2 F

PNL-8900
UC-510

Test Plan

1/12-Scale Scoping Experiments to Characterize Double-Shell Tank Slurry Uniformity

J. A. Bamberger
L. M. Liljegren

October 1994

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

PNL-8900

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.** Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under **Contract DE-AC06-76RLO 1830**

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831;
prices available from (615) 576-8401. FTS 626-8401.

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd, Springfield, VA 22161.

TEST PLAN

**1/12-SCALE SCOPING EXPERIMENTS
TO CHARACTERIZE DOUBLE-SHELL
TANK SLURRY UNIFORMITY**

**J. A. Bamberger
L. M. Liljegren**

October 1994

**Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Richland, Washington 99352**

TEST PLAN

1/12-SCALE SCOPING EXPERIMENTS
TO CHARACTERIZE DOUBLE-SHELL
TANK SLURRY UNIFORMITY

PREPARED: J. A. Bamberger DATE: 6/24/93
J. A. Bamberger, Task Leader
Pacific Northwest Laboratory

APPROVED: P. A. Scott DATE: 7/7/93
P. A. Scott, Project Manager
Pacific Northwest Laboratory

CONCUR: R. C. Schrotke, Jr. DATE: 7/7/93
R. C. Schrotke, Jr. Quality Assurance
Pacific Northwest Laboratory

APPROVED: T. M. Burke DATE: 7/7/93
T. M. Burke, Lead Engineer
DST Retrieval Development
Westinghouse Hanford Company

SUMMARY

The experiments described in this test plan address the issue of maintaining mobilized particles in a uniform suspension by using jet to mix the suspension. The tests are based on the general analysis of maintaining uniformity described in Strategy Plan: A Methodology to Predict the Uniformity of Double-Shell Tank Waste Slurries on Mixing Pump Operation (Bamberger et al. 1993).

The objectives of these 1/12-scale scoping experiments are to

- determine how Reynolds number, Froude number, and gravitational settling parameter^(a) affect the degree of uniformity achieved during jet mixer pump operation in the full-scale double-shell tanks
- develop linear models to predict the degree of uniformity achieved by jet mixer pumps operating in the full-scale double-shell tanks
- apply linear models to predict the degree of uniformity that will be achieved in tank 241-AZ-101 and determine whether contents of that tank will be uniform to within $\pm 10\%$ of the mean concentration
- obtain experimental concentration and jet velocity data to compare with the TEMPEST computational modeling predictions to guide further code development.

The scoping study will experimentally evaluate uniformity in a 1/12-scale experiment at eight corners of the Reynolds number, Froude number, and gravitational settling parameter space. Test conditions will be achieved by varying the simulant viscosity, the mean particle size, and the jet nozzle exit velocity. Concentration measurements at sampling locations throughout the tank will be used to assess the degree of uniformity achieved during each test. Concentration data will be obtained using a real time ultrasonic attenuation probe and discrete batch samples. The undissolved solids

(a) The gravitational settling parameter is defined as the ratio of the rate at which the gravitational field does work to draw particles down to the lower regions of the tank to the power supplied by the jet to suspend particulate.

concentration at these locations will be analyzed to determine whether the tank contents are uniform ($\leq \pm 10\%$ variation about mean) or nonuniform ($\geq \pm 10\%$ variation about mean) in concentration. Concentration inhomogeneity will be modeled as a linear function of dimensionless groups,

CONTENTS

SUMMARY	v
NOMENCLATURE	x i
1.0 OBJECTIVES AND SCOPE	1.1
1.1 INTRODUCTION	1.2
1.2 OBJECTIVES	1.2
1.3 SCOPE	1.5
1.4 LIMITATIONS	1.6
2.0 SIMULANT DEVELOPMENT	2.1
2.1 SPECIFICATIONS	2.1
2.2 EVALUATING SIMULANT PHYSICAL PROPERTIES	2.3
2.2.1 Density	2.3
2.2.1.1 Simulant Bulk Density	2.3
2.2.1.2 Solids Density	2.5
2.2.1.3 Supernatant Density	2.6
2.2.2 Viscosity	2.6
2.2.2.1 Viscosity as a Function of Temperature	2.8
2.2.2.2 Viscosity as a Function of Concentration	2.8
2.2.3 Particle Size	2.9
2.2.4 Particle Settling Velocity	2.9

2.3	PREPARATION OF 1/12-SCALE SIMULANT	2.13
2.3.1	Physical Property Verification	2.13
2.3.2	Simulant Manufacture and Characterization	2.14
2.3.3	Simulant Transfer to 1/12-Scale Tank	2.16
2.3.4	Simulant Transfer from 1/12-Scale Tank	2.16
3.0	SCOPING EXPERIMENTS	3.1
3.1	OPERATING CONDITIONS	3.1
3.2	1/12-SCALE TEST SYSTEM	3.1
3.2.1	1/12-Scale DST Model Tank	3.2
3.2.2	Simulated Jet Mixer Pump	3.4
3.2.3	Ancillary Equipment	3.6
3.3	TEST PROCEDURE	3.6
3.3.1	Test Period Definition	3.7
3.3.2	Period 1 Operation	3.8
3.3.3	Period 2 Operation	3.8
3.3.4	Period 3 Operation	3.12
3.4	DATA ACQUISITION	3.12
3.4.1	Mode1	3.13
3.4.2	Mode 2	3.14
3.5	INSTRUMENTATION	3.15
3.5.1	Mixing Pump Flow Rate	3.15
3.5.2	Jet Nozzle Exit Velocity	3.15
3.5.3	Mixer Pump Angular Location	3.15

3.5.4	Temperature	3.16
3.5.5	Concentration	3.16
3.5.5.1	Syringe Samplers	3.17
3.5.5.2	Ultrasonic Concentration Measurement	3.18
3.5.5.3	Static Pressure Measurements to Detect Solids Settling	3.18
3.5.6	Mean Concentration	3.20
3.5.7	Jet Velocity Near the Wall	3.21
3.5.8	Temperature Control	3.21
4.0	EXPERIMENTAL RESULTS	4.1
4.1	RESULTS OF INDIVIDUAL TESTS	4.1
4.1.1	Concentration Data	4.1
4.1.2	Dynamic Data	4.3
4.1.3	Data Associated with Simulant Properties	4.3
4.1.4	Data Associated with Detection of Steady State	4.3
4.2	ACCEPTANCE CRITERIA	4.3
4.2.1	Concentration Measurement	4.4
4.2.2	Nozzle Velocity	4.4
4.2.3	Mixer Pump Oscillation Rate	4.5
4.2.4	Simulant Properties	4.5
4.2.5	Rate of Change in Pressure and Concentration	4.5
4.2.6	Minimum Test Time	4.5
4.3	DATA REVIEW	4.5

4.3.1	Simulant Properties	4.6
4.3.2	Dynamic Properties	4.6
4.3.3	Concentration Data	4.6
4.4	DATA ANALYSIS	4.6
4.4.1	Definition of Dimensionless Numbers	4.7
4.4.2	Uncertainty in the Experimental Reynolds Number	4.9
4.4.3	Uncertainty in the Froude Number	4.9
4.4.4	Uncertainty in the Gravitational Settling Parameter	4.10
5.0	GENERAL INSTRUCTIONS	5.1
5.1	SAFETY	5.1
5.2	QUALITY ASSURANCE	5.1
5.3	TRAINING	5.2
	REFERENCES	6.1

FIGURES

1.1	Tank Uniformity Investigation Flow Chart	1.3
1.2	Conceptual Illustration of the Scoping Study Experimental Region . .	1.5
3.1	Flow Diagram for 1/12-Scale System	3.5
3.2	1/12-Scale Slurry Mixer Pump Configuration	3.5
3.3	Data Acquisition	3.13

TABLES

2.1	Target Simulant Properties	2.3
3.1	Target Operating Conditions for the Eight Scoping Tests	3.2
3.2	1/12-Scale Model Configuration	3.4
3.3	Location of Instrumentation	3.17
3.4	Location of Pressure Transducers	3.20

NOMENCLATURE

C	concentration
$C_{Bi}(X)$	concentration of an individual syringe sample taken at the location X
$\langle C \rangle(X)$	cycle average concentration at location X
$\overline{\langle C \rangle}_{\text{cycle}}$	mean cycle average concentration
$\overline{\langle C \rangle}_{\text{cycle}}(X)$	mean cycle average concentration at each ultrasonic probe location
C_d	particle drag coefficient
$\langle C \rangle_{i,1}$	mean cycle average concentrations at i th detector at time t_1
$\langle C \rangle_{i,2}$	mean cycle average concentrations at i th detector at time t_2
C_{sb}	concentration of bed of settled solids
C_{ui}	concentration measured using ultrasonic probe at time t_i
$\bar{C}(X)$	mean concentration based on replicate syringe samples
$\sqrt{\langle C \rangle'^2}$	standard deviation of mean cycle average concentration
$\sqrt{C'^2(X)}$	standard deviation of mean concentration for replicate syringe samples
D	dynamic pressure
dC/dt_{initial}	rate of change of concentration calculated during Period 1
$d\langle C \rangle/dt_i$	rate of change in mean cycle average concentration at i th detector
$d\langle C \rangle/dt_{\text{initial}}$	mean value calculated during Period 1
$d\langle C \rangle/dt_{\text{limit}}$	minimum detectable change caused by noise in the pressure transducers
$d\langle C \rangle/dt_{\text{rms}}$	root mean square rate of change in concentration

d_p	mean particle diameter
dP/dt_{initial}	rate of change in pressure calculated during Period 1
$d\langle P \rangle/dt_{\text{limit}}$	minimum detectable change caused by noise in the pressure transducers
$d\langle P \rangle/dt_i$	mean cycle average rate of change in pressure at ith transducer
$d\langle P \rangle/dt_{\text{initial}}$	mean value of rate of change in pressure calculated during Period 1
$d\langle P \rangle/dt_{\text{rms}}$	root mean square rate in change of pressure
DST	double-shell tank
D_t	tank diameter
D_0	nozzle diameter
e	shear rate
F	force exerted on particle
Fr	Froude number
g	acceleration due to gravity
G_s	gravitational settling parameter
H	fluid depth
h	transducer elevation
$\Delta H/\Delta V$	scale factor
M	mass
M_c	mass of empty container
M_{cl}	mass of container and liquid
M_{cs}	mass of container and solids
M_{csl}	mass of container, solids and liquid

MSDS	material safety data sheet
M&TE	measurement and test equipment
N_B	number of syringe samples taken at location X
N_c	number of cycles over which the cycle average concentration was measured
N_d	number of ultrasonic sensors
N_m	number of measurements
N_s	number of samples taken during a cycle
N_t	number of pressure transducers
P	hydrostatic pressure
$\overline{\langle P \rangle}_{\text{cycle}}$	mean cycle average hydrostatic pressure
$\langle P \rangle_{i,1}$	mean cycle average pressure measured at ith detector at time t_1
$\langle P \rangle_{i,2}$	mean cycle average pressure measured at ith detector at time t_2
PNL	Pacific Northwest Laboratory
Q	mixer pump volumetric flow rate
$\overline{\langle Q \rangle}_{\text{cycle}}$	mean cycle average flow rate to dual nozzles
QA	quality assurance
R	mixer pump oscillation rate
Re	Reynolds number
	particle Reynolds number
rms	root mean square
s	density ratio (ρ_s/ρ)
T	temperature
t	time

T_{ave}	average simulant temperature
$\overline{\langle T \rangle}_{cycle}$	mean cycle average tank temperature
T_i	ith temperature
t_1	time at beginning of interval
t_2	time at end of the interval
U_0	jet nozzle exit velocity
U_{0c}	mean jet nozzle exit velocity averaged over five cycles
U_{0i}	instantaneous jet nozzle exit velocity
U_r	relative velocity between particle and fluid
U_s	particle settling velocity
V	volume
V_l	liquid volume
V_{sl}	volume of solids and liquid
WHC	Westinghouse Hanford Company

Greek Letters

Δ	uncertainty
δ	uncertainty in measurement
θ	nozzle angular location
μ	viscosity
ν	kinematic viscosity
ν_i	mean kinematic viscosity based on replicate samples at T_i
$\nu_p(T_i)$	kinematic viscosity predicted using curve fit evaluated at T_i
ρ	bulk density

ρ_f	supernatant density
ρ_s	solids density
ϕ_s	volume fraction

1.0 OBJECTIVES AND SCOPE

Million gallon double-shell tanks (DSTs) at Hanford are used to store transuranic, high-level, and low-level wastes. These wastes generally consist of a large volume of salt-laden solution covering a smaller volume of settled sludge primarily containing metal hydroxides. These wastes will be retrieved and processed into immobile waste forms suitable for permanent disposal. As a part of the Hanford mission, high-level waste and transuranic waste will be disposed as vitrified glass in geologic repositories and low-level waste will be disposed as grout in near-surface vaults. Retrieval is an important step in implementing these disposal scenarios. Retrieval technologies applicable to the various double-shell tank wastes are being defined, developed, and demonstrated at Pacific Northwest Laboratory (PNL) in conjunction with Westinghouse Hanford Company (WHC). The current retrieval concept is to use submerged dual-nozzle pumps to mobilize the settled solids by creating jets of fluid that are directed at the tank solids. The pumps oscillate, creating arcs of high-velocity fluid jets that sweep the floor of the tank. After the solids are mobilized, the pumps will continue to operate at a reduced flow rate sufficient to maintain the particles in a uniform suspension.

Several types of waste and a number of tank configurations exist at Hanford. The mixer pump systems and operating conditions required to mobilize sludge and maintain slurry uniformity will be a function of the waste type and tank configuration. While it would be possible to specify the mixer pump system for each tank using scaled testing, it is more efficient to develop models that relate slurry uniformity to tank and mixer pump configurations, operating conditions, and sludge properties. These models can then be used over a range of conditions to specify mixer pumps. It is the goal of this research to develop models that will be adequate over the expected range of slurry properties and tank configurations. The most efficient method to determine appropriate pump sizes and predict the flow rates required during

the retrieval process to mobilize sludge and maintain slurry uniformity is to develop generalized relations describing the behavior of these waste slurries.

1.1 INTRODUCTION

The experiments described in this test plan address the issue of maintaining mobilized particles in a uniform suspension; the companion problem of mobilizing the settled solids is addressed separately. The tests to be conducted during this scoping study are based on the general analysis of maintaining uniformity described in Strategy Plan: A Methodoloav to Predict the Uniformity of Double-Shell Tank Waste Slurries on Mixina Pump Operation^(a) (Bamberger et al. 1993). The method outlined in the Strategy Plan was summarized in a flow chart^(b), which is reproduced in Figure 1.1. The 1/12-scale scoping study activities are listed as Steps 4b, 5, and 6b.

1.2 OBJECTIVES

The general uniformity task objectives, described in the Strategy Plan, are to define mixing pump configurations and operating limits that will ensure an adequately uniform feed waste stream during waste retrieval from the double-shell tanks. The objectives specific to this 1/12-scale scoping study are to

1. determine how the Reynolds number (Re), Froude number (Fr), and gravitational settling parameter (Gs)^(c) affect the degree of uniformity achieved during jet mixer pump operation in the full-scale DSTs

(a) This report will be referred to as the Strategy Plan.

(b) In the flow chart, steps are conducted in series, while the alphabetic subparts of each step are conducted in parallel.

(c) The gravitational settling parameter is defined as the ratio of the rate at which the gravitational field does work to draw particles down to the lower regions of the tank to the power supplied by the jet to suspend particulate.

Computational Path

Analysis Path

Experimental Path

FIGURE 1.1 Tank Uniformity Investigation Flow Chart

Computational Path

Analysis Path

Experimental Path

FIGURE 1.1 Tank Uniformity Investigation Flow Chart (contd)

2. develop linear models to predict the degree of uniformity achieved by jet mixer pumps operating in the full-scale DSTs
3. apply the linear models to predict the degree of uniformity that will be achieved in tank 241-AZ-101 and determine whether contents of that tank will be uniform to within $\pm 10\%$ of the mean concentration

4. obtain experimental concentration and jet velocity data to compare with the TEMPEST'' (Trent and Eyler 1989) computational modeling predictions to guide further code development.

1.3 SCOPE

The scoping study will experimentally evaluate uniformity, in a 1/12-scale experiment, at the eight corners of the Reynolds number, Froude number, gravitational settling parameter space shown in Figure 1.2. (The points are

FIGURE 1.2 Conceptual Illustration of the Scoping Study Experimental Region

(a) Transient energy, momentum, and pressure equation solution in three-dimensions.

defined in Table 3.1). The test conditions will be achieved by varying the simulant viscosity (μ), the mean particle diameter (d_p), and the jet nozzle exit velocity (U_0). The data acquired during these tests will be used to complete objectives 1, 2, and 4. Models developed during completion of objective 2 will be used to complete objective 3.

Concentration measurements at sampling locations throughout the tank will be used to assess the degree of uniformity achieved during each test. The undissolved solids concentration at these locations will be analyzed to determine whether the tank contents are uniform ($\leq \pm 10\%$ variation about mean) or nonuniform ($> \pm 10\%$ variation about mean) in concentration. Concentration inhomogeneity will be modeled as a linear function of the dimensionless groups.

The measured degree of inhomogeneity during the tests will be provided to the numerical analysis task for comparison with computational predictions. In addition, measurements will be taken to quantify the jet velocity along the tank wall to support computational modeling.

1.4 LIMITATIONS

This test plan describes experiments that are part of a broader strategy for developing methods to predict the uniformity of waste tank contents during waste retrieval. The Strategy Plan describes the procedure to continue analyses of uniformity via computational modeling and larger scaled experiments after completion of the scoping experiments. The understanding gained from the scoping experiments will be subject to the following limitations.

- The models developed to predict the degree of uniformity will be linear. The actual variation of concentration with the physical parameters may be nonlinear. The degree of nonlinearity will not be defined by these tests; it will be defined during the defining experiments listed in Step 9d of Figure 1.1.

The scoping experiments will be performed in a specific Reynolds number, Froude number, and gravitational settling parameter region.^(a) Prediction of the behavior outside that region will require extrapolation, which will be inaccurate if the variation with the physical parameters is nonlinear.

The models developed will be useful for predicting concentration uniformity from operating jet mixer pumps in tanks with geometries similar to double-shell tanks. The degree to which the models may be applied to predict the uniformity in geometrically dissimilar tanks is not known.

- The scoping experiments will be conducted in a tank without scaled tank components; therefore, effects of tank components, such as air lift circulators, upon uniformity will not be determined.

(a) The region chosen for these experiments is limited by fluid rheology and the need for experiments to be conducted in a turbulent Reynolds number regime. The selected range is deemed satisfactory for conducting the scoping experiments at 1/12 scale.

2.0 SIMULANT DEVELOPMENT

Four simulants are required to conduct the scoping experiments. Specific simulant physical properties are necessary to achieve the required experimental conditions. Specifications for the simulant physical properties are defined in Section 2.1, methods to measure the physical properties at laboratory scale are summarized in Section 2.2, and steps to prepare the simulants for the 1/12-scale experiments are listed in Section 2.3.

2.1 SPECIFICATIONS

Specific Reynolds numbers, Froude numbers, and gravitational settling parameters are necessary to achieve the desired experimental conditions. The Froude number is set by controlling the jet nozzle exit velocity. Simulant physical properties are chosen to obtain the required Reynolds number and gravitational settling parameter. Kinematic viscosity is varied to set Reynolds number. Particle diameter is varied to set the gravitational settling parameter. The physical properties of the simulants must meet the following criteria.

1. At the target nozzle exit velocity (U), the bulk density (ρ) and effective viscosity (μ) of each individual simulant must allow target Reynolds numbers to be achieved within $\pm 20\%$.
2. At the target nozzle exit velocity (U), the bulk density (ρ) and particle diameter (d_p) of each individual simulant must allow the target gravitational settling parameter to be achieved within $\pm 50\%$.
3. When identical viscosities (μ) are specified for two simulants, the difference between the two viscosities should not be more than $\pm 10\%$, thereby ensuring that the effect of varying the Reynolds number between a high and low value can be determined.
4. When identical mean particle diameters (d_p) are specified for two simulants, the mean particle diameters in the two simulants should match each other within $\pm 3 \mu\text{m}$ for the smaller diameter simulant and $\pm 5 \mu\text{m}$ for larger diameter simulant.

The magnitudes of the simulant physical properties have been selected to allow the values of the Reynolds number and gravitational settling parameter to be achieved. Acceptable ranges for the measured values of these properties are provided in Table 2.1. These ranges pertain to the target specifications and not the accuracy with which the properties must be measured. It is currently anticipated that the target properties can be obtained at room temperature and that temperature control of the simulant will not be required.^(a) Temperature control will be deemed necessary if the change in viscosity caused by a change in temperature equal to three standard deviations of the temperature variance is more than $\pm 10\%$. However, because the magnitude of the properties varies with temperature, temperature will be monitored during the tests. The target values of the properties at 20°C (68°F) are described in Table 2.1. The simulant rheology will be characterized at shear rates that arise near the jet nozzle exit and those that are characteristic of particle settling. The simulants are anticipated to be nominally Newtonian at the nominal shear rate that characterizes the jet motion near the nozzle exit.

(a) Temperature control may be required to achieve the target simulant properties in the tank. The requirement that the viscosity of simulants 1 and 2 match to within $\pm 10\%$ and that simulants 3 and 4 match to within $\pm 10\%$ is stringent. The kinematic viscosity (ν) of water varies approximately 33% over 20°C between 27°C and 47°C suggesting that the temperature at which the experiments are performed must not vary more than $\pm 6^{\circ}\text{C}$. The 1/12-scale system is located below grade in the 336 Building where temperature is stable; day to day variations of more than $\pm 6^{\circ}\text{C}$ are not anticipated. However, the building is a high bay, and the temperature does vary depending on weather conditions. Consequently, the need for temperature control will be assessed during simulant development. This will be done as follows. 1) The temperature of the test system location in the 336 Building will be monitored on an hourly basis prior to the start of testing during simulant development efforts. The standard deviation of the temperature near the test system will be calculated. This characterization should be done during the season in which the experiments are performed. 2) The effect of temperature on viscosity (μ) and particle settling velocity (U_s) will be determined experimentally in the laboratory.

TABLE 2.1 Target Simulant Properties^(a)

Simulant	Absolute Viscosity μ , cP	Particle Diameter d_p , μm	Bulk Density ρ , kg/m ³	Density Ratio $s=\rho_s/\rho$	Concentration wt%	Kinematic Viscosity ν , m ² /s	Nominal Particle Settling Velocity ^(b) U_s , $\mu\text{m/s}$
1	<2 ^(c)	5 $\pm$ 3	1,250 $\pm$ 10%	2 $\pm$ 25%	18 $\pm$ 5%	<1.6 $\pm$ 10%	8.5
2	<2	20 $\pm$ 5	1,250 $\pm$ 10%	2 $\pm$ 25%	18 $\pm$ 5%	<1.6 $\pm$ 10%	136
3	3.4 $\pm$ 5%	5 $\pm$ 3	1,250 $\pm$ 10%	2 $\pm$ 25%	18 $\pm$ 5%	2.7 $\pm$ 10%	5
4	3.4 $\pm$ 5%	20 $\pm$ 5	1,250 $\pm$ 10%	2 $\pm$ 25%	18 $\pm$ 5%	2.7 $\pm$ 10%	80

(a) These target properties can be obtained at any constant temperature, either ambient or elevated as described in this section.

(b) Calculated value based on particle diameter.

(c) This absolute viscosity is anticipated to approach that of water at ambient temperature (~1 cP) Two cP is the maximum permissible viscosity for simulants 1 and 2.

2.2 EVALUATING SIMULANT PHYSICAL PROPERTIES

Simulant properties will be determined. Simulant density, viscosity, particle size, and particle settling velocity will be measured.

2.2.1 Density

Three densities must be characterized: simulant bulk density (ρ), solids density (ρ_s), and supernatant density (ρ_f).

2.2.1.1 Simulant Bulk Density

The simulant bulk density (ρ) will be determined by measuring the mass (M) of a known volume (V) of simulant.^(a)

$$\rho = M/V \quad (2.1)$$

(a) To determine simulant bulk density:

1. Measure mass of empty graduated container (M_c).
2. Fill with simulant to known volume (V).
3. Measure mass of container plus simulant (M_{cs1})

$$\rho = (M_{cs1} - M_c)/V \quad (2.1a)$$

It is anticipated that the accuracy of the density determination will be within $\pm 0.5\%$. Measure the density over a temperature range that spans the temperatures expected during testing (10°C to 30°C at five points taken every $5 \pm 2^{\circ}\text{C}$) to determine the variation of the bulk density with temperatures. The density is not expected to vary markedly over this temperature range.

Bulk simulant density will be measured using a PNL test procedure.^(a) A 10-ml volumetric flask or graduated cylinder will be used; volumes will be measured to 20.04 ml; mass will be measured to 20.02 g.

(a) PNL-ALO-501 Laboratory Procedure for Measurement of Physical and Rheological Solutions, Slurries, and Sludges.

2.2.1.2 Solids Density

Prior to simulant preparation, the dry solids density (ρ_s) will be determined by measuring the mass of a known volume. ^{(a),(b)} The solids density will then be determined using the relation

$$\rho_s = (M_{cs1} - M_{c1}) / (V_{s1} - V_1) \quad (2.2)$$

Five independent samples from separate locations in the solids are required to ensure that a specific sample is not atypical. More samples will be taken if the density variability over the samples is greater than 20.9 wt%.

(a) To determine the solids density:

1. Titrate approximately 50 ml of water into a 100-ml volumetric flask. Record volume of water added (V_1); the uncertainty is expected to be ± 0.04 ml.
2. Measure mass of container and liquid (M_{c1}) to within ± 0.02 g.
3. Add solids to the volumetric flask until the total volume reading is approximately 100 ml. Record the volume of the flask contents (V_{s1}). The uncertainty is anticipated to be ± 0.4 ml.
4. Measure mass of container plus the solids and liquid (M_{cs1}) to within ± 0.02 g.

Alternative method: If the scale used has a tare feature, the scale may be tared after step 2. The recorded measurement in step 4 will then be $M_{cs1} - M_r$; uncertainty will be 0.02 g.

The simulant bulk density can be similarly obtained:

$$\rho = (M_{cs1} - M_c) / (V_{s1} - V_1) \quad (2.1a)$$

(b) The density of the solids will be determined at room temperature and is assumed to be constant over the temperature range of the experiments. The uncertainty in the solids density determination is

$$\delta \rho_s / \rho_s = \{ [\delta(M_{cs1} - M_{c1}) / (M_{cs1} - M_{c1})]^2 + [\delta(V_{s1} - V_1) / (V_{s1} - V_1)]^2 \}^{0.5} \quad (2.2a)$$

where δ = uncertainty in measurement.

Uncertainty can be kept below $\pm 1\%$ by selecting these volumes and masses.

2.2.1.3 Supernatant Density

The density of the centrifuged supernatant will be measured after simulant manufacture. The mass of a known volume will be measured over a temperature range (10 to 30°C at five points taken every 5±2°C) and the density calculated using Equation (2.1). The accuracy of the density determination should be within ±0.5%.

2.2.2 Viscosity

Absolute viscosity (μ) can be calculated by using the relation

$$\mu = \rho \nu \quad (2.3)$$

where ρ = simulant bulk density defined in Equation (2.1)

ν = simulant bulk kinematic viscosity.

The simulant kinematic viscosity (ν) will be measured using capillary tube viscometers. Capillary tube viscometers provide highly accurate measurements within ±0.2% of reading over a wide range of shear rates.^(a)

Fluid viscosity measurements are desired in two shear rate ($\dot{\gamma}$) ranges to determine whether the simulant exhibits Newtonian or non-Newtonian rheology. The viscosity of each simulant will be measured at four strain rates.

(a) The capillary tube design currently under consideration is a Cannon-Ubbelohde Ten-Fold dilution (Cannon Instrument Company, State College, Pennsylvania). A number of tubes will be required to perform viscosity measurements as a function of temperature and concentration; an appropriate viscometer will be selected for each range.

The low shear rate range, $e = 5$ to 50 s^{-1} , characterizes the rheology at shear rates comparable to those that arise when $5\text{-}\mu\text{m}$ -diameter and $20\text{-}\mu\text{m}$ -diameter particles fall through the simulants based on Stokes flow.^(a)

The high shear rate range, $e = 100$ to 450 s^{-1} , characterizes the rheology at shear rates comparable to those that arise near the nozzle exit.^(b) The maximum value of U_0/D_0 for the 1/12-scale scoping experiments is approximately 410 s^{-1} , the minimum is approximately 100 s^{-1} .

The viscosity of the simulant is expected to change as a function of temperature, concentration, and degree of settling. Consequently, when viscosity is measured, procedures to ensure that the simulant is well mixed and at a known temperature are required. A constant temperature water bath will be used to maintain the simulant at constant temperature. The simulant will be allowed to remain in the constant temperature bath until it reaches the bath temperature. If settling during equilibration is observed, then all

(a) The order of magnitude of the low shear rate range was determined by evaluating the relation

$$e = 3 U_s/d_p = (\rho_s - \rho_f) g d_p / 6 \mu \quad (2.3a)$$

which approximates the order of magnitude of the shear rate at the surface of a particle falling under the influence of gravity,

where U_s = particle settling velocity
 d_p = mean particle diameter
 ρ_s = solids density
 ρ_f = supernatant density
 g = acceleration due to gravity
 μ = absolute viscosity.

(b) The order of magnitude of the high shear rate range, corresponding to the characteristic shear of a jet, was determined by evaluating the relation

$$e = U_0/D_0 \quad (2.3b)$$

where U_0 = jet nozzle exit velocity
 D_0 = nozzle diameter.

components will be heated to constant temperature prior to filling the viscometer.

2.2.2.1 Viscosity as a Function of Temperature

To determine the need for temperature control of the simulant, kinematic viscosity measurements of the four simulants developed at laboratory scale will be taken at five points taken every $5 \pm 2^\circ\text{C}$ over the range from 10 to 30°C . This temperature range will be modified if temperature control is required to achieve the target simulant viscosities. Temperature control will be provided by a water bath. Two measurements at each temperature will be sufficient to characterize the anticipated degree of variability of the viscosity with temperature.

2.2.2.2 Viscosity as a Function of Concentration

The viscosity of the simulant will be measured as a function of concentration to guide future simulant development efforts and provide kinematic viscosity data as a function of concentration for computational modelers. The viscosity of each of the four simulants will be measured at 20°C at the standard concentration (18 wt%); the viscosity will then be measured at five additional concentrations at every 10% $\pm 2\%$ over the range for a total of six concentration measurements between 10% of the standard concentration (1.8 wt%) and 50% of the concentration of the settled bed of solids.^(a) The concentration of the settled bed (C_{sb}) can then be determined from

$$C_{sb} = C V_{s1} / (M_{cs} - M_c) \quad (2.4)$$

(a) To determine the concentration of a settled bed of solids:

1. Weigh a 100-ml volumetric flask (M_c) to within ± 0.2 g.
2. Place approximately 100 ml (V_{s1}) of simulant of known concentration (C) into the volumetric flask. The uncertainty in V_{s1} will be ± 0.4 ml.
3. Allow the solids to settle into a bed.
4. Decant the supernate.
5. Weigh the container and solids (M_{cs}) to within ± 0.2 g.

It is not anticipated that the concentration will reach the maximum packing concentration anywhere in the tank. However, some high concentration measurements are desirable to support computational modeling; measurements at 50% of the maximum concentration are sufficient. Measurements will be determined to an accuracy of $\pm 5\%$ with a confidence of **95%**.

2.2.3 Particle Size

The diameter of the dry solids will be measured prior to preparation of the simulants. After the **simulants** have been prepared, the particle size of the simulant will be measured.

Prior to simulant preparation, the dry solids particle size of five separate, independent samples will be measured to detect any **large-scale** inhomogeneities in batches of dry **samples** by laser scanning.^(a) Sufficient numbers of particles can be measured to reduce the random error to less than $\pm 0.1\%$ with **95%** confidence.

After the simulants have been prepared, determine the size of particles by laser scanning. The procedure recommends use of surfactants if particles are observed to agglomerate. If particle agglomeration is observed, particle size measurement will be made both with and without surfactants. If agglomeration occurs, the agglomerated particle size (including agglomerates) is the size that affects settling during experiments and the measured size without addition of surfactants will be used to characterize settling.

2.2.4 Particle Settling Velocity

The particle settling velocity of the solids in the simulant is one term in the gravitational settling parameter (G_s), the parameter used to characterize the tendency of material to settle in the tank.

Two sizes of particles will be used in this experiment; the settling velocity of the two particle sizes will differ by a factor of approximately

(a) M. C. Burt. Particle Size Distribution by Laser Scanning (Time of Transition) 2-50.3, Rev. 0; **12/4/89**.

16. Consequently, an uncertainty level of $\pm 10\%$ in the settling velocity will be sufficiently small to allow detection of the effects of particle size on settling.

Temperature changes affect the simulant viscosity and density and particle density; therefore, the settling viscosity can change as a function of temperature. The particle settling velocity will be measured at the same set of temperatures as the density and viscosity measurements.

Two methods will be used to determine the particle settling velocity for the slurry: 1) measure the unhindered particle settling velocity at the experimental temperature, based on a test procedure modification^{(a),(b)} and 2) calculate settling velocity based on the measured magnitudes of the mean particle diameter (d_p), the particle density (ρ_p), the mixture density (ρ) and the mixture viscosity (μ).

Method 1^(c) will be used as the standard method for slurry formulations

(a) R. D. Scheele. Laboratory Procedure for Measurement of Physical and Rheological Properties of Solutions, Slurries and Sludges, PNL-ALO-501.

(b) Procedure PNL-ALO-501 will be amended to allow a more accurate determination of the unhindered settling velocity; measurements will be taken every 10 minutes during the first hour. Interface height versus time plots will be generated. The unhindered settling velocity will be determined from the average slope of this curve during the first hour of settling. (Data in later stages of settling may be used to refine settling computational submodels).

(c) To determine particle settling velocity (U_s):

1. Hold the simulant in a constant temperature bath to achieve constant temperature.
2. Place well-mixed slurry in an empty graduated container that has been marked with regular graduations indicating volume.
3. Observe and record the level of the solid-liquid interface at regular intervals.
4. Measure the vertical distance between the regular volume graduations to obtain the conversion between height and volume.
5. Convert the volume data to height data.
6. Differentiate the height data with respect to time to obtain the settling velocity.

that produce a visible interface. The total uncertainty in measuring the settling velocity of the interface during an individual period will be dominated by the operator's ability to determine the location of the interface, and could be approximately $\pm 10\%$.

Method 2^(a) will be used as the standard method for data analysis if

The equation for the mean settling velocity between any two volume records, referred to with subscripts 1 and 2, is

$$U_s = (\Delta H / \Delta V) (V_2 - V_1) / (t_2 - t_1) \quad (2.4a)$$

where $\Delta H / \Delta V$ = scale factor determined by measuring the relationship between height and volume for the container
 V = volume
 t = time at which measurement is taken.

An estimate of the accuracy of each velocity measurement can be determined using differential error analysis

$$\begin{aligned} \{\delta U_s / U_s\}^2 = & \{\delta(\Delta H / \Delta V) / (\Delta H / \Delta V)\}^2 + \{\delta(V_2 - V_1) / (V_2 - V_1)\}^2 \\ & + \{\delta(t_2 - t_1) / (t_2 - t_1)\}^2 \end{aligned} \quad (2.4b)$$

(a) The calculated settling velocity can be determined from a published relationship between the particle drag coefficient (C_d)

$$C_d = 8 F / (\rho_f U_r^2 \pi d_p^2) \quad (2.4c)$$

and the particle Reynolds number (Re)

$$Re_p = \rho_f U_r d_p / \mu \quad (2.4d)$$

where F = force exerted on the particle
 ρ_f = density of the supernatant
 U_r = relative velocity between the particle and the supernatant
 d_p = particle diameter
 μ = viscosity of the fluid in which the particle is settling.

White (1974) provides Equation (2.4e) to evaluate the drag on a spherical particle as a function of particle Reynolds number

$$C_d = 24 / Re_p \{1 + 6 / [1 + \sqrt{Re_p}] + 0.4\} \quad (2.4e)$$

the slurry mixture formulation does not produce a visible interface during settling and will also be used to estimate the settling velocity on the basis of the measured particle size prior to simulant formulation. This is necessary to ensure the target settling velocities are achieved.

which is accurate to within $\pm 10\%$ for $Re_p < 2.5 \times 10^5$. Particle Reynolds numbers greater than 10 are not anticipated in this experiment.

The exact form of the drag correlation is expected to be a function of particle shape. In these simulants it is anticipated that the particles will be spherical, rather than needle-shaped or lenticular, with the major deviation from sphericity from rough or irregular surfaces. This correlation for spherical particles is the best available correlation for these type particles; the drag relation described in Equation (2.6c) will be used to approximate the mean particle settling velocity.

The unhindered settling velocity (U_s) is used to characterize the slurry; this velocity describes the settling rate of an individual particle in the slurry and does not account for the effects of concentration on the particle settling. The unhindered settling velocity can be obtained by assuming that the force exerted by gravity acts on the particle and then by evaluating the particle drag relation Equation (2.4e) iteratively to obtain the particle Reynolds number. The fluid velocity is zero during settling; therefore, the relative velocity (U_r) is equal to the unhindered settling velocity (U_s). The force exerted on spherical particles suspended in a liquid can be written as

$$F = (\rho_s - \rho_f) \pi d_p^3 g / 6 \quad (2.4f)$$

The drag correlation [Equation (2.4e)] may be written in a more convenient form that reduces the amount of iteration required to obtain the particle settling velocity.

$$C_d Re_p^2 = 24 Re_p \{1 + 6/[1 + \sqrt{Re_p}]\} + 0.4 \quad (2.4g)$$

where $C_d Re_p^2 = (\rho_s - \rho_f) / \rho_s (\rho_s^2 d_p^3 g / 6 \mu) \quad (2.4h)$

1. Calculate the magnitude of $C_d Re_p^2$ directly from measured quantities [Equation 2.4h].
2. Determine the particle Reynolds number iteratively by estimating a Reynolds number and evaluating Equation (2.4g), until the correct value of $C_d Re_p^2$ is replicated to within $\pm 0.01\%$.
3. Obtain the settling velocity using Equation (2.4d). The settling velocity of the particles in the uniform mixture is desired; therefore, the fluid viscosity and density will be assumed equal to the properties of the homogeneous simulant mixture.

2.3 PREPARATION OF 1/12-SCALE SIMULANT

Each simulant will be used to conduct two experiments. Experiments using the same simulants will be conducted consecutively. Consequently four experiments will begin with simulant preparation; four will re-use simulants prepared for the previous test.

2.3.1 Physical Property Verification

Prior to initiating preparation of each simulant, constituent physical properties will be analyzed to ensure that the target properties can be replicated.

1. Obtain five particulate **samples**^(a) of sufficient size (~1 l) to complete steps 2, 3, and 4 based on these samples.
2. As described in Section 2.2.3, measure the particle size distribution of a sample from each of the five separate batches of dry solids to determine that the distribution matches the particle size distribution of simulants developed at laboratory scale. The mean diameter of the particle size distribution should match that of the **recipe**^(b) within 25%.
3. Reformulate one simulant for each batch at laboratory scale.^(c)
4. As described in Section 2.2.2, measure the kinematic viscosity of each of these batches at the average temperature at which the experiments will be conducted. The viscosity should match that of the recipe within 25%.

(a) After completion of experiments using the first simulant, the need for five samples will be evaluated and reduced to three **if** viscosity measurements fall within **+5%** of the recipe.

(b) The recipes will be determined during simulant development.

(c) Materials for these batches should be made with dry solids obtained from different regions in the source batch of dry solids.

2.3.2 Simulant Manufacture and Characterization

It is essential that tests be performed with simulants that have achieved the target properties defined in Table 2.1.^(a) This requires that sufficient time be provided to perform required analyses; complete characterization of the simulant properties is expected to take at least 24 hours.

1. Prepare and blend simulant in the make-up tank according to the simulant recipe.^(b)
2. Transfer the simulant to either the 1/12-scale tank or the holding tank^{(c),(d)} and continue mixing. For the second experiment conducted with this simulant, rehomogenize the simulant in either the holding tank or the 1/12-scale tank.
3. Remove samples from either the 1/12-scale tank or the holding tank after blending, and after rehomogenization. Characterize the samples to determine

(a) It is anticipated that the recipes will vary slightly from the properties listed in Table 2.1 because the particulate and its density have not been chosen. The actual properties will be used to produce an updated table.

(b) The make-up tank capacity is 0.7 m³. To produce each simulant, 2.2 m³ of simulant are required; therefore, the simulant will be manufactured in approximately four batches.

(c) The holding tank, equipped with a mechanical agitator, is used to combine the four batches of simulant prior to insertion into the 1/12-scale tank. No measurements of simulant properties, while the simulant is in the holding tank, are required, nor is the simulant residence time in the holding tank critical to the experiment.

(d) The mechanical agitator's ability to maintain the simulant in a mixed condition will be evaluated during the initial simulant manufacture. 'If the agitator is not adequate, either an additional agitator will be added or the mixture will be transferred directly to the 1/12-scale tank from the make-up tank.

a) simulant kinematic viscosity as a function of temperature(a),(b)

(a) The number of viscosity measurements performed at each temperature will be sufficient to ensure that the viscosity of the 1/12-scale formulation is known within +1% at each temperature measured with a confidence of 95%. The repeatability of measurements performed using an individual capillary viscometer is estimated to be $\pm 0.2\%$. At least two measurements will be performed at each temperature. To describe the kinematic viscosity (ν) of the 1/12-scale simulant as a function of temperature, the data will be fit to a curve. The curve fit selected must fit the data sufficiently well to ensure that the following relation holds:

$$(1/N_m \sum [\nu_i - \nu_p(T_i)]^2)^{0.5} \leq 0.02 \quad (2.4)$$

where ν_i = mean kinematic viscosity based on replicate samples at T_i
 T_i = i th temperature at which kinematic viscosity is measured
 N_m = number of temperatures at which viscosity is measured
 $\nu_p(T_i)$ = kinematic viscosity predicted using curve fit evaluated at temperatures T_i .

(b) To describe kinematic viscosity (ν) as a function of temperature, Cannon Instrument Company (State College, Pennsylvania) and ASTM d-341-89 (ASTM 1989) recommend using an equation of the form

$$\ln(\ln Z) = b_0 + b_1 \log(T) \quad (2.4a)$$

$$\text{where } Z = \nu + 0.7 + \exp(-1.47 - 1.84 \nu - 0.51 \nu^2) \quad (2.4b)$$

Coefficients b_0 and b_1 are determined by fitting the Equation (2.4a) to measured values of the kinematic viscosity (ν in cSt) and the absolute temperature (T in K); Z has no units. Once coefficients b_0 and b_1 are obtained, the function Z may be determined for each temperature. The kinematic viscosity can then be determined using

$$\begin{aligned} \nu = & (Z - 0.7) - \exp[-0.7487 - 3.295(Z - 0.7) \\ & + 0.6119(Z - 0.7)^2 - 0.3193(Z + 0.7)^3] \end{aligned} \quad (2.4c)$$

A simple polynomial curve fit

$$\nu = A + B T + C T^2 \quad (2.4d)$$

will also be considered. The final form selected will depend on the degree of agreement between the selected form and the data; preference will be given to forms with few curve fit parameters. It is anticipated that the ASTM standard form or the quadratic fit will describe the variation of kinematic viscosity

- b) settling velocity of the solid-liquid interface (Section 2.2.4)
- c) mean diameter of the solids in the simulant (Section 2.2.3).

The properties will be compared to the target properties listed in Table 2.1 to determine if they fall in the appropriate range. If the simulant properties do not fall within the appropriate range, steps will be taken to modify the simulant to achieve the required simulant properties.

2.3.3 Simulant Transfer to 1/12-Scale Tank

After verification of the simulant properties, the simulant will be transferred from the **holding tank** to the **1/12-scale** test tank to a height of approximately 0.76 m (30 in.). The holding tank mixer and the jet mixer pumps will be operated at full speed during the transfer to minimize settling during transfer.

2.3.4 Simulant Transfer from 1/12-Scale Tank

At the completion of each test, the jet nozzle velocity will be turned to full power $>100\% U_0 D_0$ to rehomogenize the slurry prior; the slurry will be mixed for 1 hr at full speed. After remixing, the decision can be made whether to return simulant to the holding tank or to continue mixing in the **1/12-scale** tank; this decision will be based on the timing for the next test. If the simulant is returned to the holding tank, the simulant will be remixed prior to transfer back to the **1/12-scale** tank. After the simulant has been mixed, samples will be removed and characterized as specified in Section 2.3.2, Step 3. The properties of the simulant should not change during the test period. Any changes in the simulant properties that cause the properties to fall outside of the target range will be reported and corrective action determined, if appropriate.

with temperature to within $\pm 2\%$ over the narrow range tested.

3.0 SCOPING EXPERIMENTS

Operating conditions for the eight tests, the experimental system, the experimental procedure developed to conduct these tests, and the data acquisition modes and instrumentation are described in this section.

3.1 OPERATING CONDITIONS

Operating conditions for these experiments are chosen to produce the desired nondimensional Reynolds numbers, Froude numbers, and gravitational settling parameters required to model uniformity at 1/12 scale. These nondimensional numbers are chosen based on simulant physical properties defined in Table 2.1 and mixer pump operating conditions of fluid depth (H), jet nozzle exit velocity (U_j) and mixing pump oscillation rate (R). The simulant physical properties were discussed in Section 2.1 and defined in Table 2.1. Mixer pump operation is defined by the pump oscillation rate (R), which is not varied during these experiments, and mixer pump volumetric flow rate (Q). The nozzle diameter is geometrically sized to 1/12 scale thereby defining the nozzle exit velocity (U_j) based on volumetric flow rate (Q) that supplies the two opposed mixer pump nozzles. The mixer pump operating conditions and target Reynolds numbers, Froude numbers, and gravitational settling parameters for these eight tests are summarized in Table 3.1. In the experiments the actual values of the dimensionless parameters will vary slightly as a result of variations in the simulant physical properties.

3.2 1/12-SCALE TEST SYSTEM

These experiments will be conducted in a 1/12-scale system for testing double-shell tank retrieval technologies installed in the 336 Building in the 300 Area of the Hanford site. The system includes a 1/12-scale model of a Hanford DST, simulated 1/12-scale mixer pumps, simulant preparation equipment, and instrumentation. The system flow diagram is shown in Figure 3.1.

TABLE 3.1 Target Operating Conditions for the Eight Scoping Tests

Test Number	Simulant (a)	Nozzle Exit Velocity m/s, $\pm 5\%$	Mixer Pump Flow Rate m ³ /s, $\pm 5\%$	Reynolds Number (b)	Froude Number (c)	Gravitational Settling Parameter (d)	Settling Time Hours	Nozzle Oscillation Rate, rpm
S-1	1	5.2	1.3×10^{-3}	4.1×10^4	3.58	1.9×10^{-2}	24.9	0.346
S-2	1	1.3	3.3×10^{-4}	1.0×10^4	0.22	1.2×10^{-1}	24.9	0.346
S-3	2	5.2	1.3×10^{-3}	4.1×10^4	3.58	3.0×10^{-2}	1.6	0.346
S-4	2	1.3	3.3×10^{-4}	1.0×10^4	0.22	1.9	1.6	0.346
S-5	3	5.2	1.3×10^{-3}	2.4×10^4	3.58	1.1×10^{-3}	42.3	0.346
S-6	3	1.3	3.3×10^{-4}	6.0×10^3	0.22	7.0×10^{-2}	42.3	0.346
S-7	4	5.2	1.3×10^{-3}	2.4×10^4	3.58	1.7×10^{-2}	2.6	0.346
S-8	4	1.3	3.3×10^{-4}	6.0×10^3	0.22	1.1	2.6	0.346

(a) Simulant properties are defined in Table 2.1. These target properties can be obtained at any constant temperature, either ambient or elevated; temperature control within ± 6 C is estimated to be adequate to maintain physical properties within the appropriate range.

(b) Flow rate to mixer pump required to operate two nozzles.

(c) The Reynolds numbers, Froude numbers, and gravitational settling parameters are target values, and are approximate. The actual values will depend on the simulant properties and the nozzle flow rate achieved during testing.

(d) The gravitational settling parameter is defined as the ratio of the rate at which the gravitational field does work to draw particles down to the lower regions of the tank to the power supplied by the jet to suspend particulate.

3.2.1 1/12-Scale DST Model Tank

Dimensions of the **1/12-scale** tank are listed in Table 3.2. The **1/12-scale** tank models the major internal dimensions of a Hanford 3785-m³ (1-million-gal) DST. The tank knuckle, which is the corner radius connecting the tank wall and floor, will not be modeled during the **1/12-scale** tests. The absence of the knuckle is not anticipated to impact these experiments because of its small size and limited influence on flow patterns. The tank knuckle will be modeled during the **1/4-scale** defining experiments^(a) that are planned to follow the **1/12-scale** experiments. The tank is made of 304L stainless steel and can be configured to represent actual locations of the

(a) Refer to steps 9d, 10a, and 11c, listed in Figure 1.1.

FIGURE 3.1 Flow Diagram for 1/12-Scale System

TABLE 3.2 1/12-Scale Model Configuration

<u>Tank Geometry</u>	<u>Prototype</u>		<u>Model</u>	
Diameter	23 m	75 ft	1.9 m	75 in.
Knuckle radius	0.30 m	1 ft	not modeled	
Fluid depth	9.1 m	30 ft	0.76 m	30 in.
<u>Mixer Pump Dimensions</u>				
Nozzle diameter	0.15 m	0.5 ft	0.013 m	0.50 in.
Tank wall to pump vertical centerline	11.4 m	37.5 ft	0.95 m	37.5 in.
Tank bottom to nozzle centerline	0.46 m	1.5 ft	0.038 m	1.5 in.
Pump centerline to nozzle discharge	0.44 m	17.5 in.	0.037 m	1.5 in.
Tank floor to pump intake	0.15 m	0.5 ft	0.013 m	0.50 in.
Discharge angle from vertical	90° +3, -0		90° +3, -0	
<u>Jet Properties</u>				
100% U_0 jet velocity	5.46 m/s	58.8 ft/s	5.28 m/s	17.04 ft/s
Nozzle exit parameter				
100% $U_0 D_0$ condition	2.73 m ² /s	29.4 ft ² /s	0.066 m ² /s	0.71 ft ² /s
25% $U_0 D_0$ condition	0.683 m ² /s	7.35 ft ² /s	0.017 m ² /s	0.18 ft ² /s
Pump oscillation	0.1 rpm		0.346 rpm	
Pump angle of oscillation	180°		180°	

tank penetrations and internal components.^(a) No tank internal components will be modeled during these scoping experiments.

3.2.2 Simulated Jet Mixer Pump

The 1/12-scale mixer pump design shown in Figure 3.2 models operation of the proposed full-scale jet mixer pump. A Moyno^(b) progressive cavity pump

(a) Tank internal components include steam coils, air lift circulators, radiation dry wells, thermocouple trees, and other hardware.

(b) Robins & Myers, Inc., Springfield, Ohio.

FIGURE 3.2 1/12-Scale Slurry Mixer Pump Configuration

draws simulant up the inside tube of the pump model and through the **Moyno®** pump. The simulant then discharges through the mixing pump **annulus**, out two diametrically-opposed nozzles. The **1/12-scale** nozzle, with **diameter D_0** , is designed to simulate the nozzle in the prototype pump.^(a) During these **1/12-scale** scoping experiments one mixing pump located at the tank center will oscillate through a **180°** arc at 0.346 rpm. Scaled mixing pump dimensions, location, and operating conditions are summarized in Table 3.2.

3.2.3 Ancillary Equipment

Simulant preparation equipment includes make-up and holding tanks and a transfer pump. The make-up tank is a 0.684 m² (180 gal) carbon steel tank [0.762-m (30-in.) diameter by 1.5-m (5-ft) high] equipped with an agitator. Three load cells, one under each support leg, are accurate to **±0.5 kg (±1.1 lbm)**. The tank is used for slurry preparation and for slurry transfers.

The holding tank is a 2.135 m² (564 gal) carbon steel tank [1.22-m (4-ft) diameter by 1.8-m (6-ft) high]. The holding-tank piping is routed to allow transfer of slurry to or from either the make-up tank or the **1/12-scale** tank, or to drain.

The transfer pump is used for transferring slurry to or from any of the tanks, circulating slurry within the tanks, draining the tanks, and flushing the piping. The transfer pump is a centrifugal pump driven by a 1490 W (2 hp), single-phase, 230-V motor with a mechanical shaft seal. The pump has a capacity of 0.00317 m³/s (50 gpm) at 15 m (50 ft) of head.

3.3 TEST PROCEDURE

Each **1/12-scale** test involves three basic steps: 1) preparing and characterizing the simulant (described in Section 2.0), 2) obtaining the desired operating conditions inside the tank (listed in Table 3.1), and 3)

(a) **WIC** approval of nozzle design is required prior to start of testing.

conducting the test. Prior to the start of each test, instrumentation will be checked and initial conditions verified and recorded.

3.3.1 Test Period Definition

Each test is composed of three operating periods governed by the concentration distribution throughout the 1/12-scale tank.

Period 1: completely mixed tank with uniform concentration profile throughout the tank, obtained by high flow rate $\geq 100\% U_0 D_0$

Period 2: concentration profile changing because of solids settling caused by reduced mixer pump flow rate

Period 3: steady-state concentration profile at the reduced flow rate.

The concentration distribution throughout each of these periods must be recorded and monitored to ensure that the experiment is conducted correctly and that valid results are obtained.

During Period 1, the mixer pump will be operated at its highest flow rate, $\geq 100\% U_0 D_0$. Concentration will be monitored to ensure that the tank is completely mixed.

During Period 2, the mixer pump will be set to the operating conditions defined in Table 3.1. With constant mixer pump operation, steady-state concentration conditions will be achieved. The settling time to reach steady state will be assumed to be 110% of the settling time listed in Table 3.1. The settling time is defined as the length of time required for a particle of mean diameter (d_p) and density (ρ_p) to settle from the top of the tank to the bottom of the tank. Concentration will be monitored to determine that the tank has reached steady-state concentration.

During Period 3, the tank contents will have attained a steady-state concentration distribution. Measurements will be made to determine the concentration distribution throughout the tank. The measurements will be sufficient to determine whether the tank concentration is uniform within $\pm 10\%$

of the mean concentration and be statistically significant to within a 95% confidence interval.

3.3.2 Period 1 Operation

During Period 1, the simulant in the tank should be fully mixed. To ensure this condition, the mixer pumps will be operated at $\geq 100\%$ flow rate for 1 hour. During this period, the concentration distribution throughout the tank will be monitored using ultrasonic probes and static pressure taps. If the average measurements are stable within $\pm 5\%$, the mixing pump flow rate will be reduced to that required for the specific test, as listed in Table 3.1.

3.3.3 Period 2 Operation

At the start of Period 2, the flow rate will be reduced to the test flow rate; therefore, the concentration will be changing because of particle settling. Three criteria have been developed to assess when steady-state concentration has been attained.

1. The time plus 10% (110%) required for a particle of mean diameter (d) in a simulant with bulk density (ρ) to settle from the top to the bottom of the tank has passed.
2. The rate of change of the concentration as measured by each ultrasonic sampler has fallen to less than 5% of the root mean square (rms) of the rate of change detected by all ultrasonic samplers at the beginning of operation of Period 2.
3. The rate of change of the pressure readings at any individual sensor has fallen to less than 5% of the rms of the initial pressure rate of change readings of Period 2.

Criterion 1 will not be relaxed under any circumstance. The approximate time required for a particle traveling with its unhindered settling velocity to fall from the top of the tank to the bottom for each test is provided in the Table 3.1. The exact settling velocity will depend on the particle size and viscosity achieved; therefore, the target time for achieving steady state will be modified after the simulant development task.

After Criterion 1 has been satisfied, a method is required to confirm that the tank contents have reached a steady-state distribution. Two methods of interpreting the convergence to a steady-state distribution are presented as Criteria 2 and 3. The methods rely on changes in the slurry concentration as reported by the ultrasonic concentration meters and changes in the hydrostatic pressure in the tank. If either Criterion 2 or 3 is satisfied, then the experiment can proceed to Period 3.

The average rate of change in the concentration at the detector over any time interval will be calculated

$$d\langle C \rangle / dt_i = (\langle C \rangle_{i,1} - \langle C \rangle_{i,2}) / (t_1 - t_2) \quad (3.1)$$

where

$d\langle C \rangle / dt_i$ = rate of change in mean cycle average concentration at ith detector

t_1 = time at beginning of interval

t_2 = time at end of the interval

$\langle C \rangle_{i,1}$ = mean cycle average^(a) concentrations at ith detector at time t_1

$\langle C \rangle_{i,2}$ = mean cycle average concentrations at ith detector at time t_2 .

Likewise the average rate of change in the hydrostatic pressure at any pressure sensor during any time interval at the ith pressure transducer can be calculated

$$d\langle P \rangle / dt_i = (\langle P \rangle_{i,1} - \langle P \rangle_{i,2}) / (t_1 - t_2) \quad (3.2)$$

where

(a) Mean cycle average will be calculated as the average of measurements taken every 10 s over a period of five nozzle oscillation cycles, a period of 14.45 min.

$d\langle P \rangle / dt_i$ = mean cycle average rate of change in pressure transducer

$\langle P \rangle_{i,1}$ = mean cycle average pressure measured at i th detector at time t_1

$\langle P \rangle_{i,2}$ = mean cycle average pressure measured at i th detector at time t_2

The rate of change in the pressure and concentration will be determined for every detector. Measurements will be taken every **10 s** and averaged over five nozzle oscillation cycles, a period of **14.45 min**. In general, near the tank top and bottom, the magnitude of the rate of change in both the concentration and the pressure quantity is expected to exhibit its maximum value at the beginning of testing during Period 2. At the top of the tank, the concentration will fall with time; at the bottom, **it** will rise with time. At steady state, during Period 3, the rate of change is expected to display only cyclic variations. These cyclic variations will be eliminated by averaging the signal. The rms of the rate of change at any time for concentration and pressure can be calculated according to

$$d\langle C \rangle / dt_{rms} = 1/N_d \sum_{i=1}^{N_d} (d\langle C \rangle / dt_i)^2 \quad (3.3)$$

where

N_d = number of ultrasonic sensors, which will be three.

$$d\langle P \rangle / dt_{rms} = 1/N_t \sum_{i=1}^{N_t} (d\langle P \rangle / dt_i)^2 \quad (3.4)$$

where

N_t = number of pressure transducers, which will be five.

Both quantities will be initialized using the data measurements taken during Period 1. The calculated values will be referred to as dC/dt_{initial} and dP/dt_{initial} .

During Period 2, the value of dC/dt_i measured at every ultrasound detector at a given time will be compared to dC/dt_{initial} . A lower limit (noise level) below which the rate of change in the concentration cannot be determined (dC/dt_{limit}) will also be determined; it is not currently known what this lower limit will be, particularly in comparison with the rate of change in solids concentrations. These lower limits can be determined via a statistical T-test to determine whether two samples differ significantly.

Steady state will be considered to have been reached when every measurement exhibits a rate of change that is either less than the lower limit, or less than +5% of the initial rate of change. That is when

$$|dC/dt_i| < \text{Max}(0.05 dC/dt_{\text{initial}}, dC/dt_{\text{limit}}) \quad (3.5)$$

where

dC/dt_{initial} = mean value calculated during Period 1

dC/dt_{limit} = minimum detectable change caused by noise in the concentration sensors.

is true for every detector.

A similar procedure will be applied to test convergence using the pressure transducers. The mathematical criterion for pressure transducer convergence is

$$|dP/dt_i| < \text{Max}(0.05 dP/dt_{\text{initial}}, dP/dt_{\text{limit}}) \quad (3.6)$$

where

dP/dt_{initial} = mean value calculated during Period 1

$d\langle P \rangle / dt_{\text{limit}}$ = minimum detectable change caused by noise in the pressure transducers.

Neither the pressure nor the concentration data will be useful if the cut off is the result of noise. If the noise level is reached, the minimum time of operation will be defined by Criterion 1.

3.3.4 Period 3 Operation

Once the criterion for steady state has been reached, testing will enter Period 3. During Period 3, detailed ultrasonic and batch measurements will be taken to characterize the concentration at steady state. These methods are described in Sections 3.4 and 3.5.

3.4 DATA ACQUISITION

The data acquisition system will acquire data in two modes: Mode 1 - monitoring mean quantities averaged over five mixer pump nozzle oscillation cycles and Mode 2 - monitoring cyclic quantities measured every 10 s over five cycles.

During the Periods 1 and 2, the data acquisition system will be operated in Mode 1. The mean data acquired in Mode 1 will be used to confirm uniformity during Period 1 and monitor the progress of settling to determine when steady-state settling has been achieved during Period 2. During Period 3, the data acquisition system will cycle between Mode 1 and Mode 2 operation. The data acquired during Mode 2 will be used to characterize the uniformity of the tank contents after steady state has been achieved.

The data acquisition system will operate in Mode 1 for five mixing pump oscillation cycles (14.45 min); the system will then switch to Mode 2 and operate for five cycles (14.45 min). The pattern will be repeated until the completion of Period 3. Relationships between periods and data acquisition modes are illustrated in Figure 3.3.

Period 1	Period 2	Period 3
Operate mixing pump at maximum speed to ensure uniformity	Tank contents are settling	Tank contents settled to steady-state concentration distribution
$\geq 100\%$ UoDo	25% or 100% UoDo	25% or 100% UoDo Steady-state concentration Begin syringe samples
Monitor to verify tank uniformity	Monitor to detect steady state	Monitor to detect instantaneous measurements
Time in period 1 hr	Time in period as per Criteria 1 Section 3.3	Time in period 2 to 5 hr
Mode 1	Mode 1	Mode alternates between 1 and 2

FIGURE 3.3 Data Acquisition

3.4.1 Mode 1

The quantities that will be monitored and recorded during Mode 1 are

1. Elapsed time (t)
2. Mean cycle average flow rate to dual nozzles $\overline{\langle Q \rangle}_{\text{cycle}}^{(a)}$
3. Mean cycle average tank temperature at 12 locations $\overline{\langle T \rangle}_{\text{cycle}}$
4. Mean cycle average hydrostatic pressure at 5 locations $\overline{\langle P \rangle}_{\text{cycle}}$
5. Mean cycle average concentration at 3 ultrasonic sensor locations $\overline{\langle C \rangle}_{\text{cycle}}$

Mean cycle average is defined over a five cycle period; during this period, quantities will be sampled every 10 s using the data acquisition

(a) The jet nozzle exit velocity per nozzle can be calculated from this flow rate.

system and averaged over five mixing pump oscillation cycles (14.45 min) with each average consisting of approximately 87 measurements. The five-cycle running average will be recorded by the data acquisition system approximately every 5 min. The data acquisition system will operate in Mode 1 during Periods 1 and 2 until steady state has been achieved.

3.4.2 Mode 2

The quantities that will be monitored and recorded during Mode 2 are

1. Elapsed time (t)
2. Nozzle angular location (θ)
3. Instantaneous tank temperature at 12 locations (T)
4. Instantaneous hydrostatic pressure at five locations (P)
5. Instantaneous concentration at three ultrasonic sensor locations (C)
6. Dynamic velocity pressure at five elevations along the wall.

The sample interval during Mode 2 will be every 10 s. In addition, simulant concentration will be measured manually at 12 locations using syringe samplers.

Syringe samplers will be operated manually, external to the automatic data acquisition system. Each set of syringe samples will be taken after the data acquisition system has operated in Mode 2 for approximately 5 min. Repeated sets of syringe samples will be taken during Mode 2 intervals until five sets have been obtained.") It is acceptable if the time interval between syringe sample sets is slightly more than 10 min. No attempt will be

(a) The syringe sample concentration data **evaluation** is time consuming. The syringe sample concentration data taken during the first test will be evaluated after the first test is complete to determine whether an adequate number of samples were taken. Based on this analysis, the required number of samples for the tests will be specified; if required, the first test will be repeated.

made to coordinate syringe sample filling with jet mixer pump angular location. The solids concentration of each syringe sample will be analyzed.

3.5 INSTRUMENTATION

The test system will be instrumented to measure the flow rate through dual jet mixing pump (Q), nozzle angular location (θ), the tank temperature (T), real time and discrete concentration measurements, hydrostatic pressure, and the jet velocity along the tank wall.

3.5.1 Mixing Pump Flow Rate

An existing magnetic flowmeter^(a) is installed on the external flow line to measure the mixer pump total flow rate with an accuracy of $\pm 1\%$ of full scale. The flow rate will be sampled every 10 s.

3.5.2 Jet Nozzle Exit Velocity

Each 1/12-scale mixer pump model contains two 1.27-cm-diameter (0.5-in.) nozzles. The flow rate (Q) to the nozzle pair will be measured and used to calculate the nozzle exit velocity for each nozzle. The piping is designed to ensure that the flow is split equally between the two nozzles. This will be confirmed experimentally prior to testing. The signal from the flowmeter will be processed to provide nozzle exit velocity in two forms: mean velocity averaged over five cycles (14.45 min based on readings every 10 s) (U_m) and instantaneous velocity measured every 10 s (U_{oi}). Based on the accuracy in flow rate and nozzle diameter, the accuracy in the nozzle exit velocity is estimated to be $\pm 1\%$.

3.5.3 Mixer Pump Angular Location

The mixer pump will be indexed to provide a reading of angular location (θ) as a function of time. Angular position will be recorded every 10 s.

(a) Krohne American, Peabody, Massachusetts.

3.5.4 Temperature

Twelve thermocouples will be mounted to measure temperatures at three elevations and four radial positions in the tank, as listed in Table 3.3. The mean temperature will be monitored by averaging the signals taken every 10 s over 14.45 min, which will smooth fluctuations over five nozzle revolutions. The average simulant temperature (T_{ave}) will be calculated. Temperature variations in the tank will be monitored. Two factors will contribute to the uncertainty in measurements of the tank temperature: uncertainty in individual temperature measurement and spatial temperature in the tank. The standard error for a calibrated thermocouple is $\pm 0.5^{\circ}\text{C}$; the standard error in the measured tank average temperature caused by imprecision in the 12 thermocouples would be reduced by a factor of $1/12^{0.5}$, and is approximately 0.15°C . If it is assumed that the tank temperature varies spatially by no more than $\pm 2^{\circ}\text{C}$, imprecision in the mean measurement caused by tank variations is expected to be less than 0.6°C .

Uncertainty in the simulant temperature translates to uncertainty in slurry viscosity. The adequacy of uncertainty in temperature will be reevaluated after simulant development efforts are complete and the effect of temperature on the viscosity of the simulant has been quantified.

3.5.5 Concentration

The solids concentration will be measured using three methods: 1) syringe samplers to measure average concentration, 2) ultrasonic measurements to measure real time concentration, and 3) hydrostatic pressure measurements to track pressure variation at the wall induced by particle settling. The concentration sampler locations are listed in Table 3.3. Both ultrasonic measurements and hydrostatic pressure measurements will be performed in real time during Periods 1, 2, and 3. The syringe samplers are batch measurements and will be taken only during Period 3, when the tank concentration has reached steady state. The ultrasonic concentration measurements and the

TABLE 3.3 Location of Instrumentation

<u>Sensor Type</u>	<u>Identification</u>	<u>Height. in.</u> <u>±1 in. (2.5 cm)</u>	<u>Radius. in.</u> <u>±2 in. (5 cm)</u>	<u>Angle, degrees</u> <u>±5 degrees</u>
Thermocouple	TOL	7.5	0	0
	TOM	15.0	0	0
	TOH	22.5	0	0
	T1L	7.5	18	0
	T1M	15.0	18	0
	T1H	22.5	18	0
	T2L	7.5	28	90
	T2M	15.0	28	90
	T2H	22.5	28	90
	T3L	7.5	37.5	180
	T3M	15.0	37.5	180
	T3H	22.5	37.5	180
Syringe	B1L	7.5	28	0
	B1M	15.0	28	0
	B1H	22.5	28	0
	B2L	7.5	28	90
	B2M	15.0	28	90
	B2H	22.5	28	90
	B3L	7.5	18	180
	B3M	15.0	18	180
	B3H	22.5	18	180
	B4L	7.5	18	270
	B4M	15.0	18	270
	B4H	22.5	18	270
Ultrasonic probe	U1L set 1	7.5	18	0
	U1M set 1	15.0	18	0
	U1H set 1	22.5	18	0
	U2L set 2	7.5	18	90
	U2M set 2	15.0	18	90
	U2H set 2	22.5	18	90
	U3L set 3	7.5	28	180
	U3M set 3	15.0	28	180
	U3H set 3	22.5	28	180
	U4L set 4	7.5	28	270
	U4M set 4	15.0	28	270
	U4H set 4	22.5	28	270
Static pressure	P1	5	37.5	0
	P2	10	37.5	0
	P3	15	37.5	0
	P4	20	37.5	0
	P5	25	37.5	0
Dynamic pressure	D1	5	35	0
	D2	10	35	0
	D3	15	35	0
	D4	20	35	0
	D5	25	35	0

pressure measurements will be collected using the automatic data acquisition system.

3.5.5.1 Syringe Samplers. A single syringe sample carriage that can be manually filled will be used to obtain the batch samples. This technique was

used successfully during experiments conducted in 1992 (Fort et al. 1993). The accuracy of using syringe samples to measure the local average concentration at a syringe sample location depends on 1) the degree to which the syringe samplers disturb the concentration distribution, 2) the accuracy with which the concentration of solids in a syringe can be measured, and 3) the number of syringe samples taken. The disturbance caused by the presence of the syringes can be minimized by using small syringes. Peterson, McCarthy, and Muhlstein (1986) reported that the standard deviation in the concentration measured using related bottle samples located at one location is approximately ± 0.9 wt% solids. Five sets of syringe samples will be required to detect differences of ± 2 wt% concentration at two locations within a confidence level of 95%.

3.5.5.2 Ultrasonic Concentration Measurement. Ultrasonic measurements will be made using an ultrasonic concentration measurement system that is currently being developed. A single probe based on this principle was demonstrated successfully in 1992 (Fort et al. 1993). The device will provide voltage signals that are proportional to the concentration of slurry over a specified measurement distance. A calibration for voltage and concentration will be determined prior to commencement of testing. The probe consists of three transmitter receiver pairs; the pairs will be sampled simultaneously to measure concentration at three fixed elevations at one tank location. Four tank locations, listed in Table 3.3, will be monitored sequentially during Period 3. The probe signal will be monitored to allow the concentration to reequilibrate after the probe has been repositioned.

The signal from the ultrasonic concentration meter will be monitored in two forms. The instantaneous concentration will be monitored directly from the instrument every 10 s. The average concentration will be monitored by taking a running average of the instantaneous concentration readings taken over five pump oscillation cycles.

3.5.5.3 Static Pressure Measurements to Detect Solids Settling. The hydrostatic pressure in regions far from the jet is expected to vary with

depth. When the concentration is constant, the pressure will vary linearly; when the contents settle slightly, the pressure will be atmospheric at the top of the tank and will rise with depth. The relative pressure at mid-level of the tank will be less when settling occurs because settling causes the density to drop near the top and rise near the bottom. There are some difficulties associated with determining the relationship between the concentration and the pressure when velocity gradients are present. Nevertheless, the time rate of change of the cycle average pressure as a function of height is expected to approach zero as the steady-state concentration is approached, and this will be used to verify that a steady-state distribution has been approached. The average pressure will be monitored by averaging the pressure over 14.45 min (five cycles). Averaging the signal smooths the cyclic variations and provides a signal that changes only as a result of particle settling. The locations of the transducers are listed in Table 3.3. The expected accuracy in the density determination^(a) is estimated by assuming that the fluid between the two ports will have a density of $1.25 \times 10^3 \text{ kg/m}^3$. It is anticipated that doubling the volume fraction of the mixture from 20% to 40% will result in a change in mixture density on the order of 15% to 20%. Thus

(a) If the pressure varies hydrostatically, the density (ρ) between two transducers can be determined using

$$\rho = (P_2 - P_1)/[g (h_2 - h_1)] \quad (3.6a)$$

where

P = pressure measured at transducers 1 or 2
 h = elevations of transducers 1 or 2
 g = gravitational constant.

The accuracy in the mean density between a transducer and the transducer immediately above it can be determined using the formula

$$\Delta\rho/\rho = (\Delta P_2^2 + \Delta P_1^2)^{0.5}/(P_2 - P_1) \quad (3.6b)$$

where

Δ = uncertainty in a particular measurement.

as concentration increases, the density of the mixture will vary spatially; this will affect the hydrostatic pressure profile. This measurement is useful for detecting on-going settling, but it does not provide good resolution in the determination of density. Consequently, it will only be used to determine the beginning of the steady-state period.

A probe to measure hydrostatic pressure in real time as a function of height will be mounted directly against the tank wall. The location of pressure transducers^(a) and the approximate gage pressure caused by a fluid with a constant density of $1.25 \times 10^3 \text{ kg/m}^3$ are shown in Table 3.4; all pressures will be lower if settling occurs.

TABLE 3.4 Location of Pressure Transducers

(a) Elevation cm (in.)	Expected Pressure kPa (psi)	Transducer Range kPa (psi)	Accuracy		
			% full scale	% measurement	$\Delta\rho/\rho$ %
0 (0)	8.96 (1.3)	13.8 (2.0)	0.25	0.37	(b)
12.7 (5)	7.58 (1.1)	13.8 (2.0)	0.25	0.45	2.5
25.4 (10)	6.14 (0.89)	13.8 (2.0)	0.25	0.56	3.4
38.1 (15)	4.62 (0.67)	6.89 (1.0)	0.25	0.37	3.0
50.8 (20)	3.10 (0.45)	6.89 (1.0)	0.25	0.55	3.0
63.5 (25)	1.52 (0.22)	3.45 (0.5)	0.25	0.56	3.4

(a) Elevation from tank floor.

(b) Reference point for calculation of $\Delta\rho/\rho$ at 12.7-cm elevation.

3.5.6 Mean Concentration

The make-up tank will be used for preparation of simulant and to determine the mean concentration. Four batches of simulant will be prepared to fill the 1/12-scale tank. Mass measurements of solids and total mass will be used to calculate mean concentration. The load cells under each make-up tank leg measure mass to within $\pm 0.5 \text{ kg}$ providing measurement of total mass of the slurry make-up, approximately 850 kg, to within $\pm 0.02\%$. The mean

(a) Sensotech flush-mounted diaphragm pressure transducers, Sensotech, Incorporated, Columbus, Ohio.

concentration of 18% can be determined to within $\pm 0.1\%$. This uncertainty is approximately equal to the uncertainty in determining the mass of the solids added to the slurry liquid.

3.5.7 Jet Velocity Near the Wall

The jet velocity will be detected near the wall using dynamic velocity pressure taps mounted on a probe. The probe will be immersed and placed parallel to the wall several cm from the wall. Jet velocity data will provide information on the jet rise along the tank wall.

3.5.8 Temperature Control

There are currently no provisions for temperature control of the tank contents. Analysis indicates that the mean tank temperature will not rise significantly during operation from pump heat. However, elevated temperatures may be required to achieve the low target mixture viscosities; this need will be confirmed after completion of the simulant development. If elevated temperatures are required, provisions to heat and/or insulate the tank will be implemented.

Temperature control may also be required if the slurry viscosity varies more than $\pm 10\%$ as a result of naturally occurring temperature variations in the 336 Building. This is considered unlikely because the 1/12-scale system is located in a nearly constant ambient temperature zone, below ground level. If required, temperature control can be achieved by insulating the sides and bottom of the 1/12-scale vessel, providing an insulated top cover, and providing a small amount of heat at a controlled rate over the entire surface of the tank.

4.0 EXPERIMENTAL RESULTS

Each of the eight tests will provide data for one point on the Reynolds, Froude, gravitational settling matrix shown in Figure 1.2. The specific data to be obtained for each test and the acceptance criteria for the data are described here.

4.1 RESULTS OF INDIVIDUAL TESTS

The data that must be provided by each individual test consists of concentration data, dynamical data, simulant physical properties, and data to detect steady state. The types of data are summarized.

4.1.1 Concentration Data

1. Mean concentration based on **replicate** syringe samples, $\bar{C}(X)$, at each sample location.
2. Standard deviation of mean concentration for replicate syringe samples, $\sqrt{C'^2(X)}$, at each sample location.
3. Mean cycle^(a) average concentration, $\overline{\langle C \rangle}_{\text{cycle}}(X)$ at each ultrasonic probe location during Period 3.
4. Standard deviation of mean cycle average concentration, $\sqrt{\langle C \rangle'^2}$, at each ultrasonic probe location during Period 2.

The various concentrations are defined as:

Mean concentration based on **replicate** samples $\bar{C}(X)$

$$\bar{C}(X) = 1/N_B \sum C_{Bi}(X) \quad (4.1)$$

(a) A cycle is defined to be one complete oscillation of the pump nozzle; for example, from 0° orientation to 180° returning to 0°.

where

$C_{Bi}(X)$ = concentration of an individual syringe sample taken at the location X

N_B = number of syringe samples taken at location X.

The variance of the concentration of replicate samples

$$\overline{C'^2(X)} = 1/N_B \sum C_{Bi}^2(X) - \bar{C}(X)^2 \quad (4.2)$$

The standard deviation for replicate samples is $\sqrt{\overline{C'^2(X)}}$.

The cycle average concentration at an ultrasonic probe at location X is

$$\langle C \rangle(X) = 1/N_s \sum \langle C \rangle_{ui}(X) \quad (4.3)$$

where

C_{ui} = concentration measured using ultrasonic probe at time t_i

N_s = number of samples taken during a cycle.

The mean cycle average concentration is

$$\overline{\langle C \rangle(X)} = 1/N_c \sum \langle C \rangle(X) \quad (4.4)$$

where

N_c = number of cycles over which the cycle average concentration was measured.

The variance of the cycle average concentration is

$$\overline{\langle C \rangle'^2(X)} = 1/N_c \sum \langle C \rangle^2(X) - \overline{\langle C \rangle^2(X)} \quad (4.5)$$

4.1.2 Dynamic Data

1. Mean nozzle flow rate during Periods 1, 2, and 3.
2. Standard deviation of the nozzle flow rate during Periods 1, 2, and 3.
3. Mixing pump oscillation rate during Period 1, 2, and 3.
4. Jet velocity pressure near wall.

4.1.3 Data Associated with Simulant Properties

1. Mean temperature at the 12 sample locations during Period 3 (T).
2. Detailed kinematic viscosity versus temperature data of simulant prior to transfer to 1/12-scale tank (ν).
3. Density of simulant prior to transfer to 1/12-scale tank (ρ).
4. Concentration of simulant prior to transfer to 1/12-scale tank (C).
5. Kinematic viscosity at one temperature after transfer from 1/12-scale tank to holding tank (ν).
6. Settling velocity of slurry supernate interface (U_s).
7. Mean particle diameter (d_p) .
8. Supernate density (ρ_f).
9. Solids density (ρ_s).

4.1.4 Data Associated with Detection of Steady State

1. Rate of change in pressure at pressure transducers just before declaration of the onset of Period 3.
2. Rate of change in cycle average concentration $\langle C \rangle$, in the period before declaration of onset of Period 3.

4.2 ACCEPTANCE CRITERIA

The acceptance criteria for the data are described here. The first

acceptance criteria is that all data described above be collected. Special criteria for specific measurements are described in detail below.

4.2.1 Concentration Measurement

The accuracy in the determination of the mean concentration will be determined based on the mean concentration measurements obtained using both ultrasound measurement and syringe sample measurements. The mean concentration at every location determined by averaging replicate samples must be measured to within ± 1.8 wt% (10% of 18 wt%) with a confidence of 95%.

It is anticipated that the upper region of the tank cannot have a higher mean solids concentration than the lower region of the tank. Concentration data will be collected at three elevations. The data will not be considered acceptable if the concentration averaged over the four samples located at the mid-level elevations exceeds that measured at the lower four sample locations with a confidence of 95%, or if the concentration averaged over the four upper samples exceeds that measured over the four middle samples with a confidence of 95%.

That is, the data will be rejected if

$$C_{\text{top}} \geq C_{\text{middle}} \text{ with 95\% confidence} \quad (4.7)$$

or

$$C_{\text{middle}} \geq C_{\text{bottom}} \text{ with 95\% confidence.} \quad (4.8)$$

4.2.2 Nozzle Velocity

The mean nozzle velocity must fall within 4×10^{-2} m/s of the target value. This will ensure that the target velocity is achieved to within $\pm 3\%$ of the target value.

4.2.3 Mixer Pump Oscillation Rate

The mixer pump oscillation rate (rpm) must be within 5% of the target value. It is not currently known how a departure from this range will affect the results.

4.2.4 Simulant Properties

The simulant properties at the measured mean test temperatures must fall in the target range described in Table 2.1. The target value for the low viscosity simulant will be finalized during simulant development. Evaluation of this acceptance criterion will require use of temperature versus property data developed during simulant characterization.

The simulant kinematic viscosity at the end of testing must match the simulant kinematic viscosity at the same temperature measured prior to the test to within $\pm 5\%$.

4.2.5 Rate of Change in Pressure and Concentration

The rate of change in pressure and concentration used to determine the onset of Period 3 (steady-state solids distribution) must meet the requirements described in Section 3.3.3.

4.2.6 Minimum Test Time

The minimum settling time plus 10% provided in Table 3.1 must have passed for the measurements taken during Period 3 to be considered valid.

4.3 DATA REVIEW

The data will be reviewed as it is generated. The validity of each test run listed in Table 3.1 will be determined prior to performance of the following test. The review will be performed by a qualified test engineer; this will be either J. A. Bamberger or C. W. Enderlin.

The **specific** times for data reviews are selected to minimize the possibility of collecting data that does not meet the acceptance criteria; the data reviews to be performed are described here.

4.3.1 Simulant Properties

The properties of the simulant in the make-up tank will be determined and reviewed prior to transfer to the **1/12-scale** tank. Tests will not be performed unless the properties meet the acceptance criteria. The simulant kinematic viscosity will be verified immediately after transfer from the **1/12-scale** tank to the holding tank.

4.3.2 Dvynamic Properties

The dynamic quantities collected in Period 2, such as nozzle flow rate and rate of change in pressure and concentration, will be reviewed prior to the decision to begin Period 3. The dynamic quantities collected during Period 3 will be reviewed prior to the decision to end Period 3.

4.3.3 Concentration Data

The concentration data **collected** using the ultrasonic concentration probe will be reviewed prior to the end of Period 3. The concentration data collected using the syringe samples will be reviewed after the concentration analysis is complete. Because the syringe sample concentration data evaluation is time consuming, there is a risk that the acceptance criteria from the data derived from the syringe samples will not be met. This will be minimized by determining the standard deviation for **replicate** syringe samples during performance of the first test. This review will be completed prior to beginning the second test.

4.4 DATA ANALYSIS

Data analysis to determine the effect of the physical parameters on the degree of uniformity achieved in the tank will be performed as the data is

acquired. The types of analyses to be performed are described here. The following quantities will be calculated for each test:

1. magnitude of the gravitational settling parameter
2. magnitude of the Reynolds number
3. magnitude of the Froude number
4. mean simulant concentration at each sample location as measured by both the syringe samples and the ultrasonic concentration probe
5. standard deviation of the simulant concentration at each sample location as measured using both syringe samples and the ultrasonic concentration probe.

The degree of uniformity achieved will be assessed by comparing the mean concentration at each location to the concentration of the tank as a whole. Analysis of variance will be used to determine whether the tank as a whole is uniform or non-uniform.

Models will be developed to predict the difference in concentration at the upper and lower sample location by performing multiple linear regression on the Reynolds number, Froude number, and gravitational settling parameter.

4.4.1 Definition of Dimensionless Numbers

Dimensional analysis of the behavior of Newtonian slurries of equivalent concentration indicates that the concentration inhomogeneity in the geometrically similar tanks may be a function of three dimensionless parameters (Bamberger et al. 1993). These are jet Reynolds number (Re), Froude number (Fr), and gravitational settling parameter (Gs) .

The Reynolds number characterizing the nozzle discharge rate in this experiment will be calculated as

$$Re = U_0 D_0 / \nu \quad (4.9)$$

where

U_0 = jet nozzle discharge velocity calculated from mixer pump volumetric flow rate

D_0 = nozzle diameter

ν = kinematic viscosity of the mixture as a whole.

The Froude number in this experiment is defined as

$$Fr = U_0^2 / g H \quad (4.10)$$

where

g = acceleration due to gravity

H = level of the tank contents.

The gravitational settling parameter is defined as

$$Gs = 2 D_t^2 H (s - 1) C U_s g / s U_0^3 D_0^2 \quad (4.11)$$

where

D = tank diameter

H = tank level

s = ratio of solids to liquid density (ρ_s / ρ)

C = concentration of solids in mixture as a whole (wt%)

U_s = settling velocity

U_0 = nozzle discharge velocity

D_0 = nozzle diameter.

Equation (4.11) is identical to Equation (3.26) in the Strategy Plan (Bamberger et al. 1993), where the relationship between the volume fraction, ϕ_s and the concentration, C , has been substituted to allow evaluation of gravitational settling parameter in terms of quantities measured during these experiments.

4.4.2 Uncertainty in the Experimental Reynolds Number

The uncertainty in the Reynolds number caused by the uncertainty in the measurement of the nozzle velocity, the fluid kinematic viscosity, and the diameter of the nozzle can be shown to be

$$\Delta Re/Re = \{(\Delta U_0/U_0)^2 + (\Delta D_0/D_0)^2 + (\Delta \nu/\nu)^2\}^{0.5} \quad (4.12)$$

The uncertainty in the Reynolds number for each experiment is expected to be dominated by the uncertainty in the value of the kinematic viscosity. The uncertainty in the measurement of the nozzle velocity based on the uncertainty in the volumetric flow rate (Q) is calculated to be $\sim \pm 1\%$ ^(a), and the uncertainty in the measurement of the nozzle diameter is expected to be less than 1 mil or $\pm 0.2\%$. The kinematic viscosity of the fully mixed simulant is expected to be measured to within $\pm 0.5\%$. However, because the kinematic viscosity of the mixture varies as a function of temperature, its magnitude must be evaluated at the tank temperature. It is anticipated that the tank temperature will be known to within $\pm 1^\circ\text{C}$. If the kinematic viscosity of the simulant varies as much as that of water, the uncertainty in the temperature will result in an uncertainty of approximately +2% in the kinematic viscosity. Consequently, the net uncertainty in the Reynolds number at which the experiment will be run will be less than $\pm 2.2\%$.

4.4.3 Uncertainty in the Froude Number

The uncertainty in the Froude number caused by uncertainty in the nozzle velocity and fluid depth in the tank is

$$\Delta Fr/Fr = \{4(\Delta U_0/U_0)^2 + (\Delta H/H)^2\}^{0.5} \quad (4.13)$$

(a) Uncertainty in velocity is calculated as

$$(\Delta U_0/U_0)^2 = (\Delta Q_0/Q_0)^2 + 4(\Delta D_0/D_0)^2$$

The uncertainty in the nozzle velocity and the fluid depth in the tank will be approximately 1% and 0.5%, respectively; this results in a total uncertainty in the Froude number of $\pm 1.1\%$.

4.4.4 Uncertainty in the Gravitational Settling Parameter

The uncertainty in the gravitational settling parameter is

$$\Delta G_s/G_s = \{4(\Delta D_t/D_t)^2 + (\Delta H/H)^2 + (\Delta \rho_s/\rho_s)^2 + (\Delta \rho_l/\rho_l)^2 + (\Delta C/C)^2 + (\Delta U_s/U_s)^2 + 9(\Delta U_0/U_0)^2 + 4(\Delta D_0/D_0)^2\}^{0.5} \quad (4.14)$$

The main contributor to uncertainty is the accuracy of the settling velocity determination. This quantity is difficult to measure, and a consistent measuring technique is required from test to test. For the purpose of the test performed here, the particle settling velocity will be determined by measuring the velocity of the slurry supernate interface. The expected uncertainties in the contributing properties are

1. tank diameter (D_t) 0.1%
2. fluid depth in tank (H) 0.5%
3. ratio of solids to liquid density (s) 2%
4. concentration of solids in mixture as a whole (C) 2%
5. settling velocity of particles (U_s) 10%
6. nozzle exit velocity (U_0) 1%,
7. nozzle diameter (D_0) 0.2%.

The uncertainty in the particle settling velocity dominates the uncertainty calculation, which indicates that the gravitational settling parameter will be known to within $\pm 11\%$. The uncertainty in this value can be reduced significantly by developing better methods of characterizing and measuring the particle settling velocity.

5.0 GENERAL INSTRUCTIONS

5.1 SAFETY

General safety concerns for the 1/12-scale system include: 1) slipping hazards around the system when **water/simulant** is spilled, 2) tripping hazards on gratings caused by hoses running from the manifold system to the mixing pumps, and 3) impact by any objects accidentally dropped through the gratings from upper levels in the high bay area of the 336 Building. All 1/12-scale operations in the 336 Building will be conducted in accordance with the latest version of the

- 336 Building Emergency Procedure
336 Building Laboratory Procedure
- Safe Operating Procedure for the 1/12-scale Double-Shell Tank Test System.

The simulant will be stored for disposal or recycled after the tests. The simulant will consist of materials such as water, clay, and silica sand. It is planned that at the end of tests the slurries will be pumped to drums, solidified, and disposed. Approximately 9 m³ of nonhazardous liquid will be generated during these tests. These wastes will be stored in temporary collection vessels and accounted for in accordance with PNL procedures until disposed of through PNL's Laboratory Safety Department using established PNL procedures.

5.2 QUALITY ASSURANCE

Data^(a) from the tests will be used to develop models to scale operating parameters (i.e., flow rates, mixer pump oscillation rate, and pump horsepower) for the full-scale retrieval of waste from DSTs in the Hanford tank farms.

(a) Data will be stored on a hard disk. Average values will be reported.

This 1/12-scale testing task of the DST Retrieval Program has been designated Quality Assurance (QA) Impact Level III. The applicable QA requirements are defined in the project QA Program Plan, WTC-051^(a).

All instruments used will have valid calibrations per the Measurement and Test Equipment (M&TE) list generated for this task. The calibration records will be located in the project file.

Samples taken during testing will be collected per written, approved procedures. Each sample taken will be labeled with a sample number, the run number, and the date and time the sample was taken. Changes from the test plan will be recorded in the activity notebook and/or in the official copy of the test plan. It is important that any and all variations from the test plan be well documented and supported with the reason for the departure from the plan. Test engineers J. A. Bamberger and/or C. W. Enderlin may authorize minor changes to this test plan. Major changes to the test plan require approval by WHC. Major changes are defined as changes that affect objectives, scope, or expected test results.

Paper copies of reduced data will be maintained in the project file.

5.3 TRAINING

Personnel involved in the tests described in this test plan shall have read and understood this test plan, as well as the Materials Safety Data Sheets (MSDS) of all hazardous chemicals used in the tests.

(a) PNL Tank Waste Retrieval System Retrieval System Project #20066 QA Plan #WTC-051, Rev. 3.

REFERENCES

ASTM. 1989. Standard Viscosity-Temperature Charts for Liquid Petroleum Products. ASTM d-341-89, American Society for Testing and Materials, Philadelphia, Pennsylvania.

Bamberger, J. A., L. M. Liljegren, and P. S. Lowery. 1993. Strategy Plan A Methodology to Predict the Uniformity of Double-Shell Tank Waste Slurries Based on Mixing Pump Operation. PNL-7665, Pacific Northwest Laboratory, Richland, Washington.

Fort, J. A., J. A. Bamberger, J. M. Bates, C. W. Enderlin, and M. R. Elmore. 1993. 1/12-Scale Physical Modeling Experiments in Support of Tank 241-SY-101 Hydrogen Mitigation. PNL-8476, Pacific Northwest Laboratory, Richland, Washington.

Peterson, M. E., D. McCarthy, and K. D. Muhlstein. 1986. Design of Mixing System for Simulated High-Level Nuclear Waste Melter Feed Slurries. PNL-5745, Pacific Northwest Laboratory, Richland, Washington.

Trent, D. S. and L. L. Eyler. 1989. TEMPEST a Three-Dimensional Time-Dependent Computer Program for Hydrothermal Analysis. Volume 1: Numerical Methods and Input Instructions. PNL-4348, Vol. 1, Rev. 2, Pacific Northwest Laboratory, Richland, Washington.

White, F. M. 1974. Viscous Fluid Flow. McGraw Hill, New York.

DISTRIBUTION

<u>No. of Copies</u>		<u>No. of Copies</u>	
<u>OFFSITE</u>		20	<u>Pacific Northwest Laboratory</u>
2	DOE/Office of Scientific and Technical Information		J. A. Bamberger K7-15 (5) J. M. Bates K7-15 C. W. Enderlin K7-15 L. L. Eyler K7-15 M. S. Greenwood K5-26 P. A. Meyer K7-15 B. L. Mohler K5-02 L. M. Liljegren K7-15 M. R. Powell P7-19 P. A. Scott P7-43 Publishing Coordination Technical Report Files (5)
<u>ONSITE</u>			
1	<u>DOE Richland Operations Office</u> W. R. Wrzesinski S7-53		
1	<u>MACTEC</u> D. G. Morgan S7-73	1	<u>Westinghouse Hanford Company</u> E. D. Waters S4-53