System Performance Testing of the Pulse-Echo Ultrasonic Instrument for Critical Velocity Determination during Hanford Tank Waste Transfer Operations - 13584

Kayte M. Denslow*, Jagannadha R. Bontha*, Harold E. Adkins*, Jeromy W.J. Jenks*, Derek F. Hopkins*, Michael G. Thien**, Steven E. Kelly** and Theodore A. Wooley**
*Pacific Northwest National Laboratory, Richland, Washington 99354
**Washington River Protection Solutions, Richland, Washington 99354

ABSTRACT

The delivery of Hanford double-shell tank waste to the Hanford Tank Waste Treatment and Immobilization Plant (WTP) is governed by specific Waste Acceptance Criteria that are identified in *ICD 19 - Interface Control Document for Waste Feed.* Waste must be certified as acceptable before it can be delivered to the WTP. The fluid transfer velocity at which solid particulate deposition occurs in waste slurry transport piping (critical velocity) is a key waste acceptance parameter that must be accurately characterized to determine if the waste is acceptable for transfer to the WTP. Washington River Protection Solutions and the Pacific Northwest National Laboratory have been evaluating the ultrasonic PulseEcho instrument since 2010 for its ability to detect particle settling and determine critical velocity in a horizontal slurry transport pipeline for slurries containing particles with a mean particle diameter of $\geq$14 micrometers (μm). In 2012 the PulseEcho instrument was further evaluated under WRPS' System Performance test campaign to identify critical velocities for slurries that are expected to be encountered during Hanford tank waste retrieval operations or bounding for tank waste feed. This three-year evaluation has demonstrated the ability of the ultrasonic PulseEcho instrument to detect the onset of critical velocity for a broad range of physical and rheological slurry properties that are likely encountered during the waste feed transfer operations between the Hanford tank farms and the WTP.

INTRODUCTION

212,000 m^3 (~56 million gallons) of radioactive and chemical waste are currently stored in 177 underground single- and double-shell tanks on the U.S. Department of Energy Hanford nuclear reservation located in southeastern Washington State. This high-level waste (HLW) and low-activity waste (LAW) is a byproduct of plutonium production efforts that supported America's defense program during World War II and throughout the Cold War. The Hanford underground storage tanks were not designed to store this waste indefinitely; the waste will ultimately be transferred to the Hanford Tank Waste Treatment and Immobilization Plant (WTP) that is being designed, constructed and commissioned to vitrify and transform the waste into solid glass logs for safe disposal or storage.

Washington River Protection Solutions (WRPS), the U.S. Department of Energy contractor for Hanford tank farm operations, will be responsible for transferring waste from the Hanford tank farms to the WTP via slurry transport piping. WRPS must first certify the waste as acceptable per Waste Acceptance Criteria specified in *ICD 19 - Interface Control Document for Waste Feed* that were developed to ensure waste feeds can be successfully treated by the WTP [1]. Some of the specific Waste Acceptance Criteria pertaining to the waste feed physical and rheological properties are not easily measured with a small sample in an analytical laboratory environment. The critical velocity in slurry transport piping is a key waste acceptance parameter that falls into this category.

Critical velocity is defined as the nominal fluid transfer velocity at which solid particles begin to deposit on the bottom of a straight horizontal pipe section during slurry transport. Critical velocity depends on the physical properties of the solid particles and carrier fluid, as well as the geometry of the slurry transport system [2]. Critical velocity is not a slurry property that can be directly measured. Instead, the symptoms of critical velocity, chiefly the settling and deposition of solid particles in a pipe, are detected and then correlated with the fluid transfer velocity that resulted in that condition – the critical velocity. The settling and deposition of solid particles in slurry transport piping at the critical velocity are undesirable phenomena during waste transfer operations to and within the WTP because they are precursors to pipeline plugging that is potentially irreversible. Therefore, the critical velocity of Hanford tank waste must be accurately identified in order to determine if the waste feed can be accepted by the WTP.

The current baseline plan of WRPS is to determine the critical velocity of Hanford tank waste using a waste feed flow loop. The waste feed flow loop will be integrated into the WTP feed delivery systems and will allow real-time determination of the critical velocity as waste is being circulated through the transfer piping and back to the original source tank as illustrated in Fig 1. Once critical velocity and other analytically determined acceptance criteria have been shown to meet the *ICD19* Waste Acceptance Criteria, the waste feed will be certified as acceptable for transfer to the WTP receipt tank for further treatment.

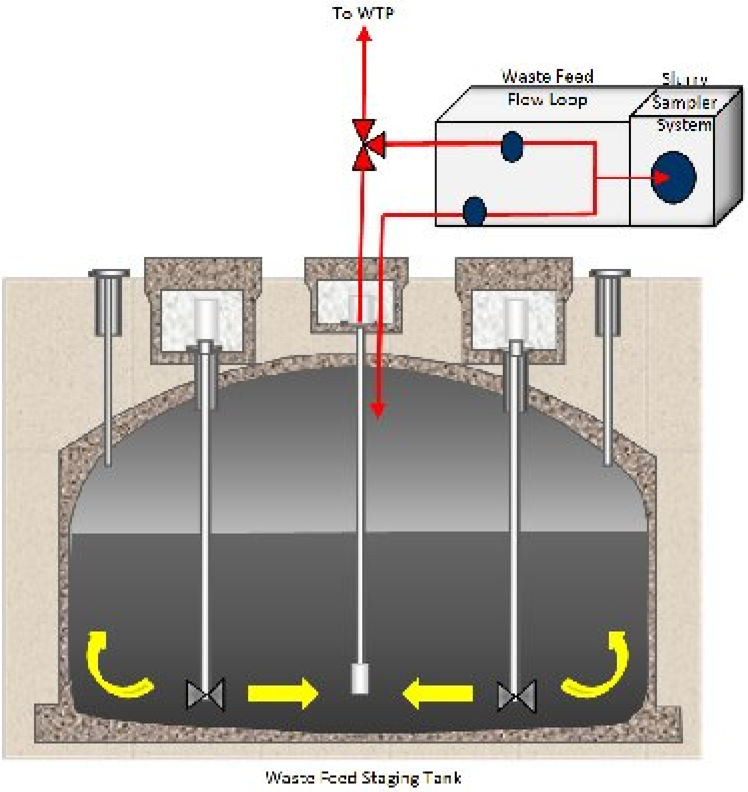

Fig 1. Conceptual Illustration of the Double Shell Tank Waste Certification and Transfer Process.

The approach of using a waste feed flow loop to determine critical velocity will require real-time monitoring of the flow loop piping for particle settling. A method that is sensitive to incipient settling of solid particles will be required to help determine critical velocity with high accuracy, which will allow WRPS to determine if the critical velocity of the waste is ≤ 1.2 m/s (≤ 4.0 ft/s) in a nominal 0.08-m (3-inch) diameter schedule 40 (Sch 40) pipe, as specified in *ICD19*, or if the waste must be blended with other liquids to achieve a critical velocity ≤ 1.2 m/s (≤ 4.0 ft/s).

In response to the need for a method that accurately detects critical velocity, WRPS and the Pacific Northwest National Laboratory (PNNL) have conducted an extensive three-year evaluation of an ultrasonic method and system, known as the PulseEcho instrument, for its ability to detect and report the onset of solid particle settling in full-scale waste feed flow loops. The PulseEcho instrument was initially tested in 2010 at PNNL using a range of Newtonian and non-Newtonian simulants that contained low and high concentrations of medium-density glass particles with a median diameter (d50) of >50 micrometers (μm) [3-5]. The PulseEcho instrument was further evaluated during a second year of testing in 2011 at PNNL with the focus on determining the instrument's particle size and concentration detection limits using simulants that contained relatively low concentrations of high-density stainless steel particles with a median diameter of <15 μm [6-7]. The instrument continued to be evaluated under a third test campaign in 2012 using slurries that are expected to be encountered during Hanford tank waste retrieval operations or are bounding for tank waste feed properties [8]. The cumulative three-year test campaign has demonstrated the ability of the PulseEcho instrument to non-invasively detect particle settling in slurry piping and identify critical velocity for a broad range of physical and rheological slurry properties that are likely encountered during the Hanford waste transfer operations.

TEST PLATFORM, INSTRUMENTS AND SIMULANTS

2012 PulseEcho testing was conducted under the WRPS System Performance test campaign using the Remote Sampler Demonstration (RSD)/Waste Feed Flow Loop cold-test platform at the Monarch test facility in Pasco, Washington. The RSD/Waste Feed Flow Loop was principally designed to evaluate the RSD configuration of the Isolok™ Sampler system for its ability to collect representative samples of large and dense particles, but also afforded an opportunity to continue evaluating the reliability of the ultrasonic PulseEcho instrument.

The RSD/Waste Feed Flow Loop cold-test platform was used to test a variety of slurry simulants at flow velocities of 0.61-2.4 m/s (2.0-8.0 ft/s). The critical velocity for each slurry simulant was accurately determined by incrementally decreasing the flow velocity and monitoring the flow loop for particle settling using transparent test sections and visual/optical detection methods. The performance of the ultrasonic PulseEcho instrument was evaluated by comparing the fluid velocities at which the PulseEcho instrument ultrasonically detected settled particles with the fluid velocities at which settled particles were detected with visual/optical methods.

Waste Feed Flow Loop

WRPS and Energy*Solutions* led the design and construction of the RSD/Waste Feed Flow Loop cold-test platform depicted in Fig. 2. The prototypic or non-prototypic components and systems of the cold-test platform are listed in Table I.

Table I. Table of Major RSD/Waste Feed Flow Loop Components and Systems.

Waste Flow Loop Components and Systems	**Prototypic**	**Non-prototypic**
Piping System	X	
Coriolis Meter for Mass Flow Rate and Specific Gravity Measurements	X	
Isolok™ Sampler	X	
Isolok™ Sampler Simulated Glove Box		X
Ultrasonic PulseEcho Test Section and Data Acquisition System	X	
Transparent Test Sections adjacent to the PulseEcho Test Section		X
Mixing Tank and Agitator for Slurry Preparation		X
Effluent Tank		X
Slurry Pump		X
Chiller Unit for Temperature Control		X

The RSD/Waste Feed Flow Loop included 77.9-mm inner diameter nominal 0.08-m (3-inch) Sch 40 stainless steel pipe with a centrifugal pump capable of pumping at slurry velocities from 0.61-2.4 m/s (2.0-8.0 ft/s). The flow loop was equipped with a data acquisition system connected to the Coriolis meter to monitor and record the mass flow rate and the specific gravity of the slurry. The ultrasonic PulseEcho instrument included a separate data acquisition system to operate the ultrasonic transducers and analyze the ultrasonic data.

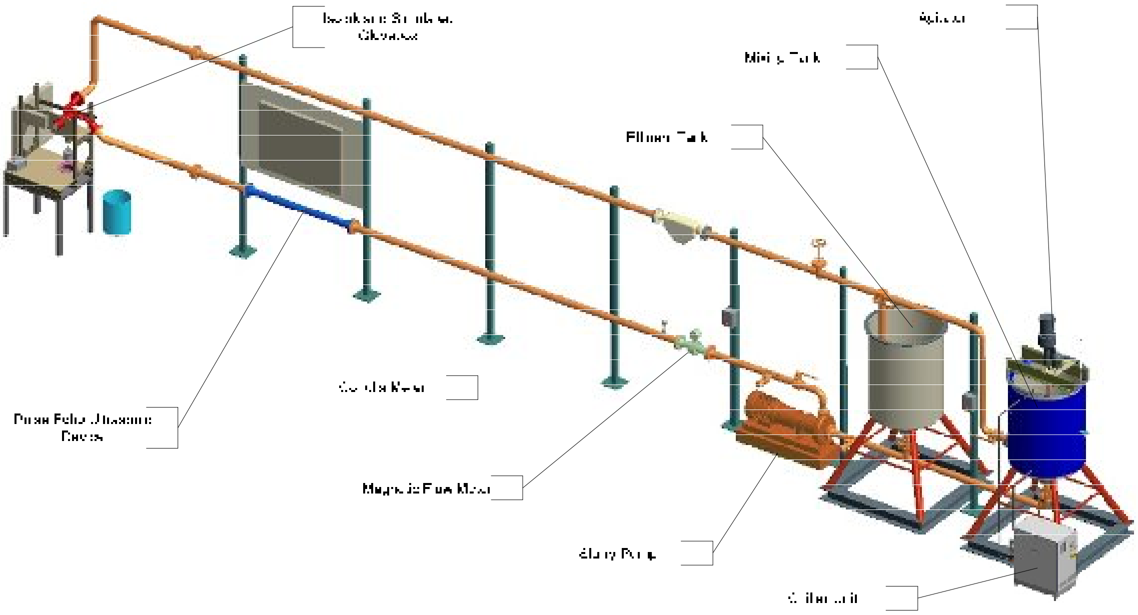

Fig 2. Layout of the WRPS RSD/Waste Feed Flow Loop.

The PulseEcho test section was installed downstream of approximately 4.6-5.5 m (15-18 ft), or 60-70 pipe diameters, of straight horizontal pipe connected to the slurry pump and approximately 1.2 m (4 ft), or 15 pipe diameters, of straight horizontal pipe were located downstream of the PulseEcho test section.

This installation location was similar to that used during 2010-2011 testing at PNNL and was selected because flow conditions at this flow loop location should be well-developed and appropriate for making observations and measurements used to determine critical velocity.

Two match-ported transparent pipe test sections were installed upstream and downstream of the PulseEcho test section and were adjacent to each end of the PulseEcho test section as shown in Fig 3. The transparent test sections facilitated visual observations by the operators and optical detection of settled particles by a high-resolution video camera system. It was assumed that particle settling had occurred in the opaque PulseEcho test section at the transducer locations if optical detection methods yielded particle settling had occurred upstream and downstream of the PulseEcho test section.

High-resolution camera placed underneath the downstream visual test section.

PulseEcho test section installed between the upstream and downstream visual test sections.

PulseEcho data acquisition electronics.

Fig 3. Photograph of the PulseEcho test section and visual test section installed in the WRPS RSD/Waste Feed Flow Loop.

Ultrasonic PulseEcho Test Section

The PulseEcho test section used during 2012 System Performance testing was the same as that used during 2011 testing at PNNL and described by Denslow et al. [7]. The PulseEcho test section was constructed from a 76-mm (3.0-inch) inner diameter (ID) stainless steel tubing with a 9.5 mm (0.375-inch) wall thickness. The bottom of the PulseEcho test section was modified on its outer diameter (OD) surface to contain several 50.8-mm (2-inch) long flat areas that served as installation locations for the ultrasonic transducers. Although the test section contained flat areas with half the nominal 0.08-m (3-inch) diameter Sch 40 wall thicknesses, which were used for 2011 testing, only the ultrasonic transducers that were installed on the flat areas with wall thicknesses greater than or equal to a full Sch 40 pipe wall thickness (i.e., ≥ 5.5 mm) were employed during the 2012 System Performance tests. A photograph of the ultrasonic transducers installed on the PulseEcho test section is provided in Fig 4.

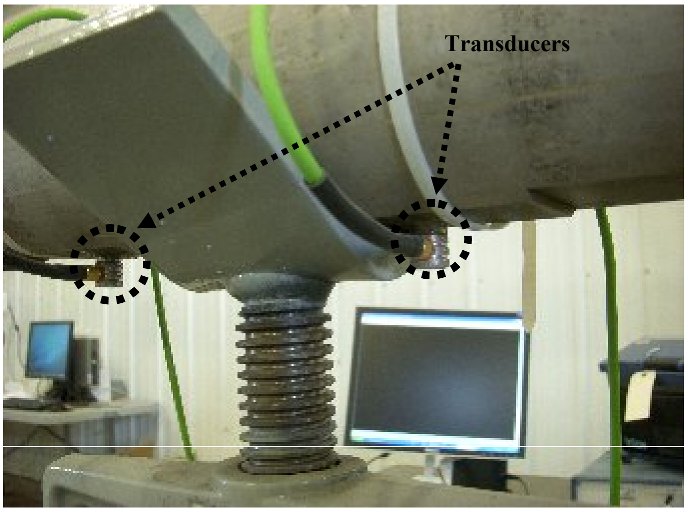

Fig 4. Photograph of two ultrasonic transducers installed on the flat areas located underneath the PulseEcho test section.

The center points of the ultrasonic transducers were aligned with the flat area centerlines during installation on the PulseEcho test section. The PulseEcho test section was then gravimetrically leveled during installation in the RSD/Waste Feed Flow Loop to ensure perpendicularity between the flat areas and the direction of gravity. This was done to ensure the ultrasonic transducers were centered along the bottom-most points of the test section where particle settling was expected to occur first.

Reference Measurements for Identifying Critical Velocity

The critical velocities for 17 slurry simulants were determined during 2012 System Performance testing by detecting settled particles with visual and optical methods and correlating this condition with a superficial flow velocity calculated from the density and the mass flow rate measured by the Coriolis meter for a nominal 0.08-m (3-inch) diameter Sch 40 pipe. The critical velocities determined with visual/optical methods served as the reference data against which the ultrasonic PulseEcho data were compared. The performance of the PulseEcho instrument was evaluated by comparing the fluid velocities at which it ultrasonically detected settled particles with the fluid velocities at which settled particles were detected visually/optically.[1] This approach is consistent with that reported in Bontha et al. [3,5] and Denslow et al. [6-8].

Critical velocity was determined for slurries in transport pipes by optically detecting the settling of solid particles. The pipeline transport of solids suspended in a carrier liquid is considered "critical" when the superficial flow velocity is just at the point where solids suspension becomes challenged. The behavior of the solids at this velocity depends on the specific properties of the solids and the carrier fluid and may exhibit conditions ranging from a solids concentration gradient, to "saltation," to a "sliding bed," or even a stationary layer of solids. Although *ICD 19 - Interface Control Document for Waste Feed* identifies critical velocity as a Waste Acceptance Criteria parameter, it does not define under which of these

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[1] Optical" indicates visual observations that were aided by a high-resolution camera.

conditions a flow is considered to have achieved "critical velocity". The critical velocity definition employed to evaluate the PulseEcho instrument encompasses the superficial flow velocity range that includes the first sign of a thin transitory or a "stop & go" settled bed of particles to the formation of a stationary settled bed of particles.

The first year of testing in 2010 revealed the best technique for 1) observing solids behaviors characteristic of imminent critical velocity and 2) confirming the formation of a stationary layer of solids to identify critical velocity was to place a high-resolution video camera beneath the transparent pipe sections. Therefore, this technique was used again during 2012 System Performance testing. The video camera employed was a Point Grey Research model Grasshopper–GRAS20S4M–monochrome (black/white) fit with a 1624 × 1224 pixel sensor, with each pixel representing a 4.4-μm × 4.4-μm square. The camera operates at 30 frames/second at full resolution (1600 × 1200 pixels). The camera lens is a Donder Zoom Module that provides a field of view (FOV) of 3200 μm to 12800 μm over the zoom range of the lens. As noted in Bontha et al. [3-4], this system is capable of detecting particle behavior from particle sizes ranging from 5 to 500 μm in diameter.

Ultrasonically Identifying Critical Velocity with the PulseEcho Instrument

The ultrasonic PulseEcho instrument was developed at PNNL in 2007 specifically to address the need to detect the onset of solid particle settling and accumulation at the bottom of vessels and pipes during slurry mixing and transport. The instrument's ultrasonic transducer is non-invasively installed on the underside of a vessel or pipe (on the OD surface) as illustrated in Fig 4. The transducer sends pulses of ultrasonic energy through the vessel or pipe wall at wavelengths (λ) that interact with the solid particles in the slurry that are on the same order as λ. These interactions result in scattering of the sound field energy, a portion of which is scattered back in the direction of the transducer. The non-coherent back-scattered energy is recorded in the form of amplitude vs. time signals, where time corresponds with depth in the slurry beyond the pipe or vessel wall via Equation 1.

$$d = c\,(t/2), \qquad \text{(Equation 1)}$$

where d=depth, c=speed of sound through the settled particles, and t=time. The user sets the range over which the instrument monitors particle behavior beyond the pipe or vessel wall. The range-gated back-scatter signals are then analyzed by the PulseEcho instrument's variance algorithm to determine if waveforms in the back-scatter signals are modulated, signifying particle motion, or not modulated, signifying no particle motion. This particle mobility information is used to determine if solids near the inside wall of the pipe or vessel are completely mobilized, beginning to settle, or settled/accumulated at the location where the transducer is installed. The PulseEcho instrument performs measurements at a rate of up to 100 times per second (100 hertz) to keep pace with rapidly changing conditions during mixing or flow. The backscattered signals, such as that shown in Fig 5 are analyzed immediately by the variance algorithm, and data on the state of the slurry are presented to the operator via the software user interface. Consequently, with these data, the operator can deduce critical flow velocities, characterize the effectiveness of mixing parameters, and quantify the thickness of a settled layer of solid particles in real time.

Fig 5. Example of a non-coherent ultrasonic backscattered signal.

The primary objective of the PulseEcho measurements during the 2012 System Performance testing was consistent with that of previous testing, which was to evaluate the ability of the PulseEcho system to detect settled particles through a pipe wall thickness that is equal to or greater than that of a nominal 0.08-m (3-inch) diameter Sch 40 stainless steel slurry pipe wall. The same two ultrasonic transducer frequencies that were used during 2011 testing were used for 2012 System Performance testing - 10 megahertz (MHz) and 5 MHz. These two transducer frequencies were selected based on particle sizes of the simulated waste slurries. The selection process is described in more detail in Denslow et al. [6-7]. In essence, a 10-MHz transducer was selected for its ability to detect smaller particle sizes of approximately 14 μm and larger and a 5-MHz transducer frequency was selected for its ability to detect particle sizes around 30 μm and larger. The 10-MHz transducer frequency was first evaluated during 2011 testing at PNNL, whereas the 5-MHz transducer frequency was evaluated during 2010 and 2011 testing and was used again for System Performance testing to continue to provide continuity across all the test phases. The 10-MHz and 5-MHz transducers have diameters of 6.4 mm (0.25 inch) to maximize measurement accuracy by monitoring the behavior of solids over a small area. The transducers were purchased from NDT Systems, Inc. (Huntington Beach, CA) and interfaced with the system of PulseEcho electronics that currently include a waveform generator to provide system timing signals, an ultrasonic pulser/receiver unit to transmit and receive ultrasonic signals, and a high-speed analog-to-digital (A/D) card to convert analog ultrasonic signals to digital signals before sending data to the laptop computer for data analysis and reporting. The digital oscilloscope is used for continuous independent monitoring. A photograph of the hardware that comprises the PulseEcho electronics is shown in Fig 3. Additional discussion on wave-particle interactions and measurement requirements is provided in the Discussion section.

Simulants

The PulseEcho instrument was initially evaluated in the RSD/Waste Feed Flow Loop using a simulant prepared with 20-wt% glass particles in water. This test was performed to verify the repeatability of the PulseEcho instrument's measurements before beginning tests with the System Performance slurry matrix. The 20-wt% glass particle in water simulant was selected for verification testing because it had also been used during 2010 and 2011 testing and the critical velocity test results from 2012 could be compared with those from 2010 and 2011.

The glass bead simulant was composed of a broad distribution of particles sizes with the same particle material density of 2500 kg/m^3 and was prepared by mixing together glass particles of different sizes. The broad particle size distribution (PSD) formulation and the property and supplier information for the glass particle constituents are provided in Table II. The density of the particles presented are the nominal values and the d(50) particle size is based on the volume fraction. This 20-wt% glass bead-in-water simulant is considered to be high in solids concentration in a carrier fluid with low viscosity and low yield stress. The dry simulant was weighed at PNNL and delivered to the Monarch test facility where the operators loaded it into the RSD/Waste Feed Flow Loop.

Table II. Formulation for the Broad PSD Simulant and Property and Supplier Information for the Broad PSD Constituent Glass Particles.

Formulation for the Broad PSD Simulant

Composition	Component (mass%)	Particle Material	Particle Material Density (kg/m^3) [a]	Particle Size d(50), µm [a]
SPHERIGLASS® 5000	7	Soda Lime Glass	2500	93.8
SPHERIGLASS® 3000	14			
BALLOTINI Mil #13	29			
BALLOTINI Mil #10	29			
BALLOTINI Mil #6	14			
BALLOTINI Mil #4	7			

Broad PSD Glass Particle Constituents

Constituent	Supplier/ Manufacturer	Product ID	Particle Material Density (kg/m^3) [a]	Particle Size (d50), µm [a]
SPHERIGLASS® 5000	Potters Industries	A Glass, 5000	2500	7.1
SPHERIGLASS® 3000	Potters Industries	A Glass, 3000	2500	34.0
BALLOTINI Mil #13	Potters Industries	MIL-PRF-9954D#13	2500	57.7
BALLOTINI Mil #10	Potters Industries	MIL-PRF-9954D#10	2500	114.9
BALLOTINI Mil #6	Potters Industries	MIL-PRF-9954D#6	2500	190.5
BALLOTINI Mil #4 sieved <500 µm	Potters Industries	MIL-PRF-9954D#4	2500	502.8

[a] Material density of the particles presented are the nominal values and the d(50) particle size is based on the volume fraction.

The System Performance slurry matrix was designed by WRPS principally to evaluate the ability of the RSD Isolok™ Sampler system to obtain reliable samples from the RSD/Waste Feed Flow Loop. The System Performance test simulants were not designed to challenge the PulseEcho instrument, as was the case during 2010 and 2011 testing, but broadened the database of simulants with which the instrument has been tested to include those slurries expected to be encountered in a "typical" service setting. A summary of the 17 waste feed slurry simulants tested under the 2012 System Performance test campaign is provided in Table III.[2] The planned simulant concentrations and constituents for each test and their properties are presented in Table IV through Table VI.

Table III. Test Matrix Comprised of 17 Slurry Simulants for which Critical Velocity was determined during 2012 System Performance Testing.

Test ID No.	Base Simulant Constituents	Supernate Simulant Composition [a]	Base Simulant Mass Loading / non-Newtonian Bingham Yield Stress
32	Typical	Typical	9 wt%
33	Typical	High	9 wt%
34	Typical	Low	13 wt%
35	Typical	Typical	13 wt%
36	Typical	High	13 wt%
37	High	Low	9 wt%
38	High	Typical	9 wt%
39	High	High	9 wt%
40	High	Low	13 wt%
41	High	Typical	13 wt%
41a	High	Typical	13 wt%
42	High	High	13 wt%
42a	High	High	13 wt%
43	--	Non-Newtonian	3 Pa [a]
44	--	Non-Newtonian	10 Pa [a]
45	Typical	Typical	13 wt% with 5 wt% added as spike particles
46	Typical	Low	9 wt%

[a] Non-Newtonian tests include quantification of added stainless steel and zirconium oxide solids. The amount of these solids added to the slurry is equivalent to the amount of these solids in Test No. 41.

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[2] The test simulants are discussed in detail in *One System Waste Feed Delivery Mixing and Sampling Program System Performance Test Plan*. RPP-PLAN-52623, Rev A, Washington River Protection Solutions, Richland, Washington, 2012.

Table IV. Test Matrix of Planned System Performance Particle Mixtures and Concentrations.

Test ID No.	**Supernate Description, wt%**	**Small Gibbsite wt%**	**Large Gibbsite wt%**	**Small Sand wt%**	**Medium Sand wt%**	**Large Sand wt%**	**ZrO_2 wt%**	**$Zr(OH)_4$ wt%**	**SS wt%**	**SS (1.59 mm) wt%**
32	Typical, 91.0	2.43	3.96	--	1.17	--	0.90	--	0.54	--
33	High, 91.0	2.43	3.96	--	1.17	--	0.90	--	0.54	--
34	Low, 87.0	3.51	5.72	--	1.69	--	1.30	--	0.78	--
35	Typical, 87.0	3.51	5.72	--	1.69	--	1.30	--	0.78	--
36	High, 87.0	3.51	5.72	--	1.69	--	1.30	--	0.78	--
37	Low, 91.0	--	0.27	3.15	--	1.89	0.72	--	2.97	--
38	Typical, 91.0	--	0.27	3.15	--	1.89	0.72	--	2.97	--
39	High, 91.0	--	0.27	3.15	--	1.89	0.72	--	2.97	--
40	Low, 87.0	--	0.39	4.55	--	2.73	1.04	--	4.29	--
41	Typical, 87.0	--	0.39	4.55	--	2.73	1.04	--	4.29	--
41a	Typical, 87.0	--	0.38	4.55	--	2.75	--	1.04	4.31	--
42	High, 87.0	--	0.39	4.55	--	2.73	1.04	--	4.29	--
42a	High, 87.0	--	0.40	4.56	--	2.73	1.03	--	4.30	--
43	Non-Newtonian 3Pa, 94.06	--	--	--	--	--	1.16	--	4.78	--
44	Non-Newtonian 10 Pa, 94.06	--	--	--	--	--	1.16	--	4.78	--
45	Typical, 87.0	3.33	5.43	--	1.61	--	1.24	--	0.74	0.65
46	Typical, 91.00	2.41	3.95	--	1.15	--	0.52	--	0.92	--

Table V. Test Matrix of Properties of the System Performance Test Simulant Constituents.

Simulant	**Material Density (kg/m^3)**	**Particle Size (d50, µm)**
Small Gibbsite	2420	1.3
Large Gibbsite	2420	10
Small Sand	2650	57
Medium Sand	2650	148
Large Sand	2650	382
Zirconium Oxide (ZrO_2)	5700	6.0
Stainless Steel (SS)	8000	112
Stainless Steel 1.59 mm (SS 1.59 mm)	8000	1587
Kaolin	2680	1.02
Sodium Thiosulfate	1670	N/A
Glycerol	1260	N/A
Water	1000	N/A
Low	1100	N/A
High	1370	N/A
Typical	1290	N/A
Non-Newtonian 3 and 10 Pa	1.20	N/A
Non-Newtonian 3 and 10 Pa	1370	N/A

Table VI. Test Matrix of Planned System Performance Supernate Mixtures.

Supernate	**Glycerol wt%** [a]	**Sodium Thiosulfate wt%** [a]	**Kaolin wt%** [a]
Low	--	12.0	--
Typical	--	31.5	--
High	19.5	33.4	--
3 Pa	--	--	22.0
10 Pa	--	--	28.0

[a] The percentages represent the relative amounts (by weight) of the constituents in water.

Test Procedure

The test procedure used for the PulseEcho System Performance tests to determine critical velocity for the test slurries was the same as that used during previous testing and is presented in greater detail by Denslow et al. [8]. Prior to collecting any ultrasonic PulseEcho data on a test simulant, pre-tests were performed to estimate the upper and lower bounds of the flow velocity range that contained the test slurry's critical velocity. This step was necessary in order to reduce the total time duration of the test. The pre-tests were accomplished by setting the flow velocity to 1.8 m/s (6.0 ft/s) or, if required, up to 2.4 m/s (8.0 ft/s) to fully suspend the slurry particles. The flow velocity was then decreased in 0.3 m/s (1.0 ft/s) increments, allowing a steady-state condition (characterized by five or more minutes of density measurements within ±100 kg/m^3) to be achieved at each setting. Flow velocity was reduced in this manner until a thin stationary bed of particles was observed in the visual test sections by the flow loop operators. This flow velocity was noted before increasing the flow velocity again to 1.8 - 2.4 m/s (6.0–8.0 ft/s) to re-suspend the particles in the slurry. After sufficient mixing time, the flow velocity was reduced to a point well above the point at which a stationary bed of particles had been observed during the pre-tests. After steady state was declared, data were collected with the PulseEcho instrument, visual observations were made, and video was recorded with the high-resolution camera. Data were collected with each transducer over a period of ≥2.5 minutes at a measurement rate of 100 Hz. Flow velocity was decreased in increments of 0.03–0.06 m/s (0.1–0.2 ft/s) and data collected at each increment after steady state was reached. This was repeated until stationary settled particles were detected visually/optically and detected by the PulseEcho instrument.

RESULTS

The verification test for the PulseEcho instrument was the first test performed in the RSD/Waste Feed Flow Loop with the PulseEcho instrument. The purpose of the verification test was primarily to evaluate the repeatability of the PulseEcho measurements. In addition, the verification test helped ensure that PulseEcho electronics recalibration, relocation from PNNL to the Monarch test facility, and the new flow loop design at Monarch had no influence on the performance of PulseEcho. The simulant selected for the verification test was 20-wt% broad PSD glass particles in water as identified in Table II. This simulant was selected because PulseEcho data had been collected for it during 2010 and 2011 testing at PNNL. Therefore, old data could be compared with new data to evaluate measurement repeatability.

A summary of the flow velocities at which settled particles were detected (critical velocities) with visual/optical methods and with the PulseEcho instrument for the 20-wt% broad PSD glass beads-in-water verification test simulant is provided in Table VII. For easy comparison, 2012 test results obtained in the RSD/Waste Feed Flow Loop are shown with test results obtained during earlier tests at PNNL. "Half Wall" is used to describe a PulseEcho test section transducer location with a wall thickness that is half that of a nominal 0.08-m (3-inch) diameter Sch 40 slurry pipe wall thickness and "Full Wall" is used to describe a test section transducer location with a full pipe wall thickness (i.e., ≥ 5.5 mm). Different combinations of pipe wall thicknesses and ultrasonic transducer frequencies have been evaluated over the three test campaigns; however, not every wall thickness/frequency combination was evaluated each year and only the full pipe wall thickness transducer locations were utilized for the verification test and the System Performance tests.

Table VII. Comparison of 2012 Verification Test Results with Results from the 2010 and 2011 Test Campaigns for a Simulant Comprised of 20-wt% Broad PSD Glass Beads in Water.

Test Campaign	$V_{critical}$ [a] **Visual/Optical** **m/s** [ft/s]	$V_{critical}$ **5-MHz Ultrasonic Transducer** **m/s** [ft/s]		$V_{critical}$ **10-MHz Ultrasonic Transducer** **m/s** [ft/s]	
		Half Wall	**Full Wall**	**Half Wall**	**Full Wall**
2010	**1.2** [4.0]	**1.2** [4.1]	N/A [b]	N/A [b]	N/A [b]
2011	**1.2** [4.0]	**1.2** [4.0]	**1.2** [4.0]	N/A [b]	**1.2** [3.9]
2012	**1.2** [4.0]	N/A [b]	**1.3** [4.3]	N/A [b]	**1.2** [4.1]

[a] Defined as a stationary bed of settled solids.

[b] Indicates that the transducer and/or wall thickness were not tested during the test campaign.

Following the verification test, the PulseEcho instrument was tested with a total of 17 System Performance test slurries in the RSD/Waste Feed Flow Loop to evaluate the ability of the instrument to detect settled particles and determine critical velocity. A summary of the flow velocities at which settled particles were detected using visual/optical methods and detected with the PulseEcho instrument is provided in Table VIII. The flow velocities at which settled particles were detected with visual/optical methods are reported for Regime III (transitory settled particles, e.g., “stop & go” behavior) and critical velocity $V_{critical}$ (stationary settled particles). The flow velocities at which settled particles were detected with the 5-MHz and the 10-MHz ultrasonic transducers are provided. These are the flow velocities at which settled particles were ultrasonically detected ≥10% of the time over an acquisition period of ≥2.5 minutes.

A wide range of particle settling behavior was observed for many of the 17 System Performance test slurries. These visual observations are provided in Table VIII with the results for Regime III and $V_{critical}$. Although *ICD 19 - Interface Control Document for Waste Feed* identifies critical velocity as a Waste Acceptance Criteria parameter, it does not define under which of these conditions a flow is considered to have achieved “critical velocity”. The critical velocity definition employed to evaluate the PulseEcho instrument therefore encompasses the flow velocity range that includes the first sign of a transitory or a “stop & go” settled bed of particles (Regime III) to the formation of a thin stationary settled bed of particles ($V_{critical}$). The PulseEcho results obtained with the 5-MHz and 10-MHz ultrasonic transducers are reported along with a checkmark symbol (✓) or a cross-out symbol (✖). The ✓ symbol indicates the PulseEcho instrument detected settled particles at a flow velocity that is within ±0.09 m/s (±0.3 ft/s) of the visually determined flow velocities for Regime III (transitory “stop & go” settled bed) and critical velocity $V_{critical}$ (stationary settled bed). See Bontha et al. (2010a) for more information on the definitions of the flow behavior observed during critical velocity measurements. The ✖ symbol indicates the PulseEcho instrument detected settled particles at a flow velocity that is outside ±0.09 m/s (±0.3 ft/s) of the range for Regime III and $V_{critical}$.

Table VIII. Summary of Critical Velocity Detection for System Performance Slurry Simulants as Determined by the PulseEcho Instrument and by Visual/Optical Methods.

	SIMULANT PROPERTIES	**VISUAL OBSERVATIONS**		**PULSE-ECHO**	
Test ID No.	**Base/Supernate Simulant, Base Simulant Mass Loading or Non-Newtonian Bingham Yield Stress**	**Regime III Transitory Settled Particles** **m/s** [ft/s]	**$V_{critical}$ Stationary Settled Particles Observed in the Upstream *and* Downstream Visual Test Sections** **m/s** [ft/s]	**5 MHz Transducer, Located Upstream** **m/s** [ft/s]	**10 MHz Transducer, Located Downstream** **m/s** [ft/s]
32	Typical/Typical, 9wt%	**1.1→0.82** [3.6→2.7]	**0.79** [2.6]	**1.0** [3.4] ✓	**1.0** [3.3] ✓
		Note: Sliding piles of particles observed, starting at 1.0 m/s [3.4 ft/s]. Settled particles in upstream visual section at 0.82 m/s [2.7 ft/s].			
33	Typical/High, 9 wt%	**1.4→1.3** [4.6→4.3]	**1.3** [4.2]	**1.3** [4.2] ✓	**1.2** [4.1] ✓
		Note: Settled particles in upstream visual section at 1.3 m/s [4.3 ft/s].			
34	Typical/Low, 13 wt%	**1.7→1.6** [5.7→5.2]	**1.5** [5.0]	**1.6** [5.1] ✓	**1.5** [4.8] ✓
		Note: Settled particles in upstream visual section at 1.6 m/s [5.2 ft/s].			
35	Typical/Typical, 13 wt%	**1.1→0.82** [3.7→2.7]	**0.79** [2.6]	**1.1** [3.5] ✓	**1.0** [3.4] ✓
		Note: Sliding piles of particles observed, starting at 1.1 m/s [3.5 ft/s].			
36	Typical/High, 13 wt%	**1.5→1.3** [4.8→4.4]	**1.3** [4.3]	**1.3** [4.4] ✓	**1.3** [4.3] ✓
		Note: Settled particles in upstream visual section at 1.4 m/s [4.5 ft/s].			
37	High/Low, 9 wt%	**2.2→2.1** [7.1→6.9]	**2.1** [6.8]	**2.1** [6.9] ✓	**2.1** [6.9] ✓
		Note: Settled particles in upstream visual section at 2.1 m/s [7.0 ft/s].			
38	High/Typical, 9 wt%	**1.6** [5.4→5.2]	**1.6** [5.1]	**1.6** [5.3] ✓	**1.5** [5.0] ✓
		Note: Settled particles in upstream visual section			

		at 1.6 m/s [5.3 ft/s].			
39	High/High, 9 wt%	**1.3→1.2** [4.4→4.1]	**1.2** [4.0]	**1.2** [4.1] ✓	**1.2** [3.9] ✓
		Note: Settled particles in upstream visual section at 1.2 m/s [4.1 ft/s].			
40	High/Low, 13 wt%	**2.3→2.2** [7.6→7.1]	**2.1** [7.0]	**2.2** [7.1] ✓	**2.2** [7.1] ✓
		Note: Settled particles in upstream visual section at 2.2 m/s [7.1 ft/s].			
41	High/Typical, 13 wt%	**1.7** [5.6→5.5]	**1.6** [5.4]	**1.6** [5.4] ✓	**1.6** [5.3] ✓
		Note: Settled particles in upstream visual section at 1.7 m/s [5.5 ft/s].			
41a	High/Typical, 13 wt%	**1.8→1.7** [5.9→5.5]	**1.6** [5.4]	**1.7** [5.5] ✓	**1.6** [5.4] ✓
		Note: Settled particles in upstream visual section at 1.7 m/s [5.5 ft/s].			
42	High/High, 13 wt%	**1.4→1.3** [4.5→4.3]	**1.3** [4.2]	**1.3** [4.3] ✓	**1.2** [4.1] ✓
		Note: Settled particles in upstream visual section at 1.3 m/s [4.3 ft/s].			
42a	High/High, 13 wt%	**1.8→1.3** [6.0→4.2]	**1.2** [4.1]	**1.2** [4.1] ✓	**1.2** [4.0] ✓
		Note: Settled particles in upstream visual section at 1.3 m/s [4.2 ft/s].			
43	Non-Newtonian, 3 Pa	**1.8→1.6** [6.0→5.1]	**1.5** [5.0]	**1.6** [5.4] ✓	**1.6** [5.1] [a] ✓
		Note: Settled particles in upstream visual section at 1.6 m/s [5.1 ft/s].			
44	Non-Newtonian, 10 Pa	**2.1→1.6** [6.8→5.3]	**1.6** [5.2]	**1.7** [5.7] ✓	**1.6** [5.3] [b] ✓
45	Typical/Typical, 13 wt% (5 wt% of the solids included as spike particles)	**1.2→1.1** [3.8→3.5]	**1.0** [3.4]	**1.0** [3.4] ✓	**1.1** [3.5] ✓
		Note: Piles of settling and eroding particles were observed, starting at 1.1 m/s [3.5 and 3.6 ft/s].			
46	Typical/Low, 9 wt%	N/A, directly to $\mathbf{V}_{\mathbf{critical}}$	**1.4** [4.7]	**1.4** [4.6] ✓	**1.2** [4.0] ✗
		Note: Motion observed again upstream at 1.2 m/s [4.0 and 3.9 ft/s].			

[a] The 10-MHz transducer did not constantly detect scattering at 2.2 m/s (7.2 ft/s) and reported sediment more than 10% of the time at this flow velocity.

[b] The 10-MHz transducer did not constantly detect scattering at 2.5 m/s (8.3 ft/s) and reported sediment more than 10% of the time at this flow velocity.

DISCUSSION

The visually determined critical velocity for the 20-wt% broad PSD simulant during the verification test in the RSD/Waste Feed Flow Loop was 1.2 m/s (4.0 ft/s). This is consistent with the visually determined critical velocities for this simulant from 2010 and 2011 testing at PNNL. The PulseEcho system determined stationary critical velocity to be 1.2 m/s (4.1 ft/s) and 1.3 m/s (4.3 ft/s), as measured by the 10-MHz and 5-MHz transducers, respectively, at the transducer locations on the PulseEcho test section that have wall thicknesses equal to or greater than that of a nominal 0.08-m (3-inch) diameter Sch 40 pipe. These results are 0.03 m/s (0.1ft/s) and 0.09 m/s (0.3 ft/s) higher than the visually determined critical velocity of 4.0 ft/s. The superficial flow velocity at which particle settling was detected during the verification test by the 10-MHz transducer at the full-wall (Sch 40) location is 0.06 m/s (0.2 ft/s) higher than the corresponding 2011 measurements. The 5-MHz verification test measurements are 0.06 m/s and 0.09 m/s (0.2 ft/s and 0.3 ft/s) higher than the 2011 and 2010 measurements at the full-wall (0.08-m or 3-inch diameter Sch 40 pipe wall thickness) and half-wall (1/2 the pipe wall thickness of a (0.08-m or 3-inch diameter Sch 40 pipe) locations. Although there are differences between the 2010/2011 PulseEcho values and the 2012 verification test PulseEcho values for this simulant, the differences are not larger than ones previously obtained between visually and ultrasonically determined measurements. Therefore, the instrument's performance was found satisfactory and suitable for System Performance testing.

The objective of the PulseEcho System Performance tests in the RSD/Waste Feed Flow Loop was consistent with the objective of prior tests at PNNL; that is, to continue to verify the reliability of the PulseEcho instrument against visual detection of stationary particles. Several different flow loop operators performed and recorded the visual observations and operated the high-resolution camera, the data from which was used to determine Regime III and $V_{critical}$. A PNNL staff member who led many of the earlier tests in 2010 and 2011 trained the RSD/Waste Feed Flow Loop operators on the test procedure for determining critical velocity and reviewed the camera files. The flow velocities at which stationary solids were reported by the PNNL operator and the RSD/Waste Feed Flow Loop operators were within 0.03 m/s (0.1 ft/s).

In general, the flow velocities at which the PulseEcho instrument detected and reported settled particles in the PulseEcho test section in the RSD/Waste Feed Flow Loop are within 0.06 m/s (0.2 ft/s) of the flow velocities at which stationary settled particles were detected visually/optically in both visual test sections ($V_{critical}$). In some cases the PulseEcho instrument detected and reported settled solids in Regime III, which is a condition that precedes the formation of a stationary bed of settled particles and is characterized by transitory settled particles or pulsatory ("stop & go") migration of particle accumulations in the piping. For example, migrating piles of settled solids were visually observed and ultrasonically detected by the PulseEcho instrument during Test # 35 and Test #32 at flow velocities that are significantly higher than the critical velocity ($V_{critical}$). These migrating "stop & go" piles were stationary for a sufficient period of time and detected by the PulseEcho transducers ≥10% of the time during the data-acquisition window of ≥2.5 minutes, which resulted in reporting settled solids at these higher flow velocities. Graphs showing the percentage of ultrasonic measurements that detected settled solids for each flow velocity are shown in Fig 6 for Test #35 and Fig 7 Test #32. The 10-percent detection-reporting criterion is represented by the horizontal line.

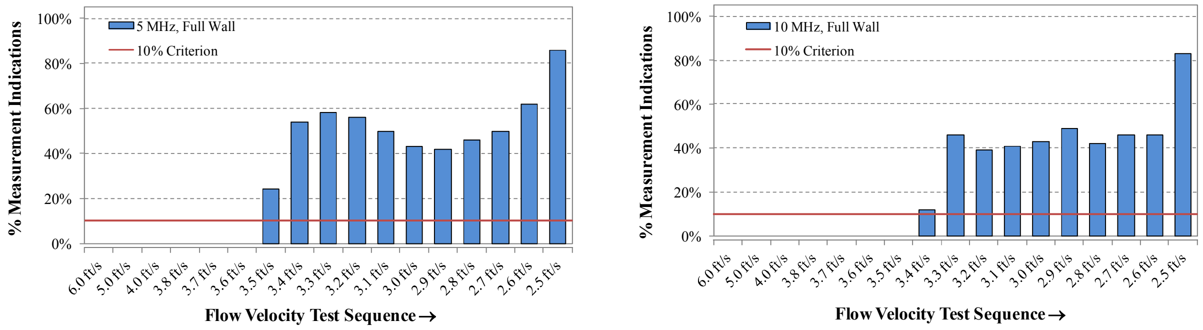

Fig 6. Graph of the Percentage of Ultrasonic Measurements by the 5-MHz and 10-MHz Transducers that Indicated Settled Particles for each Flow Velocity Tested during Test #35 (Typical/Typical, 13 wt% Simulant).

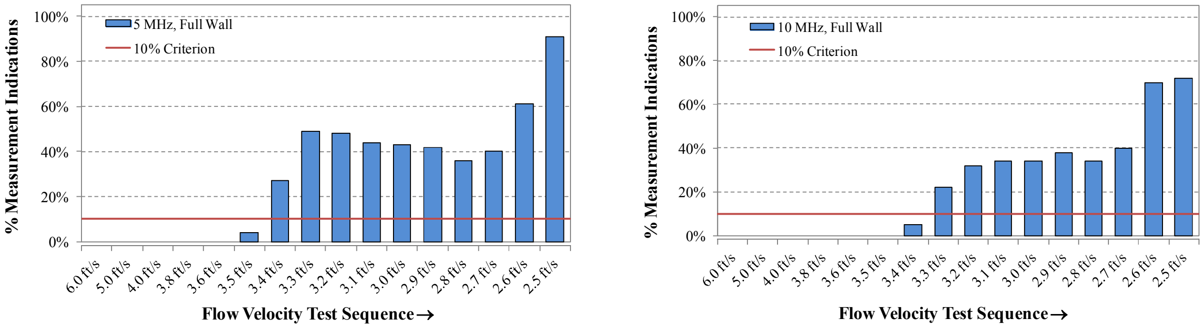

Fig 7. Graph of the Percentage of Ultrasonic Measurements by the 5-MHz and 10-MHz Transducers that Indicated Settled Particles for each Flow Velocity Tested during Test #32 (Typical/Typical, 9 wt% Simulant).

The simulants used during Tests #35 and #32 demonstrated transient particle settling (Regime III) over a wide range of flow velocities. This settling behavior emphasizes the importance of determining if this type of transitory settling will be acceptable during waste transfer to WTP.

The slight discrepancy between the 5-MHz and 10-MHz transducer readings during System Performance testing can likely be explained by the apparent settling gradient inside the PulseEcho test section. During most of the 17 tests conducted, stationary solids were observed in the upstream visual section before they were observed in the downstream visual section, indicating a stationary solids gradient was present inside the 0.61-m (24-inches) long PulseEcho test section that was located between the visual test sections. The 5-MHz transducer was located 0.15 m (6.0 inches) upstream of the 10-MHz transducer in the PulseEcho test section and typically detected stationary solids before the 10-MHz transducer. This upstream-to-downstream trend in detection is consistent with the visual observations.

Test #41 was repeated and identified as Test #41a. The original test had an incorrect constituent while the repeat test had all the correct constituents present. The visually determined critical velocity for Test #41 and Test #41a are the same at 1.6 m/s (5.4 ft/s). The PulseEcho results are very similar at 1.6 m/s (5.4 ft/s and 5.3 ft/s) for the 5-MHz and 10-MHz transducers, respectively, for Test #41 and 1.7 m/s and 1.6 m/s (5.5 ft/s and 5.4 ft/s) for the 5-MHz and 10-MHz transducers, respectively, for Test #41a.

The simulant used in Test #42 was the same as that used in the repeat test identified as Test #42a. The original test with this simulant was repeated because there were technical difficulties with the Isolok™ Sampler system during the first test. However, it also afforded a repeat test with the PulseEcho instrument. The visually determined critical velocities for Test #42 and Test #42a are 1.3 m/s and 1.2 m/s (4.2 ft/s and 4.1 ft/s), respectively. The PulseEcho instrument detected settling at 1.3 m/s and 1.2 m/s (4.3 ft/s and 4.1 ft/s) with the 5-MHz and 10-MHz transducers, respectively, during Test #42 and 1.2 m/s (4.1 ft/s and 4.0 ft/s) with the 5-MHz and 10-MHz transducers, respectively, for Test #42a. These measurements are within the ±0.03 m/s (±0.1 ft/s) uncertainty associated with visual observations and the typical ±0.06 m/s (±0.2 ft/s) uncertainty associated with the PulseEcho measurements.

In only one test case did a PulseEcho transducer detect settled particles at a flow velocity that was more than 0.09 m/s (0.3 ft/s) below the range for Regime III and $V_{critical}$. During Test #46 the 10-MHz transducer detected settling at 1.2 m/s (4.0 ft/s) while the 5-MHz detected settling at 1.4 m/s (4.6 ft/s) and the visually determined critical velocity was 1.4 m/s (4.7 ft/s). It is unclear whether the particle motion detected at the 10-MHz transducer location was a true reflection of the flow conditions at this location or a difference in sensitivity between the two transducers. The PulseEcho data were reviewed twice for this test and modulation was present in the ultrasonic signals from the 10-MHz transducer until 1.2 m/s (4.0 ft/s), indicating particle motion was detected at that location until 1.2 m/s (4.0 ft/s). The video files for this test show a bed of stationary settled particles was present in the downstream visual section at 1.4 m/s (4.7 ft/s); however, at 1.2 m/s (4.0 ft/s) the entire sediment bed was eroded and then re-deposited. This phenomenon could possibly indicated non-uniform settling in the PulseEcho test section beyond the typical upstream-to-downstream gradient. The slurry constituents used in the test slurry for Test #46 are not different from those used in several other tests and do not provide an explanation for the difference in measurements between the transducers. However, even though the 10-MHz transducer did not detect a bed when it was visually observed at 1.4 m/s (4.7 ft/s), there is enough uncertainty about both the timing and the uniformity of the settling behavior that it is difficult to conclude whether or not the 10 MHz transducer truly failed to reflect the in-pipe conditions.

Tests #43 and #44 were performed with non-Newtonian, kaolin-based supernate fluids (carrier fluids). The composition of these two test slurries only differed in the concentration of kaolin in the supernate fluid and the resulting yield stresses. Both test slurries contained zirconium oxide particles (having a PSD d50 of 6 micron) and stainless steel particles (having a PSD d50 of 112 micron). The zirconium oxide particles were too small to provide back-scatter to either transducer, but the stainless steel particles were large enough to provide back-scatter to both transducers. The solids concentration that was detectable in each test slurry was approximately 2.5 wt% for both transducers and therefore one transducer was not sensitive to more particles than the other. However, during Tests #43 and #44 the 10-MHz transducer did not consistently detect particle back-scattering at the highest flow velocities of 2.2 m/s (7.2 ft/s) and 2.5 m/s (8.3 ft/s), respectively, which led to the report of sediment. When the flow velocity was reduced and the particle population density increased near the transducers due to stratification the 10-MHz transducer was able to detect increased back-scatter and make reliable measurements. The 5-MHz transducer detected back-scattering and did not report sediment at high flow velocities during all 17 tests. Graphs showing the percentage of ultrasonic measurements that detected settled solids for each flow velocity for these two tests are shown in Fig 8 and Fig 9. Low particle back-scattering at high flow velocities for slurries containing low particle concentrations and carrier fluids with high ultrasonic attenuation has been observed in past tests and has been reported and discussed in Bontha et al. (2010a) and Denslow et al (2011).

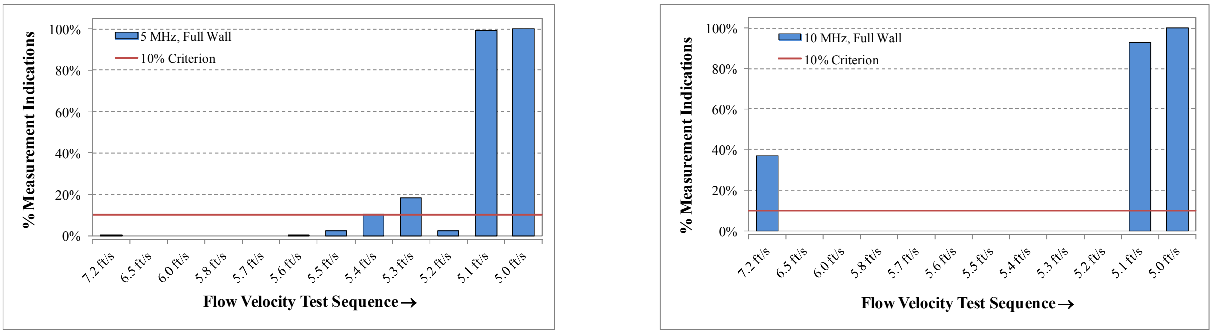

Fig 8. Graph of the Percentage of Ultrasonic Measurements by the 5-MHz and 10-MHz Transducers that Indicated Settled Particles for each Flow Velocity Tested during Test #43 (non-Newtonian, 3 Pa).

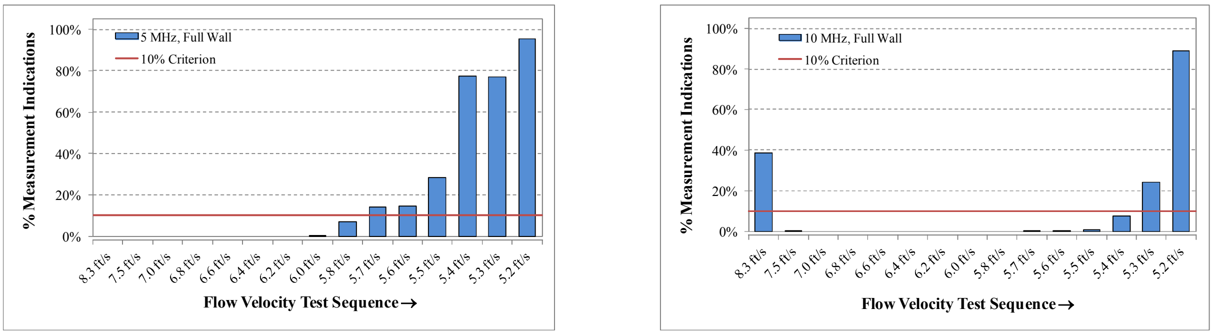

Fig 9. Graph of the Percentage of Ultrasonic Measurements by the 5-MHz and 10-MHz Transducers that Indicated Settled Particles for each Flow Velocity Tested during Test #44 (non-Newtonian, 10 Pa).

ICD 19 - Interface Control Document for Waste Feed specifies the critical velocity for high-level waste (HLW) feed slurries must be ≤ 1.2 m/s (≤ 4.0 ft/s) in a nominal 0.08-m (3-inch) diameter pipe. However, very few slurry simulants formulated for the System Performance tests had critical flow velocities that were ≤ 1.2 m/s (≤ 4.0 ft/s), and two slurry simulants had critical flow velocities near 2.1 m/s (7.0 ft/s). Differences between the target mass fraction of solids listed in Table IV and the actual mass fraction of solids that entered the RSD/Waste Feed Flow Loop are expected if mixing and/or transfer capacity in the flow loop was limited. In addition, stratification (or a solids concentration gradient) may have existed within the flow loop mixing and feed vessel that could have led to higher concentration slurries entering the flow RSD/Waste Feed Flow Loop. To quantify the exact composition of the waste stream that passed in front of the PulseEcho transducers during testing, full-diversion samples of 11-15 L (3-4 gallon) volumes were collected from the RSD/Waste Feed Flow Loop at the beginning and end of every test. Sub-samples of these full-diversion samples will be analyzed for particle concentration and PSD. These data and analyses are pending.

CONCLUSIONS

The completion of 2012 testing marks the completion of a cumulative three-year test campaign with the PulseEcho instrument. The verification test performed with the PulseEcho instrument in the RSD/Waste

Feed Flow Loop demonstrated good measurement repeatability and established that the instrument was not significantly affected by a change in flow loops. The 17 PulseEcho System Performance tests demonstrated that the instrument could detect settled particles through a full nominal 0.08-m (3-inch) diameter Sch 40 pipe wall for simulated Hanford Tank Farm slurries at flow velocities that were typically within 0.1 to 0.2 ft/s of the flow velocities at which stationary particles were detected visually/optically for the majority of the tests. These tests continue to increase confidence in the instrument's performance and its potential for field deployment.

Although *ICD-19* identifies critical velocity as a Waste Acceptance Criteria, it does not define under what conditions a flow is considered to have achieved a "critical velocity". The critical velocity definition employed to evaluate the PulseEcho instrument encompasses the flow velocity range that includes the first sign of a transitory or a "stop & go" settled bed of particles to the formation of a stationary settled bed of particles. The results obtained lead to the following conclusions:

1. The PulseEcho instrument is capable of repeatable detection of critical velocity, as defined herein.
2. For the majority of tests, the PulseEcho instrument detected settled particles at flow velocities that were within 0.03 to 0.06 m/s (0.1 to 0.2 ft/s) of the flow velocities at which stationary particles were detected visually/optically in the RSD/Waste Feed Flow Loop.
3. In some cases, the PulseEcho instrument results in a more conservative detection of critical velocity; that is, under conditions of incipient settling as characterized by transitory stationary bed or pulsatory flow (i.e., "stop & go") behavior at the bottom of the pipe (Regime III). Since Regime III happens before the formation of a settled bed, it is considered to be indicative of the onset of settling and PulseEcho would tend to see the "stop & go" motion provided it's >10% of the time.
4. The 10-MHz transducer did not consistently detect particle back-scatter at the highest flow velocities during Test #43 and Test #44 with kaolin slurries containing a detectable particle concentration of approximately 2.5 wt%. However, the 10-MHz transducer was able to detect increased back-scatter and resume reliable measurements when the flow velocity was reduced and the particle population density increased near the transducers due to stratification. The low back-scatter detected at the higher flow velocities is caused by a low particle population density near the transducers for a carrier fluid with high ultrasonic attenuation, which can occur at very high flow velocities for slurries that have particle concentrations of < 4 wt% in carrier fluids such as kaolin as reported by Denslow et al. [8]. Higher ultrasonic frequencies are more easily attenuated, which explains why only the 10-MHz transducer was impacted. The 5-MHz transducer detected back-scatter at high flow velocities during all 17 tests.
5. In only one test case did a PulseEcho transducer detect stationary particles at a flow velocity more than 0.09 m/s (0.3 ft/s) below the range for Regime III and the $V_{critical}$. It is unclear whether the particle motion detected at this 10-MHz transducer location was a true reflection of the flow conditions at this location or a difference in sensitivity between the two transducers.
6. The results from the 2012 System Performance test campaign and the 2010 and 2011 test campaigns continue to demonstrate the reliability and repeatability of the PulseEcho system to detect critical velocity in the actual Waste Feed Flow Loop.

All testing performed to date has been conducted under steady-state flow conditions and PulseEcho measurements have been performed at locations that are 60 to 70 pipe diameters downstream from points of flow disturbance in the full-scale flow loops. These monitoring locations were selected because conditions in the flow loops with well-developed flow eliminate uncertainties when assessing PulseEcho performance by comparison with visual measurements. In the actual Tank Farm Waste Feed Flow Loop, a set of two rotating jet mixers will be used to mix the feed vessel and the concentration of the solids drawn out through the transfer pump will vary depending on the location of the jets. Therefore, steady-state conditions in feed concentration cannot be expected to be present as the waste is pumped through the Waste Feed Flow Loop. It is not expected that the unsteady-state solids loading in the feed to the Waste Feed Flow loop will impact detection of a stationary bed by the PulseEcho system, but the behavior could impact the methodology used to apply the technology during actual waste feed test campaigns. In other words, based on the results obtained to date, it is believed that PulseEcho will detect the presence or absence of a stationary bed at the transducer location but translation of the PulseEcho measurement to a critical velocity will depend on 1) how the long and often measurements are made and 2) where the measurements are made. In order to address these two uncertainties in determining critical velocity, how the PulseEcho technique is implemented and used for oscillatory or transient conditions will have to be considered. Installing PulseEcho transducers at more than one location along the Waste Feed Flow Loop may be desired or necessary to ensure that settling and accumulation are detected at the points with the highest probability of settling or that have flow conditions that are representative of those that are expected to be encountered during waste transfer between the Hanford tank farms and WTP.

The two items identified above—how long and often measurements are made and where the measurements are made—will depend on the mixing and transfer systems used during actual waste feed transfer operations. Therefore, establishing the methodology for implementing the PulseEcho technology during cold testing of the Waste Feed Flow Loop is crucial to actual field deployment of the technology.

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