Testing of Air Pulse Agitators to Support Design of Savannah River Site Highly Radioactive Processing at the Salt Waste Processing Facility

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ABSTRACT

The Salt Waste Processing Facility (SWPF) is intended to concentrate the highly radioactive constituents from waste salt solutions at the Savannah River Site (SRS). Air Pulse Agitators (APAs) were selected for process mixing in high-radiation locations at the SWPF. This technology has the advantage of no moving parts within the hot cell, eliminating potential failure modes and the need for maintenance within the high-radiation environment. This paper describes the results of APA tests performed to gain operational and performance data for the SWPF design.

INTRODUCTION

Highly radioactive liquid waste at the SRS is currently stored in the F-Area and H-Area tank farms. The radioactive constituents of the waste are principally actinides, strontium (Sr), and cesium (Cs). The waste will be removed from the storage tanks and transferred to a blending tank located in the tank farm area. The blended waste will be characterized prior to transfer to the SWPF for treatment and removal of the radionuclides.

Waste processing at the SWPF occurs in three basic unit operations: Alpha Strike Process (ASP), Caustic-side Solvent Extraction (CSSX), and Alpha Finishing Process (AFP). Highly radioactive liquid waste is initially received and processed in the ASP. The ASP separates Sr and actinides from the waste feed by adsorption on monosodium titanate (MST) followed by filtration to remove the MST from the liquid stream. The CSSX process follows the ASP and is used to remove Cs from the ASP filtrate by solvent extraction. The AFP is an optional process step that mimics the ASP and is used for additional Sr and actinide removal downstream of the CSSX process.

The SWPF will produce: (1) a decontaminated salt solution (DSS) suitable for final treatment and disposal at the Saltstone Facility, and (2) a highly concentrated strontium and actinide sludge, as well as a strip effluent with concentrated cesium waste, suitable for final treatment (vitrification) at the Defense Waste Processing Facility (DWPF).

SWPF requires mixing in the high-radiation environment for several critical process steps. Traditionally, mechanical, motor-driven agitators have accomplished this type of process mixing. However, mechanical agitators are prone to failures, and they require routine maintenance and repair when breakdowns occur. To avoid these issues, the SWPF will use Air Pulse Agitators (APAs) for agitation in high-radiation locations. The design of APAs is such that all moving parts, machinery, and controls will be outside the high-radiation areas.

The APAs consist of multiple vertical pipes (pulse pots) suspended in a tank. The discharge end of the pulse pot is submerged and is equipped with a nozzle. The top end is connected to a source of compressed air and vacuum. The APAs agitate liquid in the tank by forcing out liquid from the pulse pots into the tank in a sequential manner. Compressed air or gravity (gravity drive is planned for plant-scale use; not tested) is used to force out the liquid. During the suction or fill phase, fluid is drawn into the APA pulse pot by either vacuum or the head provided by the surrounding liquid in the tank. Similar systems, such as pulsed jet mixing, have been tested in the past for use in DOE's Hanford River Protection Project, specifically the Waste Treatment Plant [1].

The rheology and solids loading of the suspended solids in Hanford and SRS wastes are sufficiently different to warrant testing of the APAs using simulants [2] that are specifically designed to mimic the waste found at SRS.

The objectives of the work presented in this paper were to:

- Demonstrate that APAs can uniformly mix simulant solids in the process vessel,
- Determine optimum nozzle discharge orientation,
- Define pulse pot operational cycles and operating parameters for mixing and re-suspending simulant solids while at the same time minimizing energy input to the vessel,
- Determine system operational efficiency under restricted pressure/flow conditions,
- Confirm that APAs can re-suspend simulant solids after they have settled and consolidated for up to 30 days, and
- Test simple concepts to determine liquid height inside the pulse pots without use of instrumentation located in the high radiation zone.

EQUIPMENT DESCRIPTION

Test System and Process Tank

The performance of the APA system was tested in a 3.66 m (12-ft) diameter, 4.27 m (14-ft) high, 38 m^3 (10,000-gallon) carbon steel tank. The tank was phenolic epoxy coated. Three different designs of pulse pots were tested in various combinations. Support systems consisted of an air compressor and associated air flow control elements, pressure regulators, a vacuum system, slurry sampling equipment, instrumentation and a data acquisition system. Although the tank size was smaller than that specified in the SWPF Conceptual Design, the volumetric scale (~33%) was large enough to provide representative data for the full-scale design. Fig. 1 shows the test system. A structure capable of supporting up to seven pulse pots was mounted above the tank.

APAs

The APAs were fabricated from standard carbon steel pipes and fittings. The APAs were located along the perimeter of the tank and at the center. The pulse pot support structure was designed to permit the installation of 3 or 6 perimeter pulse pots and the central pulse pot. Fig. 2 illustrates the various APA configurations feasible with the support structure. The structure allowed the radial distance of the

perimeter pulse pots to be varied from 0.91 m (36 in.) to 1.59 m (62.5 in.) as measured from the tank centerline.

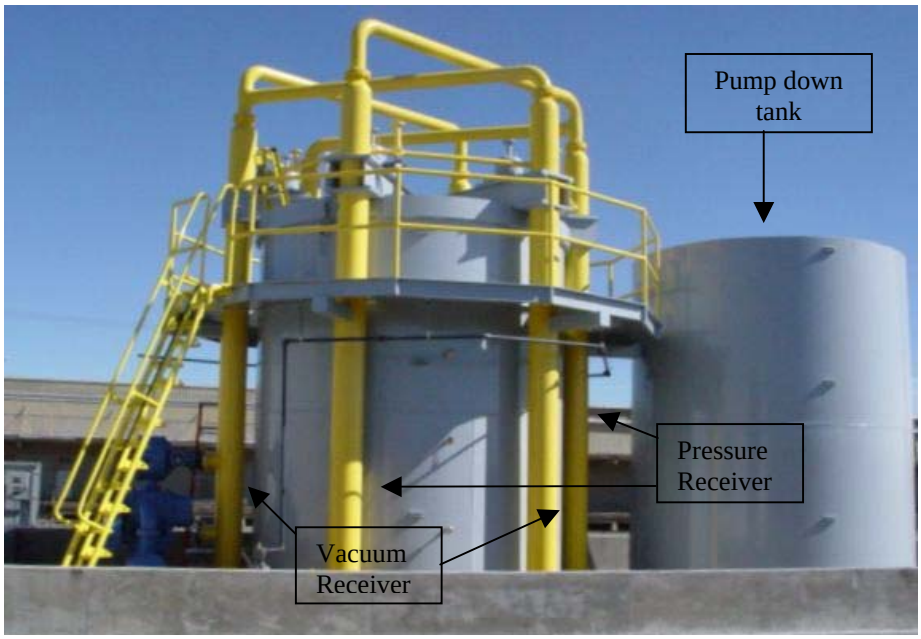

Fig. 1. APA test setup showing the process tanks, pressure, and vacuum receivers

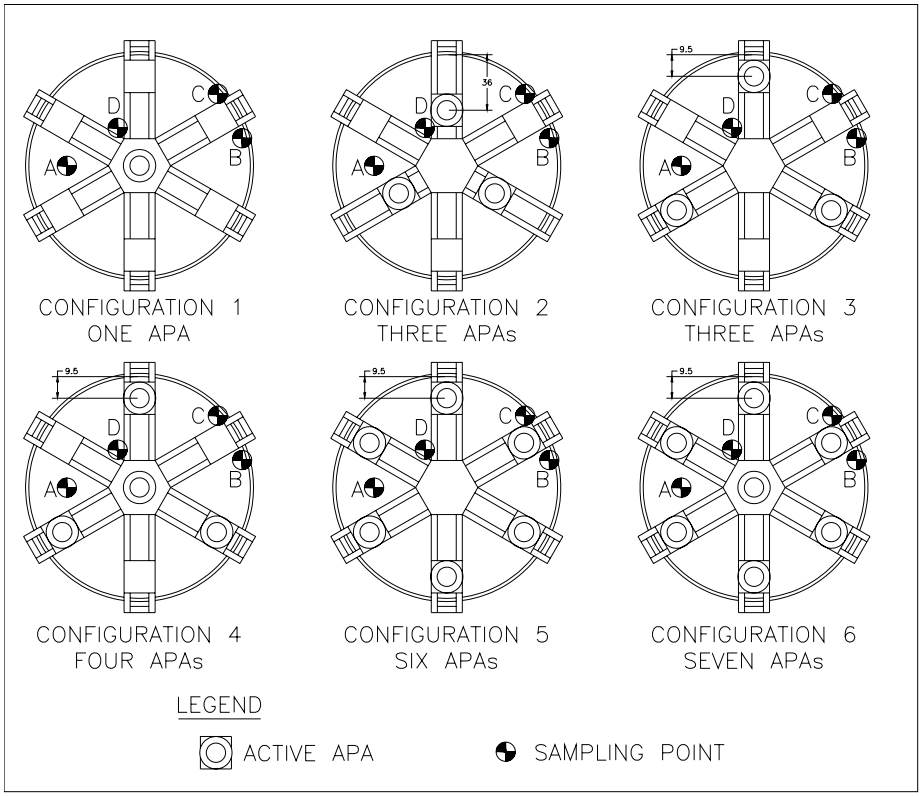

Fig. 2. APA pulse pot configurations and sample tube bundle locations

Table I summarizes the design features of the pulse pots used in this work. Three pulse pot designs were used. These were:

- Horizontally discharging pulse pots with a single 3.2 cm (1.25-in.) diameter nozzle,
- Downward discharging pulse pots with 5.1 cm (2-in.) nozzles, and
- Downward discharging pulse pots with 6.4 cm (2.5-in.) nozzles.

Table I. Design Features of Various APAs Tested

Item	Horizontal Discharge	Downward Discharge	Optimized Discharge
Perimeter APA			
Nozzle Diameter, cm	3.18	6.35	
Body Diameter, cm	30.5		
Discharge Direction	Horizontal	Downward	
Max Liquid Fill height, m (with tank containing 3.35 m of liquid)	2.62	3.15	
Maximum Operating Gauge Pressure, kPa	379	239	48
Nozzle Discharge Velocity (calculated) at operating pressure, m/s	24.4	18.3	8.5
Tank Turn over Rate[a], min (with tank containing 3.35 m of liquid)	25 (7 s pulse)	10 (3 s pulse)	22 (9 s pulse)
Elevation of APA Nozzles from tank bottom, cm	12.7		19.1
Central APA			
Nozzle Diameter, cm	5.1		
Body Diameter, cm	30.5		
Discharge Direction	Downward		
Max Liquid Fill height, m (with tank containing 3.35 m of liquid)	3.15		
Operating Gauge Pressure, kPa	379	48	
Nozzle Discharge Velocity at Operating Pressure, m/s	29	8	
Elevation of APA Nozzle from Tank Bottom, cm	28.7		

[a] Turn over rate is the time in which one working volume of the tank is displaced by the pulse pots.

Sampling Stations

Five sampling stations were mounted around the Process Tank top perimeter. Each sampling station included a self-priming peristaltic pump capable of simultaneously pulling samples from a maximum of four sampling tubes as configured by the operator. Four of the sampling stations, labeled A to D in Fig. 2, were connected to fixed sample tube bundles. Fig. 3 illustrates schematically the location of the sampling points in a tube bundle. Each bundle had six, 0.95 cm (3/8-in.) diameter stainless steel tubes. Each tube terminated at a different height above the tank bottom: 5.1 cm (2 in.), 0.30 m (1 ft), 0.61 m (2 ft), 0.91 m (3 ft), 1.83 m (6 ft), and 2.74 m (9 ft). Four of the six tubes in the bundle were connected to the peristaltic pump; the selection of tubes connected was based upon the height of liquid in the tank. The fifth sampling station was connected to a single, manually positioned sampling tube which was used primarily to sample from the bottom of the tank or when the tank was filled to a height of 3.35 m (11 ft), from just below the liquid surface. The sampling pumps were run continuously during a test in order to keep the long sample lines filled. Any excess sample was returned to the process tank.

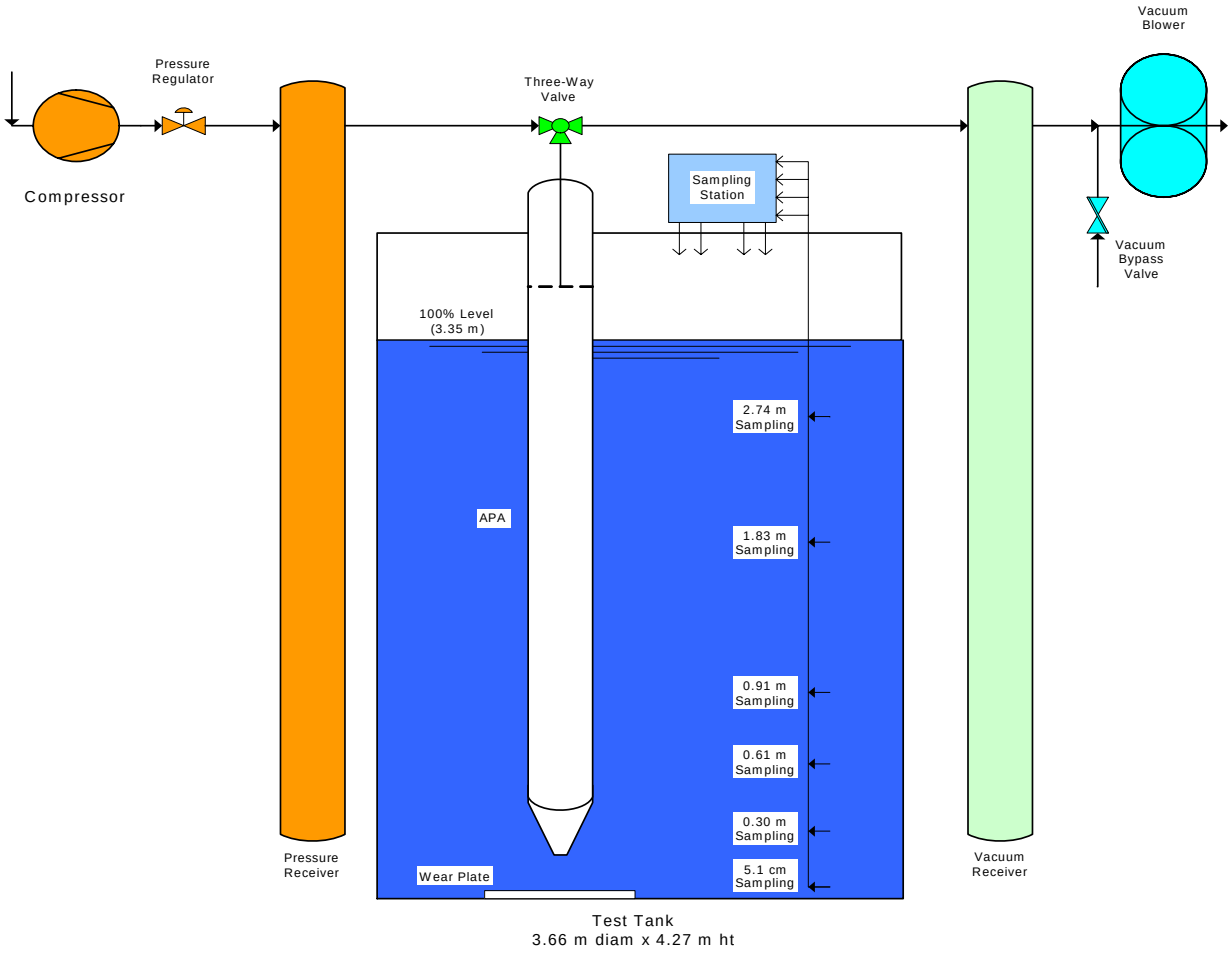

Fig. 3. Schematic flow diagram of a single APA pulse pot

Instrumentation and Automated Data Acquisition System

There were three primary instrument types:

- K-Tek Model A38 capacitance-based RF level transmitter – accuracy ±0.25% full scale (±0.3 in.).
- Siemens SITRANS P Series DS3 Differential Pressure transmitters – error ±0.1% full-scale. These were used to measure the liquid height inside two APAs.
- Pyromation Thermocouple/Thermowell Assembly Model K49U-S4D06D8 – error ±0.4% within range of 0-293 degrees Celsius.

The APA system operation parameters were configured and monitored using the Human Machine Interface (HMI) computer software (CITECT SCADA software, Version 5.42), in conjunction with Programmable Logic Controller (PLC) hardware (DirectLogic DL405 Series). Additional data collection used Rockwell Automation Software RSView Studio, Version 3.10.00.

Wear Plates

In certain tests, a wear plate was installed directly beneath each downward-discharging pulse pot to measure erosion, if any, caused by APA operation. Each 58.4 cm (23-in.) diameter, 1.27 cm (½ in.) thick wear plate was fabricated from type 316L stainless steel.

Materials and Chemicals

The simulant used for the highly radioactive liquid waste was synthesized by mixing sodium nitrate, sodium hydroxide, MST, and kaolin clay. In addition, preliminary testing was conducted with a slurry of solid glass beads and water. Table II lists the materials used in preparation of the various simulants.

Table II. Materials used in the Preparation of Highly Radioactive Liquid Waste Simulant Mixtures

Name	Description	Specification	Supplier
Glass Beads	Spheriglass Solid Glass Spheres	Diameter range: 25 to 50 microns Specific gravity 2.46 to 2.49	Potter Industries Inc, Valley Forge, PA
MST	MST Slurry	Concentration of MST 14.125% custom made as per SWPF specification	Blue Grass Chemical Specialties, LLC. New Albany, IN
Kaolin clay	Suprex, Hydrous aluminum silicate	Specific gravity 2.4. to 2.7 Specific Surface area 22-26 m^2/g	Kentucky-Tennessee Clay Company, Nashville, TN

Technical grade sodium hydroxide, 50% and technical grade sodium nitrate, 40% were used in the preparation of the salt waste simulant. The SWPF process is designed to treat a blended waste stream that has a sodium ion concentration of 5.6 mol/L. A salt waste simulant was prepared as per the following recipe:

Weight of 50% sodium hydroxide:	8,098 kg (17,854 lb)
Weight of 40% sodium nitrate	21,512 kg (47,425 lb)
Weight of 14.125% MST slurry	98 kg (216 lb; to give a concentration of 0.4 g/L)
Water	14.4 m^3 (3,816 gallon)
Weight of kaolin clay	20.9 kg (46 lb; added to give a concentration of 0.6 g/L)

The glass bead slurry in water was prepared at a concentration of 3 g/L.

EXPERIMENTAL APPROACH AND RESULTS

In our tests, uniformity of the distribution of suspended solids was assessed by evaluating the standard deviation (SD) of the suspended solid concentration in the tank. As mentioned earlier, in each sampling event, results of 16 samples taken at 4 heights and 4 radial positions were averaged and the SD calculated. The degree of agitation was assessed by comparing the average spatial concentration against the theoretical concentration of the tank assuming complete and uniform mixing. The degree of agitation was also assessed by counting the number of sample points where the concentration was more than 20 percent below the average measured concentration.

Preliminary Tests with Glass Beads – Approach and Results

The goal of the preliminary tests was to exercise the equipment, train the operators, and evaluate and develop the optimal APA control system operational mode to provide the most effective agitation.

Specific objectives of the preliminary tests were:

- Determine optimal geometrical configuration of the APAs from the six illustrated in Figure 2,
- Determine optimal nozzle discharge direction,
- Determine optimal firing sequence and pulse pot phase timing (drive and delay timing),
- Determine lowest drive phase pressure consistent with effective agitation, and
- Determine optimal vacuum levels during pulse pot filling cycles.

The test sequence consisted of the following steps:

1. Start air compressor,
2. Adjust pressure regulator to achieve the desired drive pressure,
3. Start vacuum pump if needed and set the desired vacuum level,
4. Set operation parameters (sequence, pulse and delay durations) on HMI computer,
5. Turn on sampling pumps,
6. Start APA firing sequence, and
7. Sample at 30, 60, and 120 minutes.

Preliminary tests were performed with water and solid spherical glass beads. The concentration of glass beads in all experiments when the tank was filled to the 3.35 m (11-ft) level was 3.0 g/liter. Glass beads were a conservative simulant because their settling rate was higher than the expected settling rate of MST and tank sludge.

Table III lists the operating conditions of the preliminary tests with horizontal nozzles. Ten tests were performed with the perimeter nozzles discharging in the horizontal direction. In five of these tests the central pulse pot was not used. The tank liquid level was 3.35 m (11 ft). The number of perimeter APAs used was either three or six. Pulse duration is the amount of time the pulse pots are pressurized during the drive phase. Pulse delay is the time interval between the end of drive phase of one pulse pot and the start of the drive phase of the next pulse pot. The liquid level data from the pulse pot equipped with internal liquid height instrumentation was used to calculate nozzle velocity during the drive phase.

Samples were taken from each tube bundle at an elevation of 5.1 cm (2 in.), 0.91 m (3 ft), 1.83 m (6 ft), and 2.74 m (9 ft) from the tank bottom. The average concentration of the solids from the sixteen sampling points and their standard deviation are shown in each row representing a test condition. The data show that horizontal firing perimeter APAs when used without the central pulse pot are unable to achieve high degree of mixing of the glass beads since the measured concentration was only about one ninth to one third of the actual average concentration of 3 g/L. However, the low standard deviation indicates that the mixing was fairly homogenous.

With the addition of the central APA the degree of mixing improved as indicated by the higher concentration. The standard deviation increased in some cases. It was observed that under some operating conditions, the average concentration was higher than the theoretical maximum of 3 g/L. Such results can be caused if the liquid zone above the upper sampling location does not contain solids. Based on the results of these preliminary tests, it was decided to replace all horizontal firing perimeter pulse pots with downward discharging APAs.

Table III. Experimental Conditions and Results for Horizontal Discharge Preliminary Tests with Glass Beads

Test ID	APA Configuration[a] & Firing Sequence	Supply Gauge Pressure kPa	Perimeter[b] APA (horizontal discharge)			Center APA[c] (downward discharge)			Concentration	
			No.	Pulse Duration, s	Pulse Delay, s	No.	Pulse Duration, s	Pulse Delay, s	Average, g/L	SD g/L
WU-1	3, Sequential	138	3	11	5	0			0.92	0.00
WR-1	3, Sequential	379	3	7	60	0			0.96	0.19
WR-3	3, Sequential	379	3	7	10	0			0.92	0.00
WR-4	5, Sequential	379	6	7	9	0			0.38	0.00
WR-7	5, Sequential	379	6	7	60	0			0.38	0.00
								Average	0.71	
WU-2	4, Sequential	138	3	11	5	1	2	5	2.66	0.00
WU-3	6, Sequential	138	6	11	5	1	2	5	3.81	0.00
WR-2	4, Sequential	379	3	7	60	1	3	60	3.67	0.60
WR-5	6, Sequential	379	6	7	0	1	3	0	2.69	0.72
WR-6	4, Sequential	379	3	7	5	1	3	5	2.66	1.16
								Average	3.10	

[a] From Fig. 2.
[b] All perimeter pulse pots were located 24.1 cm (9.5 in.) from the tank wall, their nozzles were 12.7 cm (5 in.) above the floor and the nozzle diameter was 3.18 cm (1.25 in).
[c] Central pulse pot was 28.7 cm (11.3 in.) above the tank floor and its nozzle diameter was 5.1 cm (2 in).

Table IV lists the operating conditions and results for preliminary tests performed with downward discharging APAs. Twenty-four tests were performed while varying configuration, firing sequence, supply pressure, pulse and delay durations. Columns sort the results in Table IV in the following sequence: Firing sequence, number of perimeter APAs, and average solid concentration. It should be noted that certain independent test variables were correlated with each other due to the way the experimental plan was designed and due to geometrical constraints. For example it was not feasible to accommodate six perimeter pulse pots located at a distance of 91.4 cm (36 in.) from the tank wall.

One of the goals of optimizing the operating conditions was to obtain adequate homogenous mixing while minimizing pressure used during the drive phase. Another consideration in selecting the optimal operating condition was to minimize or eliminate settled solids. A manually positioned sampling tube was used to sample the mixture from the floor of the tank. Qualitative observations were made based on an examination of centrifuged samples as to whether there were solids settled on the tank floor. In selecting the optimal conditions consideration was given to those conditions that had minimal or no solid settling at the bottom of the tank. Another consideration was the mixing conditions in the top two feet of the liquid in the tank. The cloud of glass beads, when present in this depth interval was clearly visible. Qualitative observations were made about the size and extent of visible bead-cloud in the upper two feet of the tank.

Prior work done at Pacific Northwest National Laboratory on pulse jet mixing has indicated that the distance between the bottom of the tank and the tip of the nozzle affects the degree and homogeneity of mixing [3]. Fourteen experiments were done during the preliminary tests to investigate the effect of nozzle height on mixing of the glass bead mixture.

Table IV. Experimental Conditions and Results for Downward Discharge Preliminary Tests with Glass Beads

Replication Code[a]	Test ID	Firing Sequence[b]	APA Configuration[c]	APA Supply, Gauge Pressure, kPa	Perimeter[d] APA				Central[e] APA			Concentration, g/L		Settled Solids
					No. of APAs	Distance from Wall, cm	Perimeter Pulse Duration, s	Perimeter Pulse Delay, s	No. of APAs	Center Pulse Duration, s	Center Pulse Delay, s	Average	SD	
Cross firing with six perimeter pulse pots:														
A	WR-10B	C	6	66	6	24.1	8	60	1	9	59	2.30	1.56	no
B	WR-9B	C	6	48	6	24.1	9	1	1	10	1	2.97	0.38	no
	WR-5B	C	5	49	6	24.1	9	0	0			3.08	0.45	yes
B	WR-14B	C	6	46	6	24.1	9	1	1	10	0	3.08	0.30	no
B	WR-15B	C	6	48	6	24.1	9	0	1	9	0	3.08	0.37	no
	WR-17B	C	6	30	6	24.1	13	0	1	13	0	3.31	1.31	no
B	WR-16B	C	6	47	6	24.1	9	1	1	9	1	3.44	0.21	no
	WR-17C	C	6	36	6	24.1	11	0	1	11	0	3.60	0.23	no
Sequential firing with no perimeter pulse pots:														
	WR-1B	S	1	37	0				1	15	16	0.64	0.14	yes
Sequential firing with three perimeter pulse pots:														
	WR-2B	S	4	29	3	24.1	14	2	1	16	0	2.07	0.51	yes
	WR-11B	S	2	99	3	91.4	5	5	0			3.21	0.61	no
	WR-11C	S	2	47	3	91.4	5	0	0			3.30	0.67	yes
Sequential firing with six perimeter pulse pots:														
	WR-3B	S	5	66	6	24.1	7	0	0			2.45	0.63	yes
	WR-7B	S	6	32	6	24.1	12	0	1	12	0	2.80	0.39	no
	WR-013105	S	6	66	6	24.1	8	0	1	8	0	2.83	0.38	no
	SV-7D-90	S	6	174	6	24.1	4	0	1	4	0	2.84	0.51	NA
	WR-7C	S	6	223	6	24.1	3	5	1	3	5	2.88	0.46	no
A	WR-8B	S	6	239	6	24.1	3	60	1	4	59	3.00	0.34	no
B	WR-13C	S	6	45	6	24.1	9	1	1	10	0	3.01	0.37	no
B	WR-13B	S	6	44	6	24.1	9	1	1	10	0	3.05	0.83	no
A	SV-7D-360	S	6	66	6	24.1	8	60	1	8	60	3.18	1.60	NA
	SV-7D-210	S	6	138	6	24.1	4	0	1	4	0	3.27	0.46	NA
A	SV-7D-300	S	6	135	6	24.1	4	60	1	4	60	3.52	1.87	NA

a) Rows with the same replication code represent experiments done with the approximately the same operating condition except for firing sequence and pressure.
b) C: Cross pattern; S: Sequential pattern.
c) from Figure 2.
d) all perimeter APA nozzles were 12.7 cm (5 in.) above the tank floor and the nozzle diameter was 6.35 cm (2.5 in).
e) all central APA nozzles were 28.8 cm (11.3 in.) above the tank floor and the nozzle diameter was 5.1 cm (2 in).

Table V shows the results of the effect of nozzle height. The results in Table V are organized by applied pressure and then by nozzle height. The applied pressure and the perimeter pulse duration were inversely correlated as higher pressures require shorter pulse durations due to increased flow rate.

The data in Table V show the average concentration of the glass beads in the elevation interval of 5.1 cm (2 in.) to 2.74 m (9 ft) and the standard deviation of the measured concentrations. The table also shows the measured concentration of the glass beads at the surface, taken from samples using the manual sample tube placed just below the liquid surface. The results indicate that the surface concentration is maximized when the nozzle height is 3 nozzle diameters. The surface concentration fell as the nozzle height was increased or decreased. As the pressure increased from 27.6 to 68.9 kPa (4 to 10 psig) the surface concentration of the glass beads also increased. Based on these results and with the desire to minimize nozzle velocity, it was concluded that the best mixing performance is obtained at a nozzle height of 3 diameters with air supplied at 48 kPa (7 psig).

Table V. Effect of Nozzle Height on Concentration of Glass Beads in the Agitated Tank

APA Supply Gauge Pressure, kPa	Nozzle Elevation[a] (number of nozzle diameters)	Perimeter Pulse Duration, s	Center Pulse Duration, s	Perimeter Pulse Delay, s	Center Pulse Delay, s	Avg. Solid, g/L	SD, g/L	Surface solid g/L
30	3	13	13	0	0	3.27	1.42	0.09
28	4	13	13	0	0	3.21	1.73	0.09
37	2	11	12	0	0	3.06	0.64	0.79
37	3	11	11	0	0	2.99	0.29	1.13
38	3	11	11	0	0	3.39	0.22	2.05
37	4	11	11	0	0	2.77	0.12	0.13
38	4	11	11	0	0	3.22	0.3	1.2
47	2	9	10	0	0	3.11	0.5	1.6
46	3	9	10	0	0	3.07	0.74	2.35
48	3	9	10	0	0	3.06	0.51	1.78
47	4	9	10	0	0	3.11	0.37	0.99
68	2	6	7	1	0	2.62	0.39	0.99
70	3	6	7	1	0	3.33	0.19	2.35
70	4	6	7	1	0	2.89	0.45	1.61

[a] Nozzle height of perimeter pulse pots was varied. Equipment design did not permit variation in the height of the center pulse pot which was fixed at 28.7 cm (11.3 in.) or 5.65 nozzle diameters.

Based on the data and observations from the preliminary tests with glass beads and water, with a fill height of 3.35 m (11 ft), the following set of operating conditions was identified as optimal:

- Air Supply Pressure: 48 kPa, gauge
- Vacuum Assist: None
- Nozzle Height: 3 nozzle diameters (Only for perimeter nozzles. Center pulse pot height was not varied. It was fixed at 5.65 nozzle diameter [3].)
- Perimeter Pulse Pots: 9 s drive pulse; 1 s delay
- Center Pulse Pots: 10 s drive pulse; no delay

One set of four additional tests was performed with glass beads to obtain final confirmation of the above conditions as well as to test the conditions when the tank fill level was reduced to a depth of 1.1 m (3.5 ft). Table VI lists the operating conditions of these four tests.

The objectives of these four tests were:

- Using glass bead and water slurry verifies the optimal operating conditions determined during the preliminary tests while evaluating the effect of applying vacuum to the pulse pots.
- Using glass bead and water slurry determines whether the operating conditions defined for a tank fill height of 3.35 m (11 ft) still provide acceptable mixing performance with a tank fill height of 1.1 m (3.5 ft). Determine vacuum levels for improved mixing performance, if required.

Table VI. Operating Conditions for Test Series 1 - Water and Glass Bead Slurry

Test No.	Test Goal	Tank Liquid Level, m	Suspended Glass Beads, g/L	Vacuum, cm H_2O	Air Supply Gauge Pressure, kPa	Average Concentration, g/L
1-1	Repeat workup tests optimal conditions	3.35	3.0	none	~ 48	3.0[a]
1-2	Test performance of optimum configuration at full tank volume with vacuum assist	3.35	3.0	~30	~ 48	ND[b]
1-3	Test performance of optimum configuration at low tank volume w/o vacuum assist	1.1	9.4	none	~11	3.7[c]
1-4	Test performance of optimum configuration at low tank volume with vacuum assist	1.1	9.4	~114	~19	8.7[c]

[a] In a well mixed tank the theoretical concentration should be 3 g/L.
[b] ND: not determined.
[c] In a well mixed tank the theoretical concentration should be 9.4 g/L.

The first two tests of this series verified the optimum operating parameters found during testing with and without the use of vacuum assist. Samples were taken at 30-minute intervals during each 2-hour test. For Test 1-1, the average solids concentration after 120 minutes of agitation was 3.0 g/L solids. The optimum parameters for agitating the tank with 3.35 m (11ft) of liquid were reconfirmed. In Test 1-2 a vacuum was applied to the pulse pots. However, this test could not be implemented because of water entering the vacuum system even at the lowest vacuum level (30 cm water).

The last two tests in this series were performed at a tank level of 1.1 m (3.5 ft), one without and one with the assistance of the vacuum blower. Test 1-3 was completed using 11 kPa (1.6 psig) air pressure, a 4 s pulse and 1s delay on the perimeter pulse pots and a 4 s pulse and a 0 s delay on the central pulse pot. These settings just precluded blowing air out of the pulse pot nozzles. Sampling showed an average solid concentration of 3.7 g/L. This result was less than half the expected 9.4 g/L solids concentration indicating that adequate mixing had not been achieved.

In Test 1-4, air was supplied at 19.3 kPa (2.8 psig) during the drive phase. A vacuum of 114 cm (45 in.) H_2O was used to assist the refilling of the pulse pots. There was a 6 s pulse and 1 s delay on the perimeter pulse pots, while the central pulse pot had an 8 s pulse and a 0 s delay. The average solids concentration

after 120 minutes of agitation was 8.7 g/L twice that measured without vacuum. The average concentration was within 93 percent of the expected concentration.

The optimum parameters for testing at 3.5-ft liquid level were:

- Air Supply Pressure: 19 kPa, gauge
- Vacuum Assist: 114 cm water
- Nozzle Height: 3 nozzle diameters (only for perimeter nozzles. Center pulse pot height was not varied. It was fixed at 5.65 nozzle diameter.)
- Perimeter Pulse Pots: 6 s drive pulse; 1 s delay
- Center Pulse Pots: 8 s drive pulse; no delay

Mixing Tests with Salt Waste Simulant and MST – Approach and Results

Mixing tests with waste simulant and MST were performed to confirm the validity of and further refine the optimum mixing conditions identified during the tests with glass beads. The effect of reducing the fill height in the process tank on the performance of the APA system was investigated. The benefit of applying vacuum to the pulse pots to increase the volume of displaced liquid during the drive phase was confirmed. These tests were performed in series. Each series was designed to accomplish a specific set of objectives. These are listed below:

Specific Objectives of Test Series 2 were:

- Verify mixing performance of the APA system when the liquid mixture consists of the salt simulant and MST.

Specific Objectives of Test Series 3 were:

- Verify mixing performance of the APA system when the liquid mixture consists of the salt simulant, kaolin clay, and MST.

Specific Objectives of Test Series 4 were:

- Verify mixing performance of the APA system when the liquid mixture concentration was increased by a factor of 20 to 30. These tests were done to simulate the conditions in the cross-flow filter feed tanks towards the end of the filtering cycle when the slurry concentration is expected to be in the range of 5 to 7 percent total suspended solids.
- Verify ability to re-suspend and mix the tank contents after a quiescent period of 30 days.

The four experiments in Test Series 2 were performed with simulant salt solution and MST. The tank was drained and cleaned after Test Series 1. Wear plates were installed underneath each pulse pot nozzle prior to loading chemicals into the Test Tank. After two hours of agitation, two sets of samples were taken from sample station at heights of 5.1 cm (2 in.), 0.91 m (3 ft), 1.83 m (6 ft), and 2.74 m (9 ft). After an hour of settling, a layer of solids became visible in the samples. Laboratory analysis showed that there was an average of 0.9 g/L of suspended solids present in the salt solution samples. The source of these solids is uncertain. It is possible that the technical grade salts contained insoluble matter. It was decided to proceed with testing without attempting to remove the solids. MST was added to the tank at a concentration of 0.4 g/L. Test operating conditions and objectives are given in Table VII.

In Test 2-1, a qualitative determination of settling time for MST in the simulant solution was made. The solution was agitated, using the APA system, to suspend solids to the surface. After agitation was stopped, samples were taken at multiple elevations at elapsed times between 1 and 40 hours. Observations showed that only trace amounts of MST remained above the 0.3 m (1 ft) level after ~17 hours of settling. This test was necessary to determine the time required between subsequent tests to ensure an unmixed starting condition.

Test 2-2 was conducted to validate the previously defined operational configuration, obtained with the glass-bead slurry, for the MST slurry made in the salt solution. Laboratory results showed an average of 1.2 g/L solids suspended after 120 minutes of agitation. The expected value was 1.3 g/L. Test 2-3 was performed to evaluate system operation with MST at the low tank level. Results showed an average of 3.6 g/L solids suspended after 120 minutes of agitation. The expected value was approximately 4.0 g/L solids.

Table VII. Test Series 2: Downward-Discharging Nozzles – Re-suspending MST

Test No.	Test Goal	Tank Liquid Level, m	Concentration of Suspended Solids, g/L	Vacuum, cm H_2O	Air Supply Gauge Pressure, kPa
2-1	Make qualitative determination of the settling rate of MST	3.35	MST 0.4 Unknown 0.9 Total 1.3	NA[a]	NA
2-2	Evaluate system operation with MST at full tank volume using best configuration (s) from Test Series 1	3.35	MST 0.4 Unknown 0.9 Total 1.3	NA	~50
2-3	Evaluate system operation with MST at low tank volume using best configuration (s) from Test Series 1	1.1	MST 1.3 Unknown 2.7 Total 4.0	~114	~23

[a] NA: not applied

Prior to testing, a criterion for uniform mixing was adopted. This criterion defined acceptable mixing if all sample points exhibited a concentration that was within 20 percent of the average measured concentration.

The data obtained in Test Series 2 was evaluated in terms of number of samples that fell outside the criterion for uniform mixing. Table VIII presents this evaluation. It became apparent during testing that, while inadequate mixing was reasonably defined by samples that were less than 20% below the expected average concentration, samples sometimes measured higher than 20% above the average concentration, even in a well-mixed system. This variation could easily be caused by small clumps of suspended material. If one or more of these clumps was included in an otherwise normal sample, the concentration reported for the sample would be significantly higher than the average solution concentration. A single spherical clump, 2.8 millimeters (mm) in diameter (or two spherical clumps 2.2 mm in diameter, or three clumps 1.9 mm in diameter) in a 100-milliliter sample is sufficient to drive the solids concentration beyond the acceptance limit. For this reason, subsequent analyses discounted the significance of occasional samples that measured higher than the +20% limit.

Table VIII. Evaluation of Uniformity of Mixing in Test Series 2

Test Series No	Tank Liquid Level, m	Vacuum, cm H_2O	Air Supply Gauge Pressure, kPa	Concentration of Suspended Solids, g/L	Agitation Time (min)	Number of Samples[a] Below Low (average-20%) Limit	Number of Samples[a] Above High (Average+20%) Limit
2-2	3.35	none	50	MST 0.4 Unknown 0.9 Total 1.3	30	0	0
					60	1	1
					90	1	0
					120	0	0
2-3	1.1	114	23	MST 1.3 Unknown 2.7 Total 4.0	30	3	0
					60	1	1
					90	2	0
					120	1[b]	2

[a] During each sampling event, 16 samples were taken from four different vertically emplaced tube bundles. Each tube bundle sampled from four different depths.

[b] One low value after 120 minutes was 21.3% below the expected mean.

Following Test Series 2, the solution level in the tank was raised to 3.35 m (11 ft). Kaolin clay was added to the tank at the initial concentration of 0.6 g/L to bring the total solids concentration in the tank to 1.9 g/L (0.4 g/L MST, 0.6 g/L kaolin clay, and 0.9 g/L unknown solids) and Test Series 3 was performed. Three experiments were performed in this series: a qualitative settling test, a high-level test, and a low-level test. These tests replicated Series 2 tests with the exception of taking an earlier sample set after 15 minutes of agitation. The operating conditions of the three experiments are listed in Table IX.

Table IX. Test Series 3: Test Conditions for Re-suspending MST and Kaolin Clay

Test No.	Test Goal	Tank Liquid Level, m	Concentration of Suspended Solids, g/L	Vacuum, cm H_2O	Air Supply Gauge Pressure, kPa
3-1	Determine settling rate of MST/kaolin clay	3.35	MST 0.4 Kaolin clay 0.6 Unknown 0.9 Total 1.9	NA[a]	NA
3-2	Evaluate system operation with MST and Kaolin Clay at full tank volume using best configuration(s) from Test Series 2	3.35	MST 0.4 Kaolin clay 0.6 Unknown 0.9 Total 1.9	NA	~51
3-3	Evaluate system operation with MST and Kaolin Clay at low tank volume using best configuration(s) from Test Series 2	1.1	MST 1.3 Kaolin clay 1.9 Unknown 2.7 Total 5.9	~114	~24
3-3A	Evaluate system operation with MST and Kaolin Clay at low tank volume using best configuration(s) from Test Series 2	1.1	MST 1.3 Kaolin clay 1.9 Unknown 2.7 Total 5.9	~114	~24

[a] NA: not applied

Test 3-1 results showed that MST and kaolin clay solids settled below the 0.3 m (1 ft) level after 16 hours, which was within 1 hour of that observed for the MST salt solution slurry.

Test 3-2 was performed using the same operational parameters as Test 2-2. Air pressure averaged 51 kPa (7.4 psig) during this test. Laboratory results showed an average of 1.9 g/L of solids suspended after 120 minutes of agitation. This value matched the expectation of 1.9 g/L. Table X shows that at 120 minutes, there were no samples outside the range of the success criteria of ±20% of the average concentration.

The test solution height was lowered to 1.1 m (3.5 ft) for Test 3-3. Test results showed an average of 5.3 g/L solids suspended after 120 minutes of agitation. As the expected value was 5.9 g/L, this test was repeated to verify the results. Results for re-test (Test 3-3A) again showed an average of 5.3 g/L solids suspended after 120 minutes of agitation.

Table X shows the number of samples outside the range of success criterion for Tests 3-3 and 3-3A. In both tests, solids were uniformly distributed, as determined from the number of samples below the minimum established limit after 120 minutes.

Table X. Evaluation of Uniformity of Mixing in Test Series 3

Test Series No	Tank Liquid Level, m	Vacuum, cm H_2O	Air Supply Gauge Pressure, kPa	Concentration of Suspended Solids, g/L	Time (min)	Number of Samples[a] Below Low (average-20%) Limit	Number of Samples[a] Above High (Average+20%) Limit
3-2	11	none	51	MST 0.4 Kaolin clay 0.6 Unknown 0.9	15	0	1
					30	0	0
					60	1	1
					90	0	0
					120	0	1
3-3	3.5	114	24	MST 1.3 Kaolin clay 1.9 Unknown 2.7	15	0	0
					30	0	0
					60	0	0
					90	0	0
					120	0	0
3-3A	3.5	114	24	MST 1.3 Kaolin clay 1.9 Unknown 2.7	15	1	0
					30	0	2
					60	2	1
					90	1	2
					120	0	3

[a] During each sampling event, 16 samples were taken from four different vertically emplaced tube bundles. Each tube bundle sampled from four different depths.

Test series 4 was performed to determine the optimal operating conditions when the concentration of the suspended solids in the slurry was increased to a range of 5 to 7 weight percent. Another purpose of these tests was to demonstrate that the slurry can be remixed after settling for 30 days. Six experiments were done in this series. Their operating conditions are given in Table XI.

In Test 4-1, MST and kaolin clay were added to the tank to increase the total solids concentration to 5 wt.% at the 1.1 m (3.5 ft) solution level. Test 4-1 was conducted by using the same operating parameters as Test 3-3. A duplicate Test 4-1A was performed one day later.

In Test 4-1, the expected average concentration was 64.6 g/L solids, but the test results showed an average concentration of 54.4 g/L after two hours of agitation. The observed accumulation of clay solids on the sides of the tank during loading probably caused the deviation. The high-solids (5 wt. %) test was

repeated to verify the results. Results from the re-test (Test 4-1A) were similar, with an average concentration of 54.2 g/L solids after 2 hours of agitation. Table XII shows the number of samples outside the range of the success criteria of ±20% of the average concentration. After 120 minutes of agitation, solids were uniformly distributed in tests 4-1 and 4-1A.

Prior to Test 4-2A, additional solids were added until the final solids concentration was 7 wt.% at the 1.1 m (3.5 ft) solution level. Following the addition of the solids the solution level increased to 1.14 m (3.75 ft). Test 4-2A was performed with approximately 6.5 wt. % solids in the tank. The expected average concentration was 81.3 g/L solids, but the test results showed an average concentration of 69.6 g/L after two hours of agitation. The measured concentration was approximately 11g/L less than expected. This is likely due to the accumulation of kaolin clay solids on the sides of the tank during solids loading for Test 4-1. Table XII shows the number of samples outside the range of the success criteria of ±20% of the average concentration. There were three samples that were less than 20 percent of the average concentration.

Table XI. Test Series 4: Test Conditions for Re-suspending High Concentration Solids

Test No.	Test Goal	Liquid Level, m	Suspended Solids, g/L	Vacuum, cm H_2O	Air Supply Gauge Pressure, kPa	Drive Pulse, s	Delay, s
4-1	Test best configuration at 5 wt% solids concentration	1.1	MST 24.7 kaolin clay 37.1 unknown 2.7 Total 64.5	~114	~25	Perimeter 6 Center 8	Perimeter 1 Center 0
4-1A	Test best configuration at 5 wt% solids concentration	1.1	MST 24.7 kaolin clay 37.1 unknown 2.7 Total 64.5	~114	~25	Perimeter 6 Center 8	Perimeter 1 Center 0
4-2A	Test best configuration at 7wt% (6.5% actual) solids concentration	~1.2	MST 31.5 kaolin clay 47.3 unknown 2.5 Total 81.3	~114	~27	Perimeter 6 Center 8	Perimeter 1 Center 0
4-2B	Test best configuration at 7wt% solids concentration (after a 30 day settling period)	1.0	MST 35.0 kaolin clay 52.4 unknown 2.8 Total 90.2	~114	~23	Perimeter 6 Center 8	Perimeter 1 Center 0
4-3A	Air Sparging w/ perimeter APAs only	1.3	MST 31.0 kaolin clay 46.4 unknown 2.3 Total 79.7	None	172	Simultaneous sparging of all pulse pots	None
4-3B	Air Sparging w/ center APA only	1.3	MST 31.0 kaolin clay 46.4 unknown 2.3 Total 79.7	None	24 -- 172	None	None

Table XII. Evaluation of Uniformity of Mixing in Test Series 4

Test Series No.	Tank Liquid Level, m	Vacuum, cm H_2O	Air Supply Gauge Pressure, kPa	Theoretical Concentration of Suspended Solids, g/L	Sampling Time, min	Number of Samples Below Low (average-20%) Limit	Number of Samples Above High (Average+20%) Limit
4-1	1.1	~114	25	MST 24.7 Kaolin clay 37.1 Unknown 2.7 Total: 64.5	30	0	0
					60	2	0
					90	3	0
					120	1[a]	0
4-1A	1.1	~114	25	MST 24.7 Kaolin clay 37.1 Unknown 2.7 Total 64.5	30	0	2
					60	0	1
					90	0	2
					120	2[b]	3
4-2A	~1.2	~114	27	MST 31.5 Kaolin clay 47.3 Unknown 2.5 Total 81.3	30	1	0
					60	4	0
					90	3	0
					120	3[c]	0
4-2B	1.0	~114	23	MST 35.0 Kaolin clay 52.4 Unknown 2.8 Total 90.2	30	0	0
					60	0	0
					90	0	0
					120	0	0
4-3A	1.3	None	172	MST 31.0 Kaolin clay 46.4 Unknown 2.3 Total 79.7	40	12	5
					80	10	5
					120	11	4
4-3B	1.3	None	24 to 172	MST 31.0 Kaolin clay 46.4 Unknown 2.3 Total 79.7	40 (0.25 m^3/min[d])	14	0
					80 (0.25 m^3/min)	14	0
					40 (1.27 m^3/min)	15	1
					80 (1.27 m^3/min)	15	1

[a] Low value after 120 minutes was 21.7 percent below the expected mean
[b] Low values after 120 minutes were 25.8 and 20.7 percent below the expected mean
[c] Low values after 120 minutes were 23.3, 20.2 and 20.6 percent below the expected mean
[d] Number in parenthesis gives the standard volumetric air flow rate through the pulse pots

After Test 4-2A was completed, the APA test equipment was secured and shut down for the 30-day settling period. The solids layer was periodically measured during the settling period. A majority of the settling occurred early as the solids layer settled from an elevation of 1.14 m to 0.76 m (3.75 to 2.5 ft) during the first 10 days. At the end of the 30-day settling period, the solids layer was at an elevation of 0.53 m (1.75 ft).

Towards the end of the 30-day settling period, some of the solution above the settled solids layer was transferred out of the tank, lowering the liquid level to 1 m (3.4 ft) and increasing the solids concentration to 7 wt.%. Test 4-2B was performed after the 30-day settling period. The procedure used was exactly the same as that used in Test 4-2A with the exception that an air supply pressure of ~23 kPa (3.3 psig) was used. The pulse pots did not have any difficulty firing during the initial pulses. At a tank level of 1 m (3.4

ft), the average concentration was expected to be 90.20 g/L solids. Laboratory analysis test results showed an average concentration of 89.75 g/L solids after 2 hours of agitation. Data in Table XII shows that no samples were outside the range of the success criteria after 120 minutes.

Tests 4-3A and 4-3B were done to determine the effectiveness of sparging air through the pulse pots on mixing in the tank. Test results shown in Table XII indicate that this method of operating the pulse pots is not as effective compared to previous operating method in which the pulse pots were driving liquid into the tank. However, this method may provide enough agitation to help dislodge radiolytic hydrogen bubbles entrapped in the mixture.

CONCLUSIONS AND RECOMMENDATIONS

The effectiveness of an air pulse agitator system was evaluated in a 38 m^3 (10,000 gallon) pilot scale system. The concentration of suspended solids in the various slurries varied from 0.03 to 7 percent. Based on the data collected the following conclusions and recommendations were made:

1. The APAs provided adequate distribution of the solids in the test tank. While the original criteria of ±20% were not consistently met (due largely to high readings that may have been caused by agglomerations captured during sampling), the APAs distributed the solids evenly throughout the test tank with only occasional samples below the -20% lower limit.
2. Downward-discharging nozzles are recommended instead of the horizontal-discharging nozzles for the SWPF because they performed better; producing a mixing effect three times that of the horizontal discharging nozzles.
3. The maximum number of APA pulse pots in the test tank (seven) provided the most uniform distribution of suspended solids
4. Of the three nozzle elevations tested (two, three, and four times the nozzle diameter), the optimum nozzle elevation was three times the nozzle diameter.
5. Real-time liquid level indication within the APA is possible with a mechanical bubbler-type system. The bubbler-type liquid level indicator with remotely mounted pressure transmitter is a viable alternative to a capacitance-type level probe with locally mounted transmitter.
6. Active pressure control is recommended for the air supply. Air supply pressure should be varied according to solution level.
7. Future testing should include taking sequential samples from a representative sample point or points to establish the variability of the samples with respect to time.

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