were derived at a constant gas generation rate (as quantified by the superficial velocity). While these data provide a relatively precise portrayal of the gas retention characteristics of the various simulants tested, there is a concern about whether the gas release behavior can be described by the same parameters. This section addresses that concern by presenting the analysis of gas releases following holdup tests using a new release model that better relates to holdup test results.

The gas retention and release model stated by Russell et al. (2005) and Bontha et al. (2005) that has been applied in WTP analyses assumes a constant bubble rise speed, U_R , that forms the time constant for gas release, $\tau_R = H/U_R$, where H is the characteristic depth of slurry that the bubbles must rise through. However, this assumption requires up to three time constants to fit most gas release data. This five-parameter model is expressed as (Russell et al. 2005):

$$\alpha(t) = \alpha_0 \left(F_1 e^{-t/\tau_1} + F_2 e^{-t/\tau_2} + F_3 e^{-t/\tau_3} \right) \quad (5.4)$$

where F_i represents the fractions of gas that follow each of the three time constants, τ_i . Forcing the sum of F_i to unity (to meet the initial condition) eliminates one of them, effectively giving a five-parameter model. While the first or smallest time constant usually implies a U_R that roughly corresponds to values obtained from steady-state holdup tests, it is very difficult to compare release tests under different conditions and to relate release to holdup using Eq. (5.4) and the constant rise velocity assumption. The new data obtained in the SRNL tests have inspired a new model that relaxes the constant rise velocity assumption and reduces the number of parameters necessary to fit the release data.

5.4.1 Revised Gas Release Model

Contrary to the constant bubble rise velocity assumption, the steady-state holdup data from the SRNL tests consistently show that the gas volume fraction increases as a power of the superficial velocity, as shown, for example, in Figure 5.9. This also means that the bubble rise velocity decreases as a power of the gas volume fraction according to Eq. (5.3). During a release, larger, faster bubbles should leave first, followed by the smaller, slower ones so the average bubble size and corresponding bubble rise speed decrease with decreasing gas content. This implies that the power function derived from holdup test results should also apply to gas release, at least in form.

Assuming Eq. (5.3) is valid to relate U_R to α during a release, the rate of change in gas volume fraction at any instant can be expressed as

$$\frac{d\alpha}{dt} = \frac{-U_R \alpha}{H} = \frac{-1}{H} \left(\frac{\alpha}{A} \right)^{1/B} \quad (5.5)$$

Assume that an air-injection holdup test that has reached its steady-state gas volume fraction, α_{SS} , and corresponding bubble rise velocity, U_{RSS} , under constant agitation. Air injection is then shut off while continued agitation keeps the simulant mobile and allows the release of the retained gas bubbles. Because α and U_R must be continuous when air ceases at $t = 0$, the two parameters A and B can be reduced to one. Specifically, at $t = 0$, it is required that $\alpha = \alpha_{SS}$ and $U_R = U_{RSS}$, so Eq. (5.5) becomes

$$\left. \frac{d\alpha}{dt} \right|_{t=0} = \frac{-U_{RSS} \alpha_{SS}}{H} = \frac{-1}{H} \left(\frac{\alpha_{SS}}{A} \right)^{1/B} \quad (5.6)$$

Solving Eq. (5.6) for A yields

$$A = \alpha_{SS}^{(1-B)} U_{RSS}^{-B} \quad (5.7)$$

Substituting this expression for A with Eq. (5.5) yields

$$\frac{d\alpha}{dt} = - \frac{U_{RSS}}{H} \alpha_{SS}^{\left(\frac{B-1}{B} \right)} \alpha^{\frac{1}{B}} \quad (5.8)$$

which has the solution:^(a)

$$\alpha(t) = \alpha_{SS} \left[1 - \left(\frac{B-1}{B} \right) \frac{U_{RSS}}{H} t \right]^{\frac{B}{B-1}} \quad (5.9)$$

The constant B is determined from a least squares fit of Eq. (5.9) to gas volume fractions calculated directly from simulant levels measured during gas release tests.

5.4.2 Application to SRNL Gas Release Data

The performance of the revised release model is demonstrated in an example from an air injection test in AZ simulant with yield strength of 10 Pa without AFA (shown in Figure 5.14). The data points represent gas volume fractions calculated from 10-s aggregated level data using Eq. (4.28) with the simulant volume held constant.^(b) The horizontal line depicts α_{SS} , and the solid curve depicts Eq. (5.9) for $B = 0.426$. The α_{SS} and U_{RSS} values are taken from the previous steady-state portion of the test.

The B parameter was actually determined from a least squares fit of data from a sequence of eight releases from steady-state conditions at two superficial gas velocities. It is remarkable that this single value of B is equally valid for all eight runs. Such a global fit was never possible with the five-parameter exponential model of Eq. (5.4).

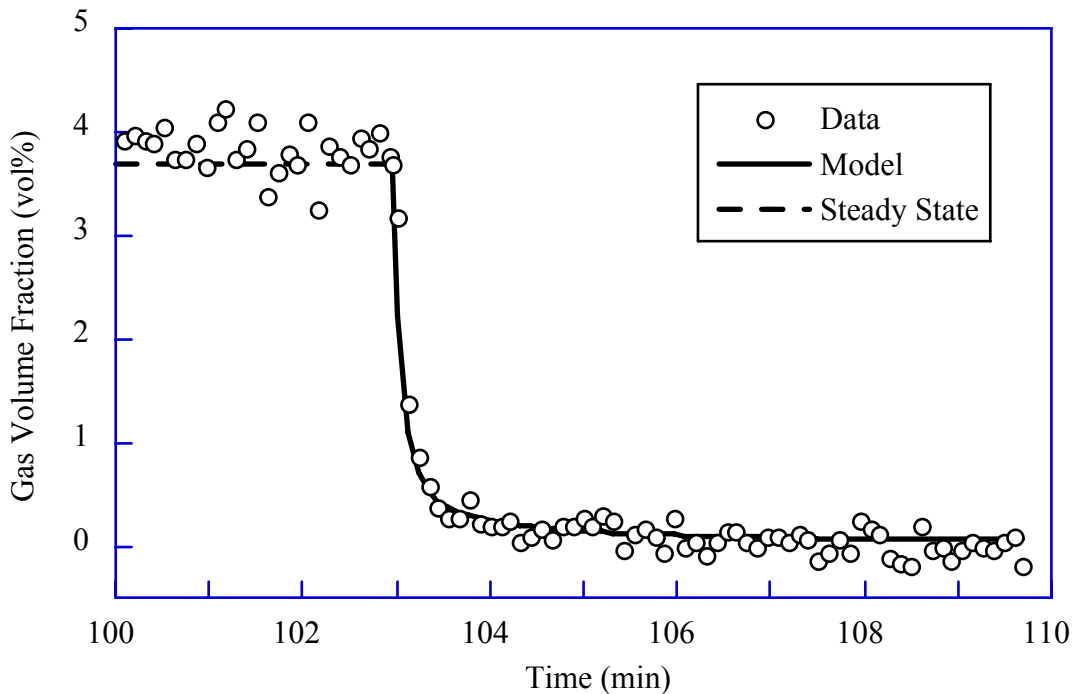


Figure 5.14. Gas Volume Fraction Versus Time, Release in 10-Pa AZ Simulant Without AFA

(a) Because $B < 1$, the exponent of Eq. (5.9) is negative so that $\alpha(t)$ approaches zero at large t .

(b) This means that evaporative water loss is ignored during the release, which is appropriate for the short 10- to 15-minute release period.

The best-fit value for $B = 0.426$ is comparable to the value of $B = 0.368 \pm 0.01$ calculated for all tests using 11-Pa AZ simulant in Section 5.3 (i.e., from the fit $\alpha = 1.806U_s^{0.368}$ in Figure 5.8). In principle, these B values should be identical. They may differ because the value from Section 5.3 is based on twice as many tests, including some that had slightly higher yield strengths. However, the ~14% difference may also be attributable to the fundamental difference between gas release, where an initial bubble population is progressively depleted, and the steady state, where the bubble size distribution is a constant balance between release and generation.

No suitable experimental data were available to test the validity of Eq. (5.8) with clay simulant, but data from other experimental runs using AZ simulant suggest the B parameter does not vary significantly with yield strength. Figure 5.15 depicts just the transient period of a release in 30-Pa AZ simulant without AFA. The B parameter value for this test is 0.409, essentially the same as was found for the 11-Pa simulant. This value of B was determined from a series of five releases, beginning from steady states at four air injection rates (i.e., different U_s). As in the previous example, it is close but not identical to the value obtained in Section 5.3, $B = 0.384 \pm 0.01$ ($\alpha = 2.203U_s^{0.384}$ in Figure 5.8).

Adding AFA to AZ simulant has the effect of decreasing the value of B . Figure 5.16 shows the transient percent volume fraction curve for a 30-Pa AZ with AFA. In this example $B = 0.365$ based on four releases. The corresponding B value from Section 5.3 determined from six steady-state holdup tests was 0.320 ± 0.01 ($\alpha = 3.481U_s^{0.320}$ in Figure 5.9). Analysis of several other tests with and without AFA shows that Eq. (5.8) is equally valid with or without AFA and that a similarly lower B -value is required to fit releases with AFA.

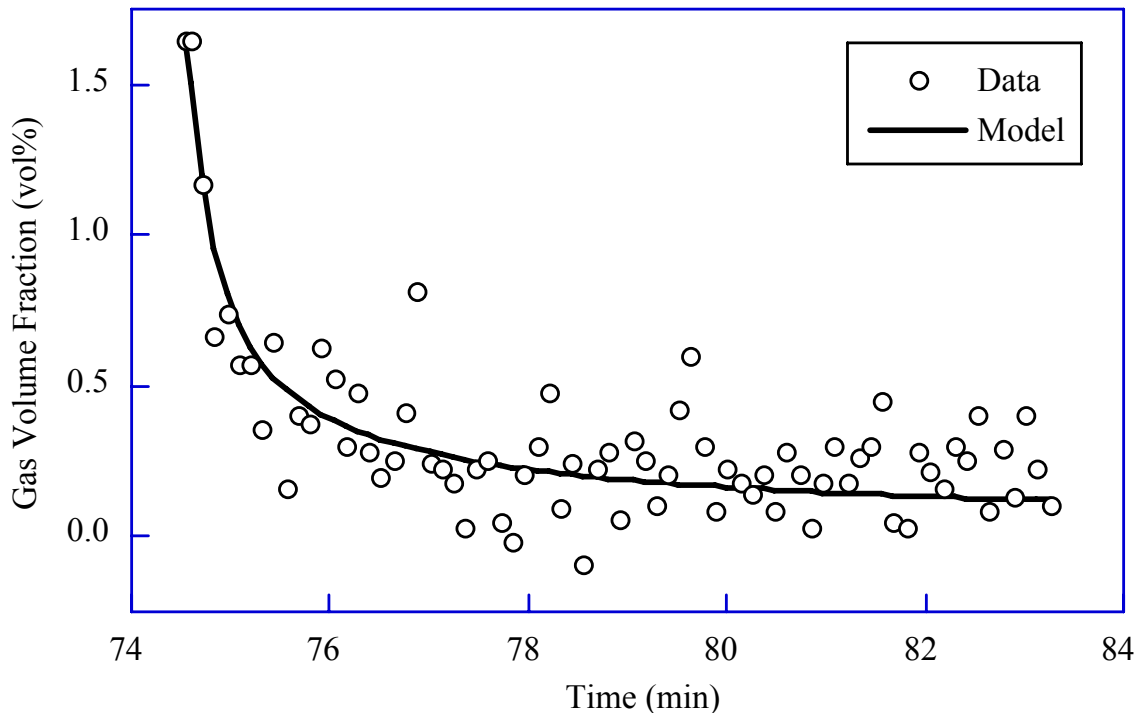


Figure 5.15. Gas Volume Fraction Versus Time, 30-Pa AZ Simulant Without AFA

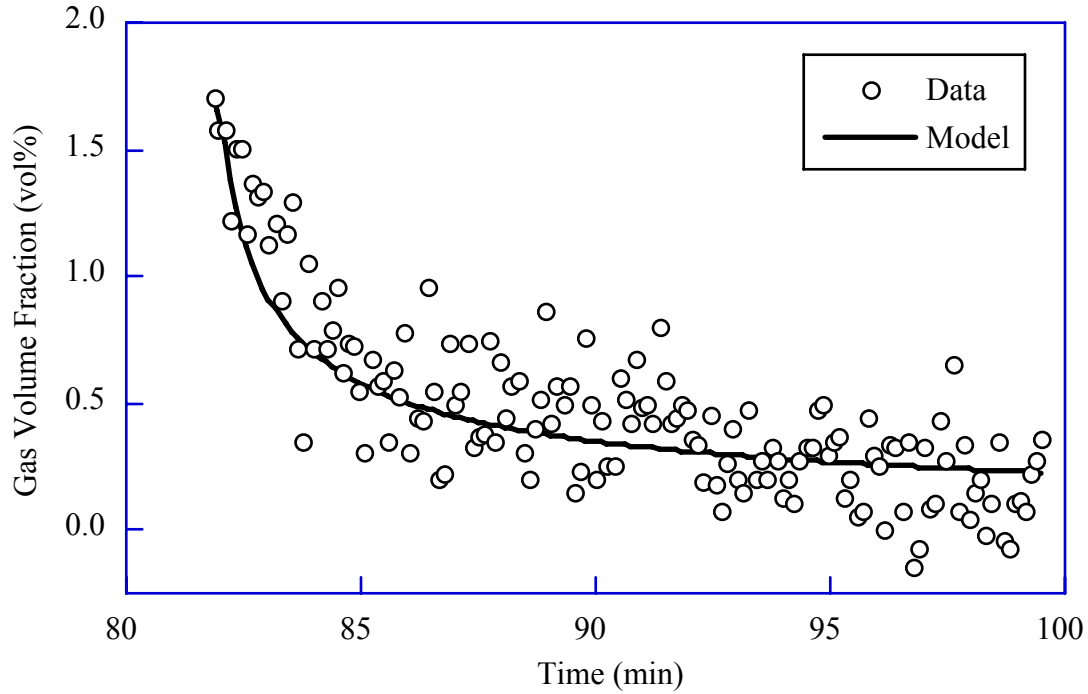


Figure 5.16. Gas Volume Fraction Versus Time, 30-Pa AZ Simulant with AFA

5.4.3 Application to Sparger- and PJM Hybrid-Induced Gas Release Data

A second transient gas release scenario for which experimental data are available is that of a static simulant that is suddenly agitated to release the trapped gas. The sparging gas release tests described by Poloski et al. (2005) and analyzed by Russell et al. (2005) are examples of this scenario. In these tests, a large cone-bottom tank was filled with clay simulant containing hydrogen peroxide that was allowed to decompose and generate oxygen bubbles in situ. During this growth period, the surface level was monitored until it reached a constant value. At this point the quiescent system was then rapidly agitated by turning on air sparging at a relatively high flow rate. Initially the surface level rose rapidly due to introduction of the sparged air bubbles (sparger holdup was consistently ~ 0.7 vol%), but then decreased as the initially trapped gas was released.

In this scenario the gas release did not start from a steady state, where α_{ss} and U_{RSS} were known, but from static conditions where only the initial retained gas volume was known. Thus Eq. (5.6) was rewritten as

$$\left. \frac{d\alpha}{dt} \right|_{t=0} = \frac{-U_{R0} \alpha_0}{H} = \frac{-1}{H} \left(\frac{\alpha_0}{A} \right)^{1/B} \quad (5.10)$$

where U_{R0} and α_0 are the initial average bubble rise velocity and initial gas volume fraction, respectively. Combining Eq. (5.10) with Eq. (5.5) and solving yields

$$\alpha(t) = \alpha_0 \left[1 - \left(\frac{B-1}{B} \right) \frac{U_{R0}}{H} t \right]^{\frac{B}{B-1}} \quad (5.11)$$

Figure 5.17 is a plot of the gas volume fraction for one example of a sparge release test in which the hollow circles indicate values based on 6-s averaged level readings and the solid curve is a least-squares fit of Eq. (5.11) to the level readings. The least-squares fit was conducted by first correcting the level reading based on sparger holdup (sparger holdup was reported to be 0.67%) using the experimentally determined $\alpha_0 = 1.2\%$ and adjusting both B and U_{R0}/H . The best fit was determined to be $B = 0.364$ and $U_{R0}/H = 0.720 \text{ min}^{-1}$. This corresponds to an initial release time constant ($\tau_R = H/U_{R0}$) of 1.39 min. This compares closely with the 1.5 minute “fast” time constant reported for this test with a three-parameter fit (Russell et al. 2005), which is shown as the dashed curve on Figure 5.17. With $U_{R0}/H = 0.720 \text{ min}^{-1}$ and $H \approx 205 \text{ cm}$, $U_{R0} \approx 2.5 \text{ cm/s}$.

A very similar result was obtained for release tests conducted with clay simulant in the $\sim 1/4$ -scale UFP test vessel (UFP Sequence 6, Run 2) described by Russell et al. (2005), where four PJMs and one center sparger were used to agitate the simulant after allowing it to stand overnight. The gas volume fraction for this test is plotted as a function of time for an example release in Figure 5.18. The values of $B = 0.498$ and $U_{R0}/H = 0.0859 \text{ min}^{-1}$ were determined by a least squares fit of the level measurement-based α . The corresponding time constant is 11.6 minutes. This is about twice the “fast” time constant from the three-parameter fit by Russell et al. (2005) but closer to the 9.8-minute time constant from the corresponding steady-state holdup test conducted in the same vessel. Given $H \approx 142 \text{ cm}$, the initial average bubble rise velocity for this run can be estimated to be $U_{R0} \approx 0.204 \text{ cm/s}$.

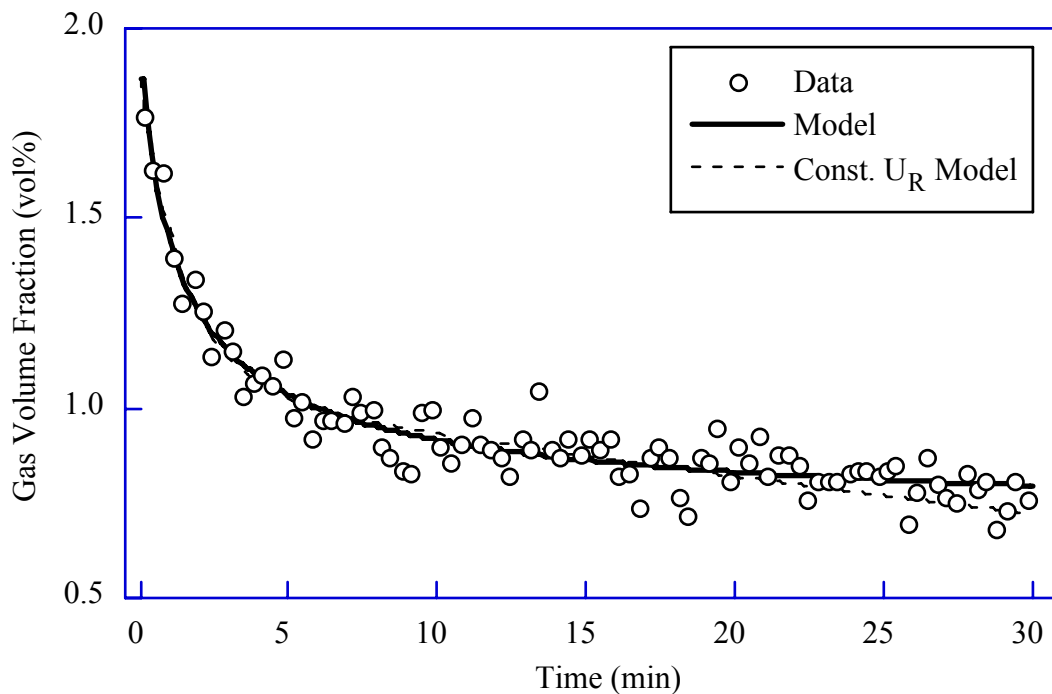


Figure 5.17. Gas Volume Fraction Versus Time, Cone-Bottom Tank Sparge Release

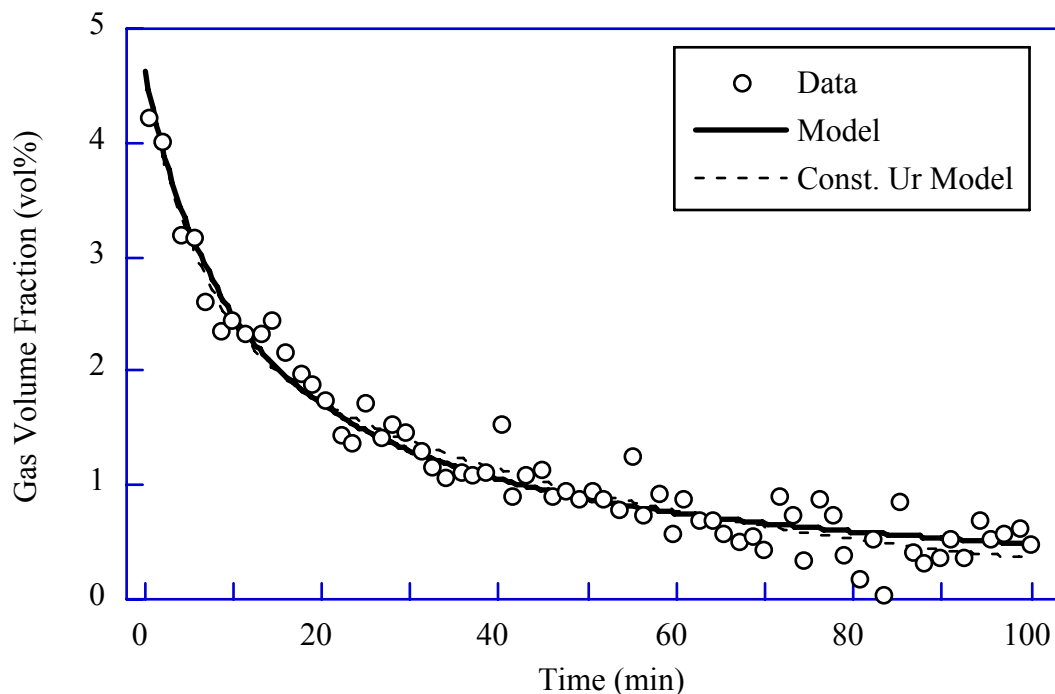


Figure 5.18. Gas Volume Fraction Versus Time, UFP PJM Hybrid Release

Another release test conducted with clay simulant in the $\sim 1/4$ -scale LS test vessel (LS Sequence 15, Run 4) (Russell et al. 2005) with seven PJMs and four spargers used for mixing. This release began after only ~ 30 minutes of standing time following a steady-state holdup test. The gas volume fraction for this test is plotted as a function of time for an example release in Figure 5.19. The values of $B = 0.242$ and $U_{R0}/H = 0.298 \text{ min}^{-1}$ were determined the same way as the UFP test above. The corresponding time constant is 3.4 minutes, closer to the “fast” time constant of 2.7 minutes from the three-parameter fit by Russell et al. (2005) than the UFP test, but lower than the 4.2-minute time constant from the prior steady-state holdup test. Given $H \approx 142 \text{ cm}$, the initial average bubble rise velocity for this run can be estimated as $U_{R0} \approx 0.35 \text{ cm/s}$.

5.4.4 Summary of Release Test Results

The conditions and fit parameters described in this section are summarized in Table 5.4. It is remarkable that the wide variety of release tests fit closely with only one (starting from steady-state holdup tests) or two (starting from static conditions) parameters. In fact, the B -parameter exponent is very similar in most of the tests, though they differed by a factor of almost 6 in scale, used different simulants varying from 2–35 Pa in yield stress, and employed very different methods to mobilize the simulant. The B values are all higher than those established from the power law fits to all the data.

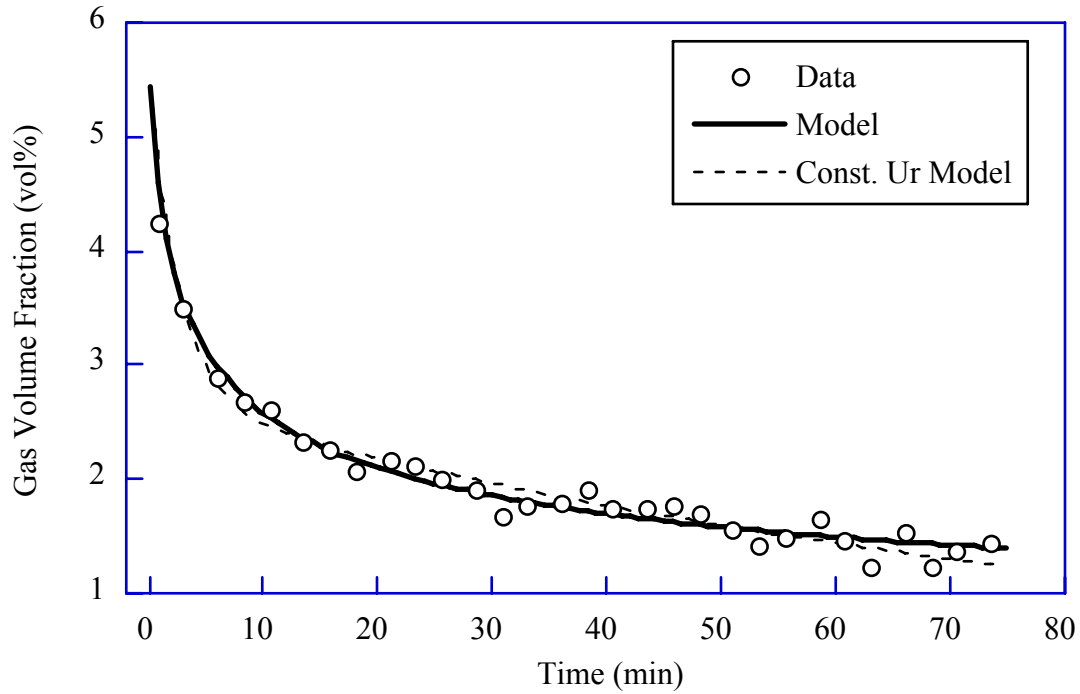


Figure 5.19. Gas Volume Fraction Versus Time, LS PJM Hybrid Release

Table 5.4. Summary of Release Tests Analyzed

Test Vessel (mobilization)	Simulant	Yield Stress (Pa)	B Release (holdup fit) ^(a)	α_{ss} (vol%)	U_{RSS} (mm/s)	Figure No.
Results discussed in this section						
SRNL (agitator)	AZ	10	0.426 (0.368)	1.3–3.9	29–214	5.14
	AZ	30	0.409 (0.384)	0.5–1.7	5–25	5.15
	AZ + AFA	30	0.365 (0.320)	1.1–1.7	2.5–7.8	5.16
Cone-bottom tank T 040707 (spargers)	Clay	35	0.364	1.2	24 ^(b)	5.17
UFP Seq. 6, R2 (PJM hybrid)	Clay	36	0.498	4.6	2.0 ^(b)	5.18
LS Seq. 15, R4 (PJM hybrid)	Clay	36	0.242	5.5	5.9 ^(b)	5.19
Other releases analyzed						
SRNL (agitator)	AZ	30	0.442 (0.384)	2.8–4.9	69–166	-
	AZ	12	0.433 (0.383)	1.6	58	-
	AZ + AFA	2	0.388	2.2–6.3	2.5–14	-
	AZ + AFA	13	0.344 (0.277)	3.4–3.5	3.6–3.7	-
	AZ + AFA	20	0.354	1.8–4.2	3.1–22	-
	AZ + AFA	13	0.416 (0.277)	5.9	15	-
UFP Seq. 5, R4 (PJM hybrid)	Clay	35	0.207	6.8	7.4 ^(b)	-
UFP Seq. 6, R4 (PJM hybrid)	Clay	34	0.301	6.9	5.2 ^(b)	-
LS Seq. 15, R2 (PJM hybrid)	Clay	37	0.503	4.7	5.9 ^(b)	-
APEL 020604 (4PJM system)	Clay	33	0.413	3.6	2.6 ^(b)	-
(a) B values for SRNL holdup fit are taken from the overall fit to all the data. See Figure 5.8 for example.						
(b) Release initiated from static condition with known α_0 , U_{R0} determined as a fit parameter.						

5.5 Determination of the Simulant and Anti-Foam Factors

As discussed in Section 1, the overall clay-to-waste bubble rise velocity ratio, F_W , is the product of two factors (a third, AZ simulant-to-waste factor assumed to be 1.0), defined by

$$F_W = \frac{U_{R-Clay}}{U_{R-AZ}} \cdot \frac{U_{R-AZ}}{U_{R-AZ+AFA}} = F_S \cdot F_{AFA} \quad (5.12)$$

where

- F_S = the ratio of bubble rise velocity in clay simulant (U_{R-Clay}) to that in AZ simulant (U_{R-AZ}) with similar rheological properties.
- F_{AFA} = the ratio of bubble rise velocity in AZ simulant (U_{R-AZ}) to that in AZ simulant with AFA ($U_{R-AZ+AFA}$)

Because these factors are defined by steady-state values for the bubble rise velocities, Eq. (4.30) can be applied to cast Eq. (5.12) in terms of the gas volume fraction so that

$$F_W = \frac{\alpha_{AZ}}{\alpha_{Clay}} \cdot \frac{\alpha_{AZ+AFA}}{\alpha_{AZ}} = F_S \cdot F_{AFA} = \frac{\alpha_{AZ+AFA}}{\alpha_{Clay}} \quad (5.13)$$

The evaluation of each of the two factors, F_S and F_{AFA} , is discussed in Sections 5.5.1 and 5.5.2. The overall F_W factor is evaluated in Section 5.5.3. The gas volume fractions versus superficial velocity data for this calculation are summarized for 13-Pa and 30-Pa simulants in Figures 5.20 and 5.21, respectively.

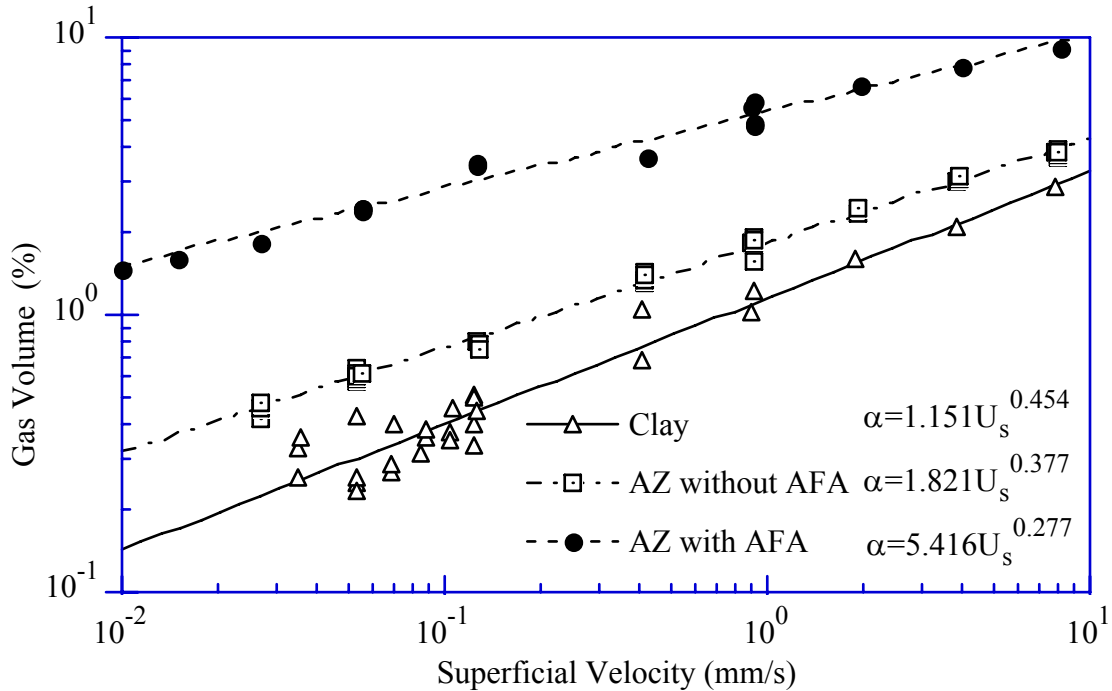


Figure 5.20. Gas Volume Fraction Versus Superficial Velocity, 13-Pa Simulants

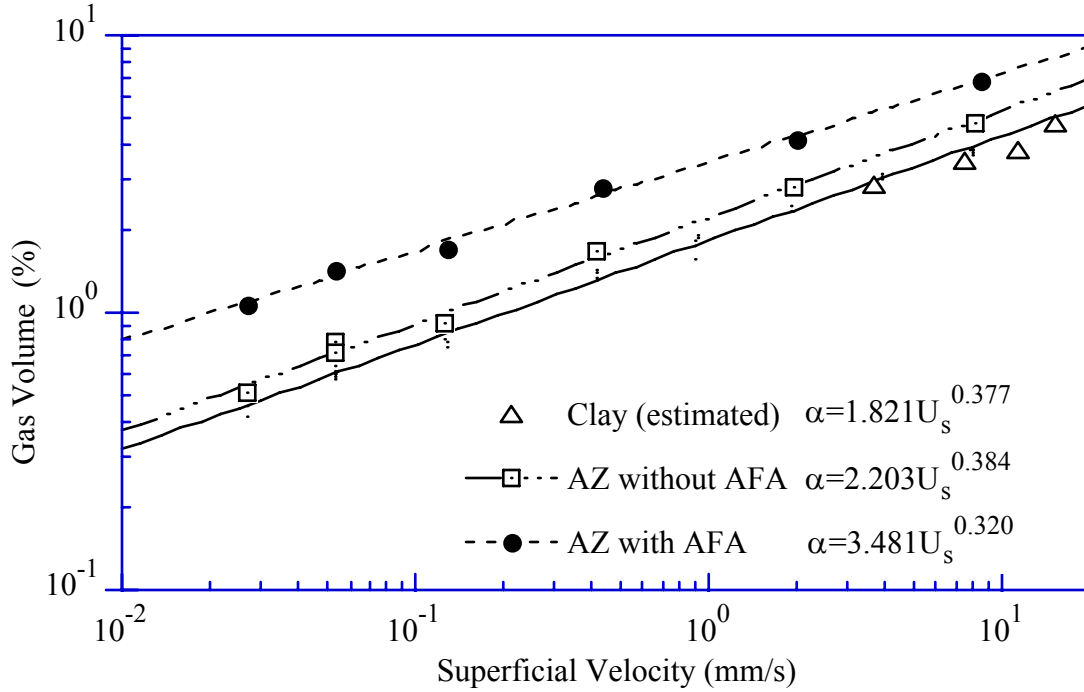


Figure 5.21. Gas Volume Fraction Versus Superficial Velocity, 30-Pa Simulants

5.5.1 Clay-to-AZ Simulant Factor

Data from the SRNL tests provides data for a direct comparison only between clay at 10- to 13-Pa yield stress and AZ simulant at 11- to 13-Pa yield stress. Referring to Figure 5.20, the power curve fits for AZ simulant and clay can be used to form F_S as a function of the superficial velocity as follows:

$$F_S(13 \text{ Pa}) = \frac{\alpha_{AZ}}{\alpha_{Clay}|_{13 \text{ Pa}}} = \frac{1.821 U_s^{0.377}}{1.151 U_s^{0.454}} = 1.582 U_s^{-0.077} \quad (5.14)$$

The resulting value of F_S for slurry in the range of 10- to 13-Pa yield stress decreases with increasing superficial velocity from 2.0 to 1.3 over the range of data.

The data do not permit a direct evaluation of F_S for 30-Pa slurry, but an estimate can be made using data for 30-Pa AZ simulant and 22-Pa clay. Referring to Figure 5.11, the 22-Pa clay data appears to follow the trend of 10- to 13-Pa AZ simulant very well, falling slightly below the trend of 30-Pa AZ simulant, which follows essentially the same slope. Therefore, assuming that the gas volume fraction in clay does not vary with yield stress consistent with Figure 5.6, such that 22-Pa clay is an adequate representative for 30-Pa clay, an approximate power function for 30-Pa clay (shown in Figure 5.21) would be that of 10-13-Pa AZ simulant, or

$$\alpha_{C30} \approx \alpha_{AZ13} = 1.821 U_s^{0.377} \quad (5.15)$$

With Eq. (5.15), the simulant factor for 30-Pa clay can be derived as follows:

$$F_S(30 \text{ Pa}) = \frac{\alpha_{AZ}}{\alpha_{Clay}} \bigg|_{30 \text{ Pa}} = \frac{2.203U_s^{0.384}}{1.821U_s^{0.377}} = 1.210U_s^{0.007} \quad (5.16)$$

Given the small exponent in Eq. (5.16), we shall consider F_S a constant 1.21 for 30-Pa simulants.

5.5.2 AFA Factor

SRNL data are available to define F_{AFA} as a function of superficial velocity for 13- and 30-Pa AZ simulant. Referring to the power curve fits in Figure 5.20 and following Eq. (5.14), we have

$$F_{AFA}(13 \text{ Pa}) = \frac{\alpha_{AZ+AFA}}{\alpha_{AZ}} \bigg|_{13 \text{ Pa}} = \frac{5.416U_s^{0.277}}{1.831U_s^{0.383}} = 2.958U_s^{-0.106} \quad (5.17)$$

$$F_{AFA}(30 \text{ Pa}) = \frac{\alpha_{AZ+AFA}}{\alpha_{AZ}} \bigg|_{30 \text{ Pa}} = \frac{3.481U_s^{0.320}}{2.203U_s^{0.384}} = 1.580U_s^{-0.064} \quad (5.18)$$

Each of these factors also decreases with increasing superficial velocity, $F_{AFA}(13 \text{ Pa})$ from 4.2 to 2.3 and $F_{AFA}(30 \text{ Pa})$ from 2.0 to 1.4 over the range of data. Comparing Eq. (5.17) and (5.18), it is clear that the effect of AFA is stronger at lower yield stress, as was also shown in Figure 5.10.

5.5.3 Overall Clay-to-Waste Factor

The overall F_W is the product of F_S and F_{AFA} for similar yield stress simulants. It is also equal to the ratio of gas volume fractions in AZ simulant with AFA to those in clay at the same yield stress. For 10- to 13-Pa slurry, we can combine Eq. (5.14) and (5.17) to yield the following function for $F_W(13 \text{ Pa})$ as a function of superficial velocity:

$$F_W(13 \text{ Pa}) = \frac{\alpha_{AZ+AFA}}{\alpha_{Clay}} \bigg|_{13 \text{ Pa}} = \frac{5.416U_s^{0.277}}{1.151U_s^{0.454}} = 4.706U_s^{-0.177} \quad (5.19)$$

Likewise, Eq. (5.16) and (5.18) can be combined to express $F_W(30 \text{ Pa})$ as

$$F_W(30 \text{ Pa}) = \frac{\alpha_{AZ+AFA}}{\alpha_{Clay}} \bigg|_{30 \text{ Pa}} = \frac{3.481U_s^{0.320}}{1.821U_s^{0.377}} = 1.912U_s^{-0.057} \quad (5.20)$$

These functions and ratios of individual data points, where available, are plotted in Figure 5.22 for 13-Pa simulants and in Figure 5.23 for 30-Pa simulants. The overall F_W factor for 10- to 13-Pa slurry

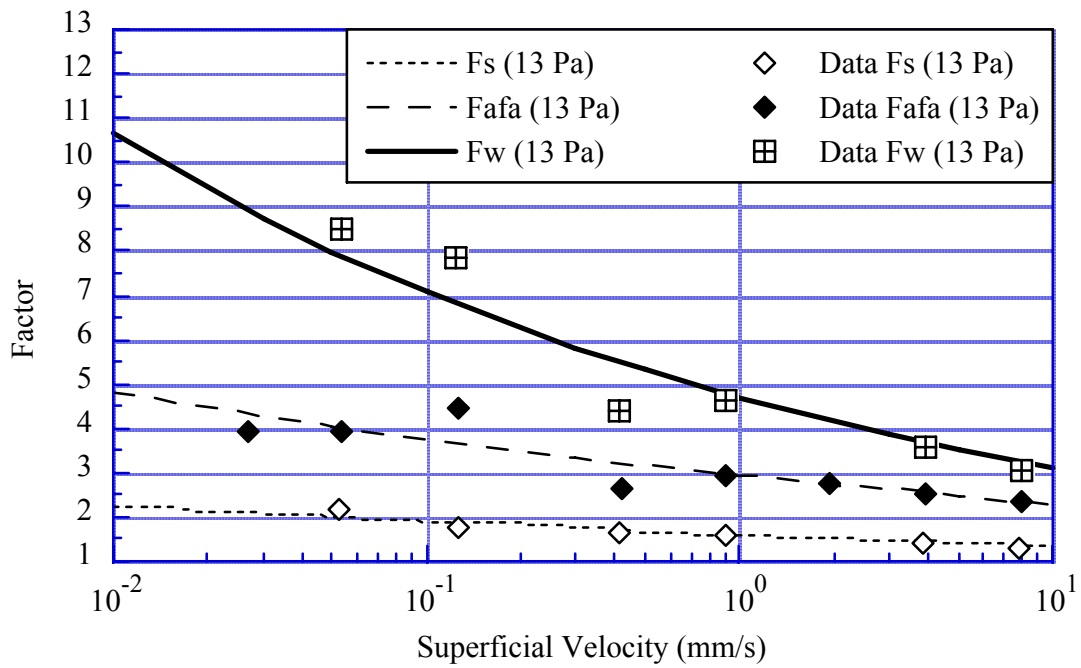


Figure 5.22. Estimated F_s , F_{AFA} , and F_w Versus Superficial Velocity, 13-Pa Simulants

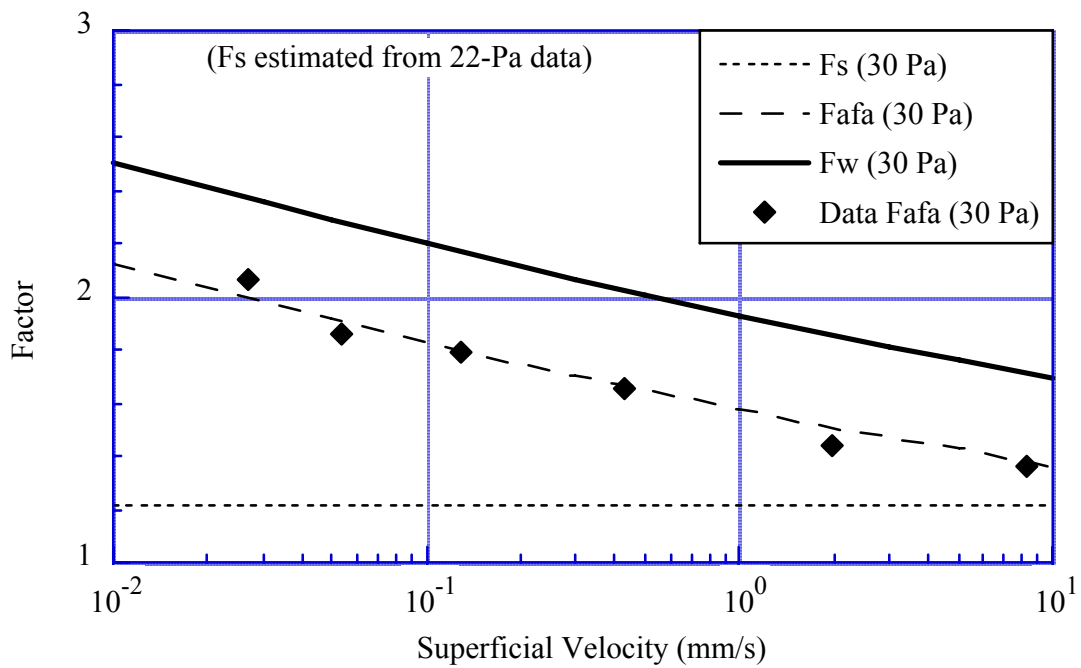


Figure 5.23. Estimated F_s , F_{AFA} , and F_w Versus Superficial Velocity, 30-Pa Simulants

varies with increasing superficial velocity from 8.0 to 3.2 over the range of data, while F_w (30 Pa) assumes values of 2.4 down to 1.7 over the same range. At a superficial velocity of 0.01 mm/s, F_w (13 Pa) reaches 10.6 and F_w (30 Pa) rises to 2.5.

The prediction interval at 95% confidence (via Eq. 4.50 through 4.52) for both F_w (13 Pa) and F_w (30 Pa) are shown in Figure 5.24. The prediction interval for 30 Pa simulant is only estimated because there are no data for 30-Pa clay simulant on which to base an $\alpha = AU_s^B$ curve fit. At a superficial velocity of 0.01 mm/s, F_w (13 Pa) ranges from 7.4 to 15.3, while F_w (30 Pa) runs from 2.1 to 3.1.

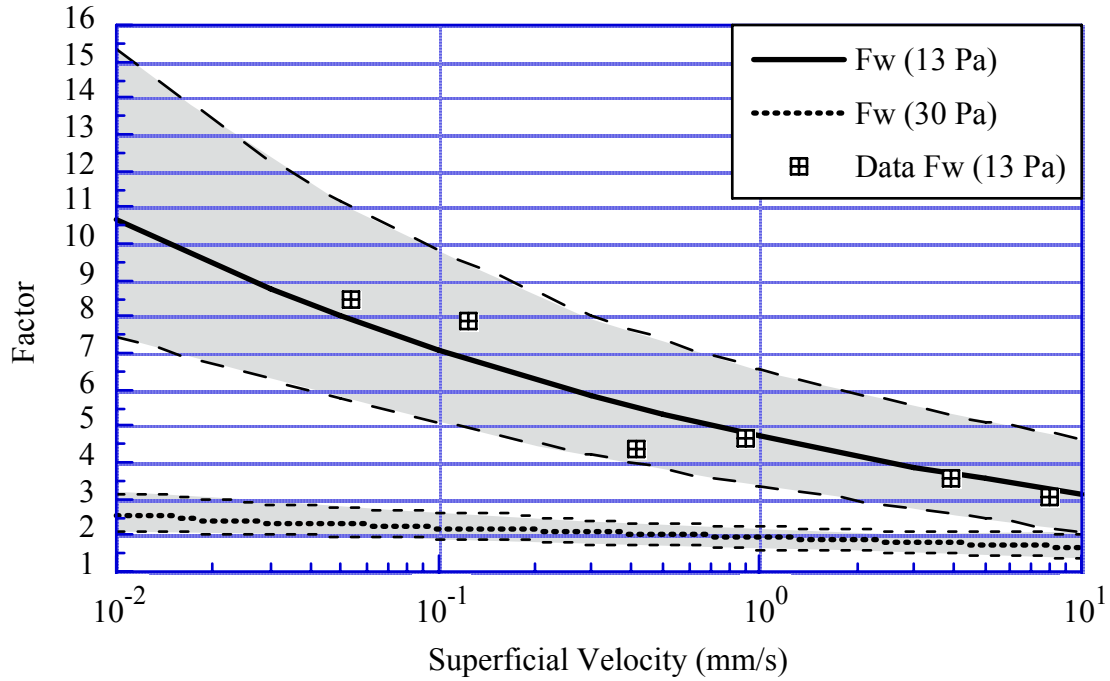


Figure 5.24. Prediction Interval for F_w Versus Superficial Velocity, 13- and 30-Pa Simulants

6.0 Conclusions and Recommendations

6.1 Trends in SRNL Data

Data were analyzed from tests in the SRNL mixing vessel using water, water with salt and AFA added, clay simulant, and AZ simulant with and without AFA. The gas volume fractions derived from the test data all followed a power law, $\alpha = AU_s^B$, increasing with superficial velocity, U_s . Both the coefficient A and exponent B varied with simulant type, yield stress, and agitator rpm, though the variation in B was much less. In addition:

- Gas volume fractions increased approximately in proportion to agitator rpm.
- Gas volume fractions did not appear to vary significantly with simulant yield stress in absence of AFA. Changes with yield stress were masked by the effect of agitator rpm since higher rpm was necessary to mix stiffer simulants.
- Gas volume fractions were higher in AZ simulant than in clay and much higher in AZ simulant with AFA than without.
 - o The effect of AFA in raising the gas volume fraction increased markedly with decreasing yield stress, dominating the counter-effect of decreasing agitator rpm required to mixing thinner slurry. This result indicates that 30-Pa is not the bounding yield stress for gas retention.
 - o The trend of increasing gas volume fraction with decreasing yield stress in simulants with AFA is weaker at lower superficial velocity.

6.2 Bubble Rise Velocity Reduction Factors

Values for the simulant factor, F_S , the AFA factor, F_{AFA} , and the combined waste factor, F_W (which is the product of F_S and F_{AFA}), were derived directly from SRNL mixing vessel data for simulants with 10 to 13 Pa. The factors could also be estimated for simulants with 30-Pa yield stress. These factors all increase exponentially with decreasing superficial velocity (Figures 5.22 and 5.23).

For 10- to 13-Pa simulants, the factors are defined directly from the data as follows:

$$F_S(13 \text{ Pa}) = 1.582U_s^{-0.077}$$

$$F_{AFA}(13 \text{ Pa}) = 2.958U_s^{-0.106}$$

$$F_W(13 \text{ Pa}) = 4.706U_s^{-0.177}$$

For 30-Pa simulants, the factors are estimated as follows:

$$F_S(30 \text{ Pa}) = 1.21$$

$$F_{AFA}(30 \text{ Pa}) = 1.580U_s^{-0.064}$$

$$F_W(30 \text{ Pa}) = 1.927U_s^{-0.064}$$

At a superficial velocity of 0.01 mm/s, F_W (13 Pa) is ~10.7 and F_W (30 Pa) is ~2.5.

6.3 Improved Gas Release Model

The power law relationship between the bubble rise velocity and gas volume fraction indicated by the SRNL data inspired a revised gas release model that substitutes this power relationship for the original constant-bubble rise velocity assumption. The model fits essentially all the SRNL release data, data from ~1/4-scale PJM hybrid systems, and data from sparge-induced release tests in the PNNL cone-bottom tank equally well with consistent parameter values (Section 5.4). This model implicitly bases gas release parameters on the corresponding steady state values. Thus, by definition, gas release behavior is affected by AFA, simulant rheology, and other factors in the same way as steady-state holdup.

6.4 Recommendations

These recommendations are based on the findings of the analyses conducted for this report in the context of the overall WTP PJM mixing program.

- The strength of the AFA effect on gas retention confirmed in the SRNL tests and the unexpected effect of AFA in increasing the holdup with decreasing yield stress have broad implications in plant operation, especially concerning sparger operation. It is likely that the AFA would reduce the size of sparged bubbles or increase their tendency to break up, thereby increasing sparger holdup by a potentially large factor. The net effect of this change on mixing effectiveness and gas release is unclear. A series of tests with AZ simulant with and without AFA in a vessel of sufficient size to allow study of large sparge bubbles would reveal any potential problems.
- Because these tests confirmed that AFA greatly increases gas retention and slows gas release, it is important to estimate the consequences of these effects on full-scale plant operations. Because the SRNL vessel mixing system was very different from plant PJM/hybrid systems, the SRNL data do not provide the necessary technical basis for these predictions. A similar series of tests in a larger-scale prototype PJM/hybrid-mixed vessel using clay, AZ simulant (or similar chemical simulant) and AZ simulant with AFA over a range of yield stress and gas generation rates is recommended to provide this basis. The sparger holdup tests recommended above, as well as sparger mass-transfer tests, could also be performed in this vessel under the same test program.
- The results of these recommended prototype PJM/hybrid tests, along with the SRNL data, will provide a much better and more detailed definition of the F_W factor and the variation of bubble rise velocity with yield stress than is now used in the gas retention and release scale-up model given by Bontha et al. (2005). The new gas release model described in Section 5.4 is consistent with the data and provides a better description of gas release. The current scale-up model should be updated to incorporate these new data and improved models.

7.0 References

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Appendix

Listing of Test Conditions and Analysis Results

Appendix – Listing of Test Conditions and Analysis Results

This appendix lists all the data transmitted to PNWD from SRNL. However, not all of these data were analyzed. The data status column (6th column from the right in Table A.1) describes how each data item was treated, as follows:

- reviewed data file was reduced, reviewed and used in the analysis.
- not used data was not needed for the analysis and the data file was not reduced or reviewed by PNWD.
- missing test missing from a data file containing other tests sent to PNWD by SRNL.
- unusable data file was reduced but not reviewed or used in the analysis because of high uncertainty in the recorded levels, difficulty in establishing a reference level, or similar problem.
- anomalous data file was reduced by not reviewed or used in the analysis because the level trends were anomalous (e.g., decreasing level with increasing superficial velocity)

The results of data reduction calculations for reviewed files are entered in the last five columns on the right as follows:

- Alpha gas volume fraction determined from the level difference (vol%)
- Sigma alpha standard deviation of the gas volume fraction (vol%)
- Ustar superficial gas velocity determined from air injection flow rate or hydrogen peroxide injection rate (mm/s)
- Urise bubble rise velocity calculated from the gas volume fraction and superficial velocity (mm/s)
- Sigma Urise standard deviation of the bubble rise velocity (mm/s).

Table A.1. Listing of Test Conditions and Analysis Results

Test #	Date & Start Time	Data file	Simulant	Initial yield strength (Pa)	Initial consistency (cP)	Final yield strength (Pa)	Final consistency (cP)	Agitator RPM	MNO ₂ content (ppm)	H ₂ O ₂ injection rate (mL/min)	H ₂ O ₂ solution density (g/mL)	AFA present? (350 mg/L)	Air flow rate (acfm)	Salt content	Data status	Alpha (vol%)	Sigma alpha (vol%)	Ustar (mm/s)	Urise (mm/s)	Sigma Urise (mm/s)
51	3/28/06 14:32	GH1435280306	H ₂ O	NA	NA	NA	NA	400	NA	NA	NA	No	1.085	No	reviewed	2.21	0.29	3.642	164.8	21.8
52	3/28/06 14:42	GH1435280306	H ₂ O	NA	NA	NA	NA	400	NA	NA	NA	No	2.217	No	reviewed	2.95	0.29	7.437	252.5	25.0
53	3/28/06 14:52	GH1435280306	H ₂ O	NA	NA	NA	NA	400	NA	NA	NA	No	3.349	No	reviewed	3.52	0.32	11.232	319.5	28.7
54	3/28/06 14:59	GH1435280306	H ₂ O	NA	NA	NA	NA	400	NA	NA	NA	No	4.478	No	reviewed	3.70	0.32	15.018	406.3	35.3
55	3/28/06 15:06	GH1435280306	H ₂ O	NA	NA	NA	NA	550	NA	NA	NA	No	1.085	No	reviewed	2.20	0.43	3.638	165.1	32.3
56	3/28/06 15:13	GH1435280306	H ₂ O	NA	NA	NA	NA	550	NA	NA	NA	No	2.216	No	reviewed	3.24	0.39	7.430	229.3	27.3
57	3/28/06 15:20	GH1435280306	H ₂ O	NA	NA	NA	NA	550	NA	NA	NA	No	3.347	No	reviewed	3.89	0.40	11.220	288.7	30.0
58	3/28/06 15:27	GH1435280306	H ₂ O	NA	NA	NA	NA	550	NA	NA	NA	No	4.478	No	reviewed	4.27	0.46	15.008	351.6	38.3
59	3/28/06 15:34	GH1435280306	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	No	1.085	No	reviewed	2.13	0.67	3.636	171.1	54.2
60	3/28/06 15:41	GH1435280306	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	No	2.216	No	reviewed	2.94	0.62	7.426	252.3	53.3
61	3/28/06 15:48	GH1435280306	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	No	3.350	No	reviewed	4.29	0.49	11.223	261.8	30.2
62	3/28/06 15:55	GH1435280306	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	No	4.482	No	reviewed	4.67	0.55	15.013	321.8	37.7
63	3/28/06 16:29	GH1625280306	H ₂ O	NA	NA	NA	NA	400	NA	NA	NA	Yes	1.086	No	reviewed	3.49	0.26	3.638	104.2	7.7
74	3/28/06 16:38	GH1625280306	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	Yes	4.481	No	reviewed	9.74	0.35	15.008	154.1	5.5
64	3/28/06 17:03	GH1702280306	H ₂ O	NA	NA	NA	NA	400	NA	NA	NA	Yes	2.219	No	reviewed	5.19	0.30	7.437	143.2	8.3
65	3/28/06 17:10	GH1702280306	H ₂ O	NA	NA	NA	NA	400	NA	NA	NA	Yes	3.353	No	reviewed	6.24	0.27	11.239	180.1	7.9
66	3/28/06 17:17	GH1702280306	H ₂ O	NA	NA	NA	NA	400	NA	NA	NA	Yes	4.484	No	reviewed	6.69	0.26	15.039	224.8	8.7
71	3/28/06 17:24	GH1702280306	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	Yes	1.086	No	reviewed	4.50	0.46	3.645	81.0	8.2
72	3/28/06 17:31	GH1702280306	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	Yes	2.220	No	reviewed	7.53	0.58	7.454	98.9	7.6
73	3/28/06 17:38	GH1702280306	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	Yes	3.354	No	reviewed	9.44	0.40	11.268	119.4	5.0
79	3/29/06 9:58	GH1000290306	Clay	27	31	22	30	700	NA	NA	NA	No	1.090	No	reviewed	2.91	0.26	3.678	126.2	11.1
80	3/29/06 10:07	GH1000290306	Clay	22	30	22	30	700	NA	NA	NA	No	2.231	No	reviewed	3.52	0.60	7.533	213.8	36.6
81	3/29/06 10:18	GH1000290306	Clay	22	30	22	30	700	NA	NA	NA	No	3.370	No	reviewed	3.89	0.99	11.380	292.4	74.4
82	3/29/06 10:29	GH1000290306	Clay	22	30	22	30	700	NA	NA	NA	No	4.510	No	reviewed	4.81	0.94	15.235	317.0	62.1
75	3/29/06 10:42	GH1000290306	Clay	22	30	22	30	400	NA	NA	NA	No	1.093	No	reviewed	1.46	0.16	3.690	252.3	28.4
76	3/29/06 10:53	GH1000290306	Clay	22	30	22	30	400	NA	NA	NA	No	2.231	No	reviewed	1.70	0.20	7.534	444.1	51.8
77	3/29/06 11:04	GH1000290306	Clay	22	30	22	30	400	NA	NA	NA	No	3.367	No	reviewed	2.48	0.32	11.370	458.2	59.7
78	3/29/06 11:15	GH1000290306	Clay	22	30	22	30	400	NA	NA	NA	No	4.502	No	reviewed	2.54	0.58	15.198	598.2	136.4
90	3/29/06 13:30	GH1330290306	Clay	22	30	22	30	700	NA	NA	NA	Yes	4.597	No	missing	NA	NA	NA	NA	NA
87	3/29/06 14:05	GH1330290306	Clay	22	30	22	30	700	NA	NA	NA	Yes	1.101	No	not used	NA	NA	NA	NA	NA
88	3/29/06 14:14	GH1330290306	Clay	22	30	22	30	700	NA	NA	NA	Yes	2.251	No	not used	NA	NA	NA	NA	NA
89	3/23/06 12:00	GH1330290306	Clay	22	30	22	30	700	NA	NA	NA	Yes	3.401	No	not used	NA	NA	NA	NA	NA
83	3/23/06 14:48	GH1330290306	Clay	22	30	22	30	400	NA	NA	NA	Yes	1.103	No	not used	NA	NA	NA	NA	NA
84	3/24/06 14:03	GH1330290306	Clay	22	30	22	30	400	NA	NA	NA	Yes	2.252	No	not used	NA	NA	NA	NA	NA
85	3/24/06 16:20	GH1330290306	Clay	22	30	22	30	400	NA	NA	NA	Yes	3.399	No	not used	NA	NA	NA	NA	NA
86	3/28/06 14:32	GH1330290306	Clay	22	30	16	29	400	NA	NA	NA	Yes	4.544	No	not used	NA	NA	NA	NA	NA
83	4/3/06 9:21	GH0900030406	Clay	15	27	14	27	400	NA	NA	NA	Yes	1.103	No	not used	NA	NA	NA	NA	NA
86a	4/3/06 9:31	GH0900030406	Clay	14	27	14	27	400	NA	NA	NA	Yes	4.557	No	not used	NA	NA	NA	NA	NA
86b	4/3/06 9:31	GH0900030406	Clay	14	27	14	27	400	NA	NA	NA	Yes	4.557	No	not used	NA	NA	NA	NA	NA
86c	4/3/06 9:31	GH0900030406	Clay	14	27	14	27	400	NA	NA	NA	Yes	4.557	No	not used	NA	NA	NA	NA	NA
87	4/3/06 10:05	GH0900030406	Clay	14	27	14	27	700	NA	NA	NA	Yes	1.104	No	not used	NA	NA	NA	NA	NA
90	4/3/06 10:14	GH0900030406	Clay	14	27	13	26	700	NA	NA	NA	Yes	4.560	No	not used	NA	NA	NA	NA	NA

Table A.1 (contd)

Test #	Date & Start Time	Data file	Simulant	Initial yield strength (Pa)	Initial consistency (cP)	Final yield strength (Pa)	Final consistency (cP)	Agitator RPM	MNO ₂ content (ppm)	H ₂ O ₂ injection rate (ml/min)	H ₂ O ₂ solution density (g/mL)	AFA present? (350 mg/L)	Air flow rate (acfm)	Salt content	Data status	Alpha (vol%)	Sigma alpha (vol%)	Ustar (mm/s)	Urise (mm/s)	Sigma Urise (mm/s)
95	4/5/06 13:01	GH1305050406	Carbopol	35	59	35	59	825	NA	NA	NA	Yes	1.124	No	not used	NA	NA	NA	NA	NA
97	4/5/06 13:26	GH1305050406	Carbopol	35	59	35	59	825	NA	NA	NA	Yes	4.654	No	not used	NA	NA	NA	NA	NA
96	4/5/06 13:02	GH1305050406	Carbopol	35	59	35	59	825	NA	NA	NA	Yes	1.125	No	not used	NA	NA	NA	NA	NA
98	4/5/06 14:18	GH1305050406	Carbopol	35	59	33	58	825	NA	NA	NA	Yes	4.680	No	not used	NA	NA	NA	NA	NA
103	4/7/06 10:04	GH0958070406	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	No	1.105	=AZ101	reviewed	3.94	0.95	3.709	94.0	22.7
104	4/7/06 10:16	GH0958070406	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	No	2.257	=AZ101	reviewed	5.37	0.91	7.577	141.1	24.0
105	4/7/06 10:25	GH0958070406	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	No	3.408	=AZ101	reviewed	5.68	0.94	11.443	201.3	33.1
106	4/7/06 10:32	GH0958070406	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	No	4.559	=AZ101	reviewed	6.46	0.74	15.312	237.1	27.2
107a	4/7/06 12:21	GH1216040706	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	Yes	2.258	=AZ101	unusable	NA	NA	NA	NA	NA
108a	4/7/06 12:32	GH1216040706	H ₂ O	NA	NA	NA	NA	700	NA	NA	NA	Yes	3.413	=AZ101	unusable	NA	NA	NA	NA	NA
115	4/11/06 9:26	GH0925110406	H ₂ O	NA	NA	NA	NA	550	NA	NA	NA	Yes	1.080	=AZ101	reviewed	6.27	0.66	3.615	57.6	6.1
116	4/11/06 9:35	GH0925110406	H ₂ O	NA	NA	NA	NA	550	NA	NA	NA	Yes	2.215	=AZ101	reviewed	8.47	0.52	7.417	87.6	5.4
117	4/11/06 9:44	GH0925110406	H ₂ O	NA	NA	NA	NA	550	NA	NA	NA	Yes	3.347	=AZ101	reviewed	9.87	0.52	11.212	113.6	6.0
118	4/11/06 9:54	GH0925110406	H ₂ O	NA	NA	NA	NA	550	NA	NA	NA	Yes	4.477	=AZ101	reviewed	11.10	0.56	15.007	135.2	6.9
119	4/11/06 10:06	GH0925110406	H ₂ O	NA	NA	NA	NA	900	NA	NA	NA	Yes	1.086	=AZ101	reviewed	7.12	1.98	3.642	51.2	14.2
120	4/11/06 10:15	GH0925110406	H ₂ O	NA	NA	NA	NA	900	NA	NA	NA	Yes	2.222	=AZ101	reviewed	8.70	2.07	7.454	85.6	20.4
121	4/11/06 10:24	GH0925110406	H ₂ O	NA	NA	NA	NA	900	NA	NA	NA	Yes	3.360	=AZ101	reviewed	10.77	1.72	11.279	104.7	16.7
122	4/11/06 10:40	GH0925110406	H ₂ O	NA	NA	NA	NA	900	NA	NA	NA	Yes	4.508	=AZ101	reviewed	11.30	1.64	15.143	134.1	19.4
143	4/22/2010 9:54	GH0950210406	Clay	36	50	28	49	700	NA	NA	NA	No	0.237	No	anomalous	NA	NA	NA	NA	NA
144	4/22/2010 9:59	GH0950210406	Clay	28	49	28	49	700	NA	NA	NA	No	0.521	No	anomalous	NA	NA	NA	NA	NA
145	4/22/2010 10:05	GH0950210406	Clay	28	49	28	49	700	NA	NA	NA	No	0.805	No	anomalous	NA	NA	NA	NA	NA
146	4/22/2010 10:10	GH0950210406	Clay	28	49	28	49	700	NA	NA	NA	No	1.088	No	anomalous	NA	NA	NA	NA	NA
147	4/22/2010 10:15	GH0950210406	Clay	28	49	28	49	700	NA	NA	NA	No	2.222	No	anomalous	NA	NA	NA	NA	NA
148	4/22/2010 10:20	GH0950210406	Clay	28	49	28	49	700	NA	NA	NA	No	3.356	No	anomalous	NA	NA	NA	NA	NA
149	4/22/2010 10:25	GH0950210406	Clay	28	49	28	49	700	NA	NA	NA	No	4.521	No	anomalous	NA	NA	NA	NA	NA
150	4/22/2010 12:30	GH1235210406	Clay	28	49	28	49	400	NA	NA	NA	No	0.239	No	unusable	NA	NA	NA	NA	NA
151	4/22/2010 12:38	GH1235210406	Clay	28	49	28	49	400	NA	NA	NA	No	0.523	No	unusable	NA	NA	NA	NA	NA
152	4/22/2010 12:42	GH1235210406	Clay	28	49	28	49	400	NA	NA	NA	No	0.808	No	unusable	NA	NA	NA	NA	NA
153	4/22/2010 12:48	GH1235210406	Clay	28	49	28	49	400	NA	NA	NA	No	1.093	No	unusable	NA	NA	NA	NA	NA
154	4/22/2010 12:53	GH1235210406	Clay	28	49	28	49	400	NA	NA	NA	No	2.232	No	unusable	NA	NA	NA	NA	NA
155	4/22/2010 12:58	GH1235210406	Clay	28	49	28	49	400	NA	NA	NA	No	3.372	No	unusable	NA	NA	NA	NA	NA
156	4/22/2010 13:03	GH1235210406	Clay	28	49	29	48	400	NA	NA	NA	No	4.515	No	unusable	NA	NA	NA	NA	NA
157a	4/24/06 12:27	GH1220240406	Clay	26	47	26	45	700	NA	NA	NA	Yes	2.231	No	not used	NA	NA	NA	NA	NA
158a	4/24/06 12:42	GH1220240406	Clay	26	47	26	47	700	NA	NA	NA	Yes	0.238	No	not used	NA	NA	NA	NA	NA
159a	4/24/06 12:59	GH1220240406	Clay	26	47	26	47	700	NA	NA	NA	Yes	3.371	No	not used	NA	NA	NA	NA	NA
160a	4/24/06 13:14	GH1220240406	Clay	26	48	26	47	700	NA	NA	NA	Yes	0.523	No	not used	NA	NA	NA	NA	NA

Table A.1 (contd)

Test #	Date & Start Time	Data file	Simulant	Initial yield strength (Pa)	Initial consistency (cP)	Final yield strength (Pa)	Final consistency (cP)	Agitator RPM	MNO ₂ content (ppm)	H ₂ O ₂ injection rate (mL/min)	H ₂ O ₂ solution density (g/mL)	AFA present? (350 mg/L)	Air flow rate (acfm)	Salt content (ppm)	Data status	Alpha (vol%)	Sigma alpha (vol%)	Ustar (mm/s)	Urise (mm/s)	Sigma Urise (mm/s)
161a	4/24/06 12:26	GH1220240406	Clay	26	47	26	47	700	NA	NA	NA	Yes	4.512	No	not used	NA	NA	NA	NA	NA
162a	4/24/06 12:36	GH1220240406	Clay	26	47	26	47	700	NA	NA	NA	Yes	0.808	No	not used	NA	NA	NA	NA	NA
163a	4/24/06 12:48	GH1220240406	Clay	26	47	26	47	700	NA	NA	NA	Yes	1.103	No	not used	NA	NA	NA	NA	NA
164	4/25/06 9:27	GH0850250406	Clay	21	44	21	45	400	NA	NA	NA	Yes	0.241	No	not used	NA	NA	NA	NA	NA
165	4/25/06 9:44	GH0850250406	Clay	21	45	21	45	400	NA	NA	NA	Yes	0.528	No	not used	NA	NA	NA	NA	NA
166	4/25/06 9:56	GH0850250406	Clay	21	45	21	45	400	NA	NA	NA	Yes	0.815	No	not used	NA	NA	NA	NA	NA
167	4/25/06 10:12	GH0850250406	Clay	21	45	21	45	400	NA	NA	NA	Yes	1.102	No	not used	NA	NA	NA	NA	NA
168	4/25/06 10:24	GH0850250406	Clay	21	45	21	45	400	NA	NA	NA	Yes	2.250	No	not used	NA	NA	NA	NA	NA
169	4/27/06 9:47	GH0850250406	Clay	21	45	21	45	400	NA	NA	NA	Yes	3.398	No	not used	NA	NA	NA	NA	NA
170	4/27/06 10:02	GH0850250406	Clay	21	45	21	45	400	NA	NA	NA	Yes	4.547	No	not used	NA	NA	NA	NA	NA
171	4/27/06 10:19	GH0930270406	Clay	22	10	22	10	700	NA	NA	NA	No	0.2452	200	not used	NA	NA	NA	NA	NA
172	4/27/06 10:32	GH0930270406	Clay	22	10	22	10	700	NA	NA	NA	No	0.5389	200	not used	NA	NA	NA	NA	NA
173	4/27/06 10:48	GH0930270406	Clay	22	10	22	10	700	NA	NA	NA	No	0.8338	200	not used	NA	NA	NA	NA	NA
173a	4/27/06 11:01	GH0930270406	Clay	22	10	22	10	700	NA	NA	NA	No	0.8338	200	not used	NA	NA	NA	NA	NA
174	4/27/06 11:14	GH0930270406	Clay	22	10	22	10	700	NA	NA	NA	No	1.1304	200	not used	NA	NA	NA	NA	NA
175	4/27/06 11:27	GH0930270406	Clay	22	10	22	10	700	NA	NA	NA	No	2.3106	200	not used	NA	NA	NA	NA	NA
176	4/27/06 13:10	GH0930270406	Clay	22	10	22	10	700	NA	NA	NA	No	3.4915	200	not used	NA	NA	NA	NA	NA
177	4/27/06 13:22	GH0930270406	Clay	22	10	22	10	700	NA	NA	NA	No	4.6720	200	not used	NA	NA	NA	NA	NA
187	4/27/06 13:37	GH1305270406	Clay	21	10	23	11	700	NA	NA	NA	Yes	0.5424	200	not used	NA	NA	NA	NA	NA
189a	4/27/06 13:55	GH1305270406	Clay	23	11	23	11	700	NA	NA	NA	Yes	1.1317	200	not used	NA	NA	NA	NA	NA
190	4/27/06 16:54	GH1305270406	Clay	23	11	23	11	700	NA	NA	NA	Yes	2.3156	200	not used	NA	NA	NA	NA	NA
189b	4/27/06 17:04	GH1305270406	Clay	23	11	24	12	900	NA	NA	NA	Yes	1.1375	200	not used	NA	NA	NA	NA	NA
202	4/27/06 17:14	GH1645270406	Clay	11	16	11	16	525	NA	NA	NA	No	0.037	No	reviewed	0.45	0.37	0.126	28.1	23.3
203	4/27/06 17:44	GH1645270406	Clay	11	16	11	16	525	NA	NA	NA	No	0.122	No	reviewed	1.05	0.37	0.412	39.3	14.0
204	4/27/06 18:22	GH1645270406	Clay	11	16	11	16	525	NA	NA	NA	No	0.267	No	reviewed	1.23	0.37	0.904	73.2	22.1
207	5/4/06 10:55	GH1645270406	Clay	10	16	10	16	525	100	8.7	1.1166	No	NA	No	reviewed	0.67	0.41	0.117	17.5	11.0
208	5/4/06 12:44	GH1645270406	Clay	10	16	9	16	525	100	17	1.1166	No	NA	No	reviewed	1.05	0.41	0.235	22.3	9.1
209	5/9/06 12:55	GH1050040506	Clay	16	18	16	18	525	100	8	1.1166	No	NA	No	reviewed	0.55	0.22	0.114	20.7	9.0
210	5/9/06 13:13	GH1235040506	Clay	16	18	16	18	525	100	4	1.1166	No	NA	No	reviewed	0.37	0.29	0.061	16.7	14.5
211	5/9/06 13:41	GH1245090506	Clay	13	15	13	15	525	NA	NA	NA	No	0.0364	No	reviewed	0.52	0.62	0.123	23.6	27.9
212	5/9/06 13:56	GH1245090506	Clay	13	15	13	15	525	NA	NA	NA	No	0.0309	No	reviewed	0.38	0.62	0.104	27.4	44.4
213	5/9/06 14:11	GH1245090506	Clay	13	15	13	15	525	NA	NA	NA	No	0.0252	No	reviewed	0.32	0.60	0.085	27.0	51.7
214	5/9/06 14:28	GH1245090506	Clay	13	15	13	15	525	NA	NA	NA	No	0.0201	No	reviewed	0.27	0.59	0.068	25.1	55.1
215	5/9/06 15:06	GH1245090506	Clay	13	15	13	15	525	NA	NA	NA	No	0.0156	No	reviewed	0.26	0.58	0.053	20.0	43.8
216	5/9/06 15:24	GH1245090506	Clay	13	15	13	15	525	NA	NA	NA	No	0.0104	No	reviewed	0.33	0.62	0.035	10.7	20.2
211	5/9/06 15:42	GH1500090506	Clay	13	15	13	15	525	NA	NA	NA	No	0.0364	No	reviewed	0.50	0.36	0.123	24.8	18.2
212	5/9/06 15:59	GH1515090506	Clay	13	15	13	15	525	NA	NA	NA	No	0.0310	No	reviewed	0.46	0.34	0.105	22.9	16.9
213	5/9/06 16:16	GH1515090506	Clay	13	15	13	15	525	NA	NA	NA	No	0.0257	No	reviewed	0.39	0.34	0.087	22.2	19.2
214	5/9/06 16:33	GH1515090506	Clay	13	15	13	15	525	NA	NA	NA	No	0.0206	No	reviewed	0.40	0.33	0.070	17.5	14.5
215	5/10/06 14:12	GH1515090506	Clay	13	15	13	15	525	NA	NA	NA	No	0.0157	No	reviewed	0.43	0.38	0.053	12.4	11.0
216	5/10/06 14:29	GH1515090506	Clay	13	15	13	16	525	NA	NA	NA	No	0.0105	No	reviewed	0.36	0.38	0.036	9.8	10.3
211	5/10/06 14:47	GH1405100506	Clay	11	14	10	14	525	NA	NA	NA	No	0.0364	No	reviewed	0.34	0.40	0.123	36.6	44.0
212	5/10/06 15:04	GH1405100506	Clay	10	14	10	14	525	NA	NA	NA	No	0.0308	No	reviewed	0.35	0.40	0.104	29.5	33.6
213	5/10/06 15:21	GH1405100506	Clay	10	14	10	14	525	NA	NA	NA	No	0.0256	No	reviewed	0.36	0.38	0.087	24.1	25.6
214	5/10/06 15:39	GH1405100506	Clay	10	14	10	14	525	NA	NA	NA	No	0.0205	No	reviewed	0.29	0.40	0.069	23.7	32.6
215	5/11/06 10:06	GH1405100506	Clay	10	14	10	14	525	NA	NA	NA	No	0.0156	No	reviewed	0.23	0.40	0.053	23.5	42.0
216	4/25/06 9:27	GH1405100506	Clay	10	14	10	14	525	NA	NA	NA	No	0.0105	No	reviewed	0.26	0.39	0.035	13.8	21.2
219	4/25/06 9:44	GH0940110506	Clay	10	14	10	14	525	100	8	1.1166	No	NA	No	reviewed	0.56	0.40	0.124	22.0	18.7

Table A.1 (contd)

Test #	Date & Start Time	Data file	Simulant	Initial yield strength (Pa)	Initial consistency (cP)	Final yield strength (Pa)	Final consistency (cP)	Agitator RPM	MNO ₂ content (ppm)	H ₂ O ₂ injection rate (mL/min)	H ₂ O ₂ solution density (g/mL)	AFA present? (350 mg/L)	Air flow rate (acfm)	Salt content	Data status	Alpha (vol%)	Sigma alpha (vol%)	Ustar (mm/s)	Urise (mm/s)	Sigma Urise (mm/s)
220	5/11/06 12:03	GH1155110506	Clay	10	14	10	15	525	100	4	1.1166	No	NA	No	reviewed	0.38	0.41	0.061	16.1	18.4
275	5/15/06 9:15	GH0905150506	Clay	10	14	9	14	525	NA	NA	NA	No	0.0156	No	reviewed	0.25	0.48	0.053	21.0	40.2
276	5/15/06 9:32	GH0905150506	Clay	9	14	9	14	525	NA	NA	NA	No	0.0365	No	reviewed	0.40	0.46	0.123	30.7	34.8
277	5/15/06 9:50	GH0905150506	Clay	9	14	9	14	525	NA	NA	NA	No	0.1208	No	reviewed	0.68	0.50	0.408	60.4	44.4
278	5/15/06 10:08	GH0905150506	Clay	9	14	9	14	525	NA	NA	NA	No	0.2654	No	reviewed	1.02	0.50	0.897	87.7	43.2
279	5/15/06 10:25	GH0905150506	Clay	9	14	9	14	525	NA	NA	NA	No	0.5548	No	reviewed	1.61	0.52	1.877	116.5	37.7
280	5/15/06 10:44	GH0905150506	Clay	9	14	9	14	525	NA	NA	NA	No	1.1344	No	reviewed	2.10	0.62	3.840	182.6	54.3
281	5/15/06 11:01	GH0905150506	Clay	9	14	8	14	525	NA	NA	NA	No	2.2936	No	reviewed	2.88	0.62	7.768	269.4	57.8
273	5/15/06 12:51	GH1315150506	Clay	8	14	8	14	525	100	8	1.1166	No	NA	No	reviewed	0.56	0.65	0.114	20.4	22.9
274a	5/15/06 14:54	GH1435150506	Clay	8	14	8	14	525	100	4	1.1166	No	NA	No	reviewed	0.27	0.63	0.060	21.9	51.0
274b	5/15/06 16:48	GH1640150506	Clay	8	14	8	14	525	100	4	1.1166	No	NA	No	unusable	NA	NA	NA	NA	NA
284a	5/16/06 13:53	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.0157	NA	reviewed	0.60	0.34	0.053	8.9	5.0
339a/327	5/16/06 14:11	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.00795	NA	reviewed	0.46	0.34	0.027	5.9	4.3
285a	5/16/06 14:28	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.0370	NA	reviewed	0.81	0.37	0.126	15.5	7.1
286a	5/16/06 14:47	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.1220	NA	reviewed	1.40	0.36	0.416	29.7	7.6
287a	5/16/06 15:05	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.2682	NA	reviewed	1.89	0.36	0.915	48.4	9.3
288a	5/16/06 15:22	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.5612	NA	reviewed	2.40	0.39	1.917	80.0	13.0
289a	5/16/06 15:43	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	1.1477	NA	reviewed	3.09	0.40	3.925	127.0	16.6
290a	5/16/06 16:00	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	2.3221	NA	reviewed	3.83	0.53	7.947	207.4	28.8
284b	5/16/06 16:23	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.0159	NA	reviewed	0.61	0.35	0.055	8.9	5.1
285b	5/16/06 16:42	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.0374	NA	reviewed	0.79	0.36	0.128	16.1	7.3
284c	5/16/06 17:05	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.0160	NA	reviewed	0.61	0.35	0.055	8.9	5.1
285c	5/16/06 17:22	GH1345160506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.0375	NA	reviewed	0.75	0.33	0.129	17.2	7.6
339b/327	5/17/06 9:30	GH0925170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.00793	NA	reviewed	0.42	0.38	0.027	6.4	5.6
286b	5/17/06 9:49	GH0925170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.1220	NA	reviewed	1.30	0.36	0.414	31.8	8.7
287b	5/17/06 10:07	GH0925170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.2671	NA	reviewed	1.81	0.40	0.907	50.0	11.1
288b	5/17/06 10:24	GH0925170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.5585	NA	reviewed	2.34	0.42	1.899	81.3	14.5
289b	5/17/06 10:41	GH0925170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	1.1420	NA	reviewed	3.05	0.46	3.886	127.5	19.3
290b	5/17/06 10:58	GH0925170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	2.3109	NA	reviewed	3.87	0.57	7.870	203.6	29.9
339c/327	5/17/06 13:10	GH1300170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.00799	NA	reviewed	0.48	0.36	0.027	5.7	4.3
286cb	5/17/06 13:41	GH1300170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.1225	NA	reviewed	1.41	0.31	0.418	29.6	6.5
287c	5/17/06 13:49	GH1300170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.2690	NA	reviewed	1.88	0.35	0.918	48.8	9.2
288c	5/17/06 14:07	GH1300170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	0.5627	NA	reviewed	2.42	0.39	1.921	79.5	13.0
289c	5/17/06 14:24	GH1300170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	1.1508	NA	reviewed	3.14	0.41	3.933	125.1	16.3
290c	5/17/06 14:41	GH1300170506	AZ-101	14	10	14	10	650	NA	NA	NA	No	2.3270	NA	reviewed	3.83	0.45	7.959	207.7	24.2
339d/339	5/18/06 16:24	GH1615180506	AZ-101	14	11	14	10	650	NA	NA	NA	Yes	0.00798	NA	reviewed	1.80	0.35	0.027	1.5	0.3
295a	5/18/06 17:34	GH1725180506	AZ-101	14	11	14	10	650	NA	NA	NA	Yes	0.1229	NA	reviewed	3.73	0.35	0.423	11.3	1.1
337	5/19/06 10:13	GH1005190506	AZ-101	14	10	14	10	650	NA	NA	NA	Yes	0.0029	NA	reviewed	1.47	0.36	0.010	0.7	0.2
338	5/19/06 11:08	GH1005190506	AZ-101	14	10	14	10	650	NA	NA	NA	Yes	0.0044	NA	reviewed	1.61	0.35	0.015	0.9	0.2
343a	5/19/06 12:48	GH1245190506	AZ-101	14	10	14	10	650	NA	NA	NA	Yes	0.2684	NA	reviewed	4.89	0.36	0.915	18.7	1.4
343b	5/19/06 13:04	GH1245190506	AZ-101	14	10	14	10	650	NA	NA	NA	Yes	0.2686	NA	reviewed	4.80	0.40	0.916	19.1	1.6
340a	5/19/06 14:12	GH1405190506	AZ-101	14	10	14	10	650	NA	NA	NA	Yes	0.0159	NA	reviewed	2.44	0.33	0.055	2.2	0.3
340b	5/19/06 14:32	GH1405190506	AZ-101	14	10	14	10	650	NA	NA	NA	Yes	0.0160	NA	reviewed	2.38	0.35	0.055	2.3	0.3
340c	5/19/06 14:52	GH1405190506	AZ-101	14	10	14	10	650	NA	NA	NA	Yes	0.0160	NA	reviewed	2.42	0.35	0.055	2.3	0.3
344	5/19/06 17:01	GH1405190506	AZ-101	14	10	14	10	650	NA	NA	NA	Yes	0.5679	NA	reviewed	6.71	0.32	1.952	29.1	1.4
345	5/19/06 17:10	GH1405190506	AZ-101	14	10	14	10	650	NA	NA	NA	Yes	1.1603	NA	reviewed	7.87	0.37	3.988	50.7	2.4
346	5/19/06 17:19	GH1405190506	AZ-101	14	10	13	9	650	NA	NA	NA	Yes	2.3441	NA	reviewed	9.14	0.41	8.057	88.1	4.0
341a	5/20/06 8:51	GH0845200506	AZ-101	13	9	13	9	650	NA	NA	NA	Yes	0.0370	NA	reviewed	3.50	0.33	0.126	3.6	0.3

Table A.1 (contd)

Test #	Date & Start Time	Data file	Simulant	Initial yield strength (Pa)	Initial consistency (cP)	Final yield strength (Pa)	Final consistency (cP)	Agitator RPM	MNO ₂ content (ppm)	H ₂ O ₂ injection rate (mL/min)	H ₂ O ₂ solution density (g/mL)	AFA present? (350 mg/L)	Air flow rate (acfm)	Salt content	Data status	Alpha (vol%)	Sigma alpha (vol%)	Ustar (mm/s)	Urise (mm/s)	Sigma Urise (mm/s)
341b	5/20/06 9:14	GH0845200506	AZ-101	13	9	13	9	650	NA	NA	NA	Yes	0.0370	NA	reviewed	3.44	0.30	0.126	3.7	0.3
341c	5/20/06 9:37	GH0845200506	AZ-101	13	9	13	9	650	NA	NA	NA	Yes	0.0371	NA	reviewed	3.43	0.32	0.126	3.7	0.3
348a	5/20/06 13:00	GH1250200506	AZ-101	13	9	14	9	650	NA	8	1.1166	Yes	NA	NA	reviewed	2.83	0.37	0.132	4.7	0.6
343c	5/20/06 16:42	GH1620200506	AZ-101	14	9	14	10	650	NA	NA	NA	Yes	0.2697	NA	unusable	NA	NA	NA	NA	NA
347a	5/20/06 18:08	GH1755200506	AZ-101	14	10	13	9	650	NA	4	1.1166	Yes	NA	NA	reviewed	1.94	0.31	0.062	3.2	0.5
343d	5/22/06 10:24	GH1010220506	AZ-101	13	9	13	9	650	NA	NA	NA	Yes	0.2643	NA	reviewed	5.59	0.30	0.895	16.0	0.9
347b	5/22/06 11:05	GH1010220506	AZ-101	13	9	13	9	650	NA	4	1.1166	Yes	NA	NA	reviewed	2.14	0.32	0.062	2.9	0.5
348b	5/22/06 16:32	GH1617220506	AZ-101	13	9	13	9	650	NA	8	1.1166	Yes	NA	NA	reviewed	2.56	0.34	0.129	5.1	0.7
343e	5/23/06 10:42	GH1040230506	AZ-101	13	9	13	9	650	NA	NA	NA	Yes	0.2660	NA	reviewed	5.86	0.32	0.905	15.4	0.8
343f	5/23/06 18:57	GH1900230506	AZ-101	12	9	11	9	650	NA	NA	NA	No	0.2651	NA	reviewed	1.56	0.40	0.908	58.1	14.9
369a	5/24/06 10:13	GH1003240506	AZ-101	12	9	11	9	650	NA	NA	NA	No	0.0155	NA	reviewed	0.64	0.45	0.053	8.2	5.7
369b	5/24/06 10:26	GH1003240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	0.0156	NA	reviewed	0.57	0.44	0.053	9.2	7.1
369c	5/24/06 10:39	GH1003240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	0.0156	NA	reviewed	0.60	0.45	0.053	8.8	6.5
369d	5/24/06 10:52	GH1003240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	0.0156	NA	reviewed	0.61	0.45	0.053	8.7	6.4
369e	5/24/06 11:05	GH1003240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	0.0156	NA	reviewed	0.59	0.43	0.053	9.0	6.5
287c	5/24/06 11:18	GH1003240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	0.2649	NA	reviewed	1.83	0.46	0.900	49.3	12.3
370a	5/24/06 12:40	GH1230240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	0.1215	NA	reviewed	1.42	0.44	0.415	29.2	9.0
370b	5/24/06 12:56	GH1230240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	0.1216	NA	reviewed	1.33	0.40	0.415	31.1	9.4
370c	5/24/06 13:10	GH1230240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	0.1217	NA	reviewed	1.39	0.39	0.416	29.9	8.3
370d	5/24/06 13:24	GH1230240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	0.1218	NA	reviewed	1.38	0.48	0.416	30.2	10.5
371a	5/24/06 13:38	GH1230240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	2.3066	NA	reviewed	3.84	0.62	7.889	205.2	33.1
371b	5/24/06 13:52	GH1230240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	2.3081	NA	reviewed	3.94	0.56	7.898	200.3	28.6
371c	5/24/06 14:06	GH1230240506	AZ-101	11	9	11	9	650	NA	NA	NA	No	2.3087	NA	reviewed	3.70	0.52	7.903	213.6	30.2
371d	5/24/06 14:20	GH1230240506	AZ-101	11	9	10	8	650	NA	NA	NA	No	2.3096	NA	reviewed	3.76	0.58	7.911	210.6	32.8
336a	5/24/06 15:44	GH1535240506	AZ-101	10	8	10	8	650	NA	8	1.115	No	NA	NA	reviewed	1.05	0.44	0.124	11.8	5.1
336b	5/25/06 8:40	GH0830250506	AZ-101	10	8	11	9	650	NA	8	1.118	No	NA	NA	reviewed	0.99	0.41	0.123	12.4	5.6
335a	5/25/06 11:44	GH1115250506	AZ-101	12	9	12	9	650	NA	4	1.118	No	NA	NA	reviewed	0.49	0.45	0.063	13.0	13.4
335b	5/25/06 14:34	GH1425250506	AZ-101	13	9	10	8	650	NA	4	1.118	No	NA	NA	reviewed	0.47	0.39	0.063	13.6	11.9
373	6/6/06 10:32	GH1025060606	AZ-101	29	14	29	14	970	NA	NA	NA	Yes	0.0079	NA	reviewed	1.08	0.71	0.027	2.5	1.6
374a	6/6/06 10:54	GH1025060606	AZ-101	29	14	29	14	970	NA	NA	NA	Yes	0.0159	NA	reviewed	1.43	0.76	0.054	3.8	2.0
374b	6/6/06 11:13	GH1025060606	AZ-101	29	14	29	14	970	NA	NA	NA	Yes	0.0159	NA	reviewed	1.47	0.74	0.055	3.7	1.9
375	6/6/06 11:36	GH1025060606	AZ-101	29	14	29	14	970	NA	NA	NA	Yes	0.0377	NA	reviewed	1.70	0.73	0.130	7.7	3.3
376	6/6/06 13:16	GH1305060606	AZ-101	29	14	29	14	970	NA	NA	NA	Yes	0.1247	NA	reviewed	2.82	0.83	0.434	15.4	4.5
377	6/6/06 13:41	GH1305060606	AZ-101	29	14	29	14	970	NA	NA	NA	Yes	0.5754	NA	reviewed	4.24	0.86	2.014	47.5	9.6
378	6/6/06 14:05	GH1305060606	AZ-101	29	14	28	14	970	NA	NA	NA	Yes	2.3883	NA	reviewed	6.91	1.03	8.402	121.7	18.1
372	6/6/06 15:59	GH1550060606	AZ-101	28	14	27	12	970	NA	8	1.1166	Yes	NA	NA	reviewed	2.00	0.72	0.137	6.8	2.5
386	6/7/06 10:41	GH1031060706	AZ-101	20	13	20	13	800	NA	NA	NA	Yes	0.0158	NA	reviewed	1.75	0.43	0.054	3.1	0.8
387	6/7/06 11:05	GH1031060706	AZ-101	20	13	20	13	800	NA	NA	NA	Yes	0.2695	NA	reviewed	4.22	0.53	0.925	21.9	2.7
388	6/7/06 14:17	GH1415060706	AZ-101	18	10	18	10	760	NA	NA	NA	Yes	0.0159	NA	reviewed	1.66	0.45	0.054	3.3	0.9
389	6/7/06 14:40	GH1415060706	AZ-101	18	10	18	10	760	NA	NA	NA	Yes	0.2695	NA	reviewed	3.98	0.47	0.925	23.3	2.7
390	6/7/06 15:49	GH1545060706	AZ-101	14	8	14	8	650	NA	NA	NA	Yes	0.0159	NA	reviewed	2.04	0.42	0.055	2.7	0.6
391	6/7/06 16:12	GH1545060706	AZ-101	14	8	14	8	650	NA	NA	NA	Yes	0.2701	NA	reviewed	4.81	0.48	0.928	19.3	1.9
392	6/7/06 17:17	GH1715060706	AZ-101	9	8	9	8	580	NA	NA	NA	Yes	0.0159	NA	reviewed	2.27	0.45	0.055	2.4	0.5
393	6/7/06 17:42	GH1715060706	AZ-101	9	8	9	8	580	NA	NA	NA	Yes	0.2698	NA	reviewed	5.48	0.48	0.926	16.9	1.5
394	6/8/06 9:28	GH0925060806	AZ-101	5	6	5	6	525	NA	NA	NA	Yes	0.0158	NA	reviewed	2.41	0.49	0.054	2.2	0.5

Table A.1 (contd)

Test #	Date & Start Time	Data file	Simulant	Initial yield strength (Pa)	Initial consistency (cP)	Final yield strength (Pa)	Final consistency (cP)	Agitator RPM	MNO ₂ content (ppm)	H ₂ O ₂ injection rate (mL/min)	H ₂ O ₂ solution density (g/mL)	AFA present? (350 mg/L)	Air flow rate (acfm)	Salt content	Data status	Alpha (vol%)	Sigma alpha (vol%)	Ustar (mm/s)	Urise (mm/s)	Sigma Urise (mm/s)
395	6/8/06 9:55	GH0925060806	AZ-101	5	6	5	6	525	NA	NA	NA	Yes	0.2648	NA	reviewed	6.60	0.53	0.898	13.6	1.1
396	6/8/06 11:08	GH1100060806	AZ-101	2	4	2	4	400	NA	NA	NA	Yes	0.0156	NA	reviewed	2.15	0.57	0.053	2.5	0.6
397	6/8/06 11:54	GH1100060806	AZ-101	2	4	2	4	400	NA	NA	NA	Yes	0.2643	NA	reviewed	6.29	0.47	0.895	14.2	1.1
398	6/8/06 13:18	GH1315060806	AZ-101	2	4	2	4	525	NA	NA	NA	Yes	0.0156	NA	reviewed	2.69	0.63	0.053	2.0	0.5
399	6/8/06 13:34	GH1315060806	AZ-101	2	4	2	4	525	NA	NA	NA	Yes	0.2646	NA	reviewed	7.06	0.61	0.896	12.7	1.1
400	6/8/06 14:10	GH1315060806	AZ-101	2	4	2	4	650	NA	NA	NA	Yes	0.0157	NA	reviewed	2.92	0.75	0.053	1.8	0.5
401	6/8/06 14:40	GH1315060806	AZ-101	2	4	2	4	650	NA	NA	NA	Yes	0.2661	NA	reviewed	7.02	0.77	0.902	12.8	1.4
380	6/9/06 10:35	GH1035060906	AZ-101	30	14	30	15	940	NA	NA	NA	No	0.0079	NA	reviewed	0.52	0.55	0.027	5.2	5.5
381a	6/9/06 10:51	GH1035060906	AZ-101	30	15	30	15	940	NA	NA	NA	No	0.0156	NA	reviewed	0.79	0.60	0.053	6.7	5.1
381b	6/9/06 11:08	GH1035060906	AZ-101	30	15	30	15	940	NA	NA	NA	No	0.0157	NA	reviewed	0.72	0.54	0.054	7.4	5.5
382	6/9/06 11:23	GH1035060906	AZ-101	30	15	30	15	940	NA	NA	NA	No	0.0370	NA	reviewed	0.92	0.57	0.126	13.7	8.4
383	6/9/06 11:39	GH1035060906	AZ-101	30	15	30	15	940	NA	NA	NA	No	0.1224	NA	reviewed	1.65	0.60	0.420	25.4	9.2
384	6/9/06 12:56	GH1255060906	AZ-101	30	15	30	15	940	NA	NA	NA	No	0.5647	NA	reviewed	2.83	0.66	1.943	68.7	16.1
385	6/9/06 13:11	GH1255060906	AZ-101	30	15	30	15	940	NA	NA	NA	No	2.3398	NA	reviewed	4.87	0.78	8.071	165.7	26.7
379	6/9/06 14:25	GH1425060906	AZ-101	30	15	30	16	950	NA	8	1.1166	No	NA	NA	reviewed	1.22	0.68	0.132	10.8	7.0

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