Savannah River Site
Incipient Sludge Mixing in Radioactive Liquid Waste Storage Tanks During Salt Solution Blending

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ABSTRACT

This paper is the second in a series of four publications to document ongoing pilot scale testing and computational fluid dynamics (CFD) modeling of mixing processes in 85 foot diameter, 1.3 million gallon, radioactive liquid waste, storage tanks at Savannah River Site (SRS). Homogeneous blending of salt solutions is required in waste tanks. Settled solids (i.e., sludge) are required to remain undisturbed on the bottom of waste tanks during blending. Suspension of sludge during blending may potentially release radiolytically generated hydrogen trapped in the sludge, which is a safety concern. The first paper (Leishear, et. al. [1]) presented pilot scale blending experiments of miscible fluids to provide initial design requirements for a full scale blending pump. Scaling techniques for an 8 foot diameter pilot scale tank were also justified in that work. This second paper describes the overall reasons to perform tests, and documents pilot scale experiments performed to investigate disturbance of sludge, using non-radioactive sludge simulants. A third paper will document pilot scale CFD modeling for comparison to experimental pilot scale test results for both blending tests and sludge disturbance tests. That paper will also describe full scale CFD results. The final paper will document additional blending test results for stratified layers in salt solutions, scale up techniques, final full scale pump design recommendations, and operational recommendations.

Specifically, this paper documents a series of pilot scale tests, where sludge simulant disturbance due to a blending pump or transfer pump are investigated. A principle design requirement for a blending pump is *UoD*, where *Uo* is the pump discharge nozzle velocity, and *D* is the nozzle diameter. Pilot scale test results showed that sludge was undisturbed below $UoD = 0.47$ ft^2/s, and that below $UoD = 0.58$ ft^2/s minimal sludge disturbance was observed. If sludge is minimally disturbed, hydrogen will not be released. Installation requirements were also determined for a transfer pump which will remove tank contents, and which is also required to not disturb sludge. Testing techniques and test results for both types of pumps are presented.

INTRODUCTION

Radioactive liquid waste is stored in forty-nine (49), underground tanks at SRS in three different waste forms (Figures 1.A and 1.B). These waste forms are precipitated salts referred to as saltcake, lighter salt solutions referred to as supernates, and heavier fluids referred to as sludge. Note that about half of the residual waste radioactivity is contained in the sludge which is only eight percent of the total waste volume (Figure 1.B).

Research presented here focuses on supernate preparations in waste tanks prior to transfer to the Salt Waste Processing Facility (SWPF, Figure 1E). At SWPF, separations processes yield two products, which are decontaminated supernate and sludge that contains Strontium, Cesium, and actinides. Once separations are complete, the sludge is washed and transferred to the Defense Waste Processing Facility (DWPF, Figure 1D), where sludge is mixed with molten glass for future disposition. Decontaminated salt solutions are transferred to the Saltstone facility (Figure 1C), where the decontaminated salt solutions are mixed with grout for permanent disposition at SRS in South Carolina.

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Several tanks will be used for the Salt Disposition Integration portfolio of projects (SDI). The tanks for SDI are referred to as SWPF blend or feed tanks. Salt solutions will be transferred from other waste tanks into these tanks, where different salt batches are expected to stratify in the feed tanks due to specific gravity (SpG) differences (Figure 1.F). Sludge may already be present in the tanks initially, or sludge may accumulate on the tank floors over time during transfers of salt solutions into waste tanks, since mall amounts of sludge are expected to be entrained in salt solutions transferred from other waste tanks into the blend or feed tanks. One goal of waste blending in the SDI tanks is to reduce the amount of solids in the waste prior to transfer to SWPF. A second goal is to prevent hydrogen release from sludge, where radiolysis dissociates water into hydrogen and oxygen, and trapped hydrogen can be released during sludge disturbance. Hydrogen release can potentially cause flammable conditions. Minimizing sludge disturbance facilitates both of these goals. This paper provides research results for sludge disturbance studies, as well as a preliminary review of related blending research and CFD modeling.

PREVIOUS RESEARCH

Previous experimental research on incipient sludge disturbance due to pump operations in waste tanks is unavailable. Even so, previous work was the foundation of this research. Previous research showed that: 1) CFD modeling could be used predict sludge mixing, 2) Hydrogen release from sludge is caused by sludge agitation, and 3) Measured sludge properties were available. This available data provided a basis for the research presented in this paper.

Sludge Mixing

Research at SRS demonstrated that CFD modeling could be used to predict the performance of mixing pumps to remove sludge from the bottom of waste tanks (Leishear, Lee, et. al. [2 and 3]). In that work, a combination of CFD modeling and experimental data predicted that sludge could be scoured from a tank bottom, which was required for waste tank closure. In short, CFD modeling was compared to full scale experimental data measured in a non-radioactive tank, and those results were used to successfully predict clearing of sludge from the bottom of an actual waste tank. Incipient sludge mixing occurs at much lower velocities than sludge scouring. Another result of this research was that the yield stress of the sludge was shown to be the governing property with respect to sludge scouring. Sludges behave as non-Newtonian, Bingham plastic fluids, which require that a stress be applied to the fluid to exceed the yield stress prior to fluid motion, while Newtonian fluids have a zero yield stress.

To exceed the yield stress and scour sludge to the tank bottom, critical velocities along the tank floor were required. If these critical velocities were exceeded anywhere in the tank, sludge was assumed to shear and then lift into solution. In short, single phase CFD models were used to determine the velocities throughout a waste tank, and then those velocities were used to estimate where sludge would scoured from the waste tank floor. Mixing in the actual waste tank confirmed predictions, as also discussed by Leishear, Lee, et. al. [3]. Research for this paper was performed to provide experimental sludge disturbance results for comparison to CFD models

Sludge Disturbance

A significant assumption for this paper was that minimizing sludge disturbance prevents hydrogen release. This assumption was demonstrated by joint research between Savannah River National Laboratory (SRNL) and the Waste Treatment Project in Hanford (Leishear, et. al. [4]). Required for Safety Analysis concerns at Hanford, full scale testing was performed to investigate the effects of using an air sparger to remove trapped gases from sludge. To mimic hydrogen retention in waste, a 30 foot tall column was filled with simulated sludge, and oxygen was bubbled up through the sludge to saturate the sludge. An air sparger then bubbled air up through the sludge, and dissolved oxygen sensors were used to measure the changes in oxygen content as the oxygen was removed from solution. That research focused on mass transfer as trapped gas was released during air sparging to demonstrate that an air sparger could successfully remove hydrogen from solution in waste tanks.

However, several results pertinent to this research were observed in those tests. First, trapped gases slowly diffuse from sludge unless mechanical agitation is applied. Second, as yield stress increases in sludge, more gas is trapped in the interstitial spaces of the settled sludge, and additional agitation is required to remove the gas from the sludge. And third, sludge settles quickly and a layer of supernate is formed on top of the sludge. This separation process affects the material properties of the sludge, since the density and yield stress increase as the sludge compacts.

Together, these three results demonstrate that sludge disturbance is controlled by mechanical agitation, and the agitation required to release hydrogen increases with increasing settling time. Research is also available concerning hydrogen retention (Weber, et. al. [5]), but the amount of hydrogen in the settled sludge is not a topic of the paper, hydrogen release from sludge is a concern for this paper.

Fluid Properties

Another significant assumption for this paper concerns fluid properties, and previous SRS research provided guidance for this paper. Various sludge simulants have been developed to imitate radioactive waste at SRS. From these simulants, a slower settling sludge provides a more conservative case for sludge disturbance studies, since slower settling sludge has smaller particles that are more easily suspended. Sludge Batch 6 (SB6) met this requirement (Herman [6]). SB6 radioactive liquid waste samples had a yield stress of 3.5 Pascal, as measured by SRNL Engineering staff. Other SRS reports showed that yield stresses for other radioactive waste samples were typically above this value (Bannochie [7] and [8]).

However, research presented in this paper shows that sludge properties may vary significantly. As water is added a lower yield stress is obtainable from a specific sample. Yield stresses also change as sludge settles. In other words, sampling from a waste tank can provide different results at different times. Another concern is that sludge varies from tank to tank, and the exact composition of sludge transferred into an SDI tank from another tank is indeterminate. To address this concern, a lower yield strength sludge was selected for pilot scale testing, where the initial yield stress of the sludge equaled 1.55 Pascal. This simulant, as received, has the lowest yield stress of any SRS simulant processed to date. Yield stress has deceased during testing and will be further evaluated. Supernate was specified to be a 6.4 molar sodium solution as specified by SRR. Some data is available on salt simulant properties (Walker, et.al. [9]), but fluid properties were measured during this research.

PROCESS REQUIREMENTS AND PILOT SCALE ACCEPTANCE CRITERIA

Blending of radioactive liquid waste salt solutions required further investigation, even though mixing of sludge has long been performed at SRS. Salt batches of 300,000 to 800,000 gallons will be transferred into SWPF blend or feed tanks and blended. The blender pump is required to adequately blend the tank contents, while not disturbing the sludge. Weeks after completion of blending, a transfer pump will transfer the blended salt solutions from the waste tank. The transfer pump is required to minimize sludge disturbance and prevent excessive sludge transfer from the tank. Blending time, pump requirements, and sludge disturbance were initially unknown. Pilot scale testing and CFD modeling were selected as a technique to investigate these processes.

Acceptance criteria were required for pilot scale testing for blending and transfer pump operations. The SWPF waste acceptance criteria for feed solids concentration is that solids concentrations must be less than 1200 mg/liter (0.09 weight percent). This requirement for maximum solids concentration is distinct from the safety requirement to not disturb the sludge. For pilot scale transfer pump testing, the acceptance criterion was that no solids were transferred from the tank, as determined by zero change in measured concentrations. In short, test equipment was calibrated for concentration measurements, but acceptance criteria were simply that concentrations did not change. For blending pump operation, the acceptance criterion was that the sludge surface was negligibly disturbed. During blending, sludge disturbance was assessed from visual observation of the sludge surface during operation. If the sludge level did not change in 24 hours, the sludge was assessed as undisturbed. Concentrations were measured during blending, but were not used for acceptance. In other words concentration magnitudes have little to do with pilot scale test acceptance.

PILOT SCALE TESTING

This paper provides a description of the pilot scale equipment and pilot scale test results. Major equipment consisted of pilot scale pump models, tank internals, external pumping, flow monitors, and turbidity probes, which were used to monitor insoluble solids concentration. As stated, this paper focuses on minimizing disturbance of a sludge simulant layer in pilot scale tests, while ensuring that the supernate simulant above the sludge is adequately blended. The non-Newtonian SB6 sludge simulant selected for research was a very low yield stress solution which poured like milk, and the supernate simulant was similar to water, in that the fluid was a Newtonian fluid with a viscosity of 2.3 times that of water. Visually, the goal of this research was to mix a solution similar to water on top of a solution similar to milk, without disturbing the milk. To better understand the tests performed, an equipment description is required.

Pilot Scale Test Equipment
Pilot scale test equipment was fabricated, such that waste tank components were geometrically scaled (1/10.85), and installed in an 8 foot diameter, clear acrylic tank. The total volume in the pilot scale tank was 939 gallons, where the total fluid level was 32.1 ± 0.5 inches, and the initial sludge level was calculated at ≈15/16 inch (24.6 gallons). Scaling was performed in accordance with available techniques (Poirier and Qureshi [10], Paul, et al. [11]), and further design details and scaling assumptions are available (Leishear, et.al. [12]). Approximately three miles of serpentine, two inch diameter cooling coils are present in some waste tanks, as shown in Figures 2.A and 2.B. Models of those coils are shown in Figures 2.C and 2.D. Some tests were performed using installed cooling coil models and some tests were performed without cooling coils. A centrally mounted, vertical, tank roof, support column was scaled and installed. Transfer pumps and blender pumps were geometrically scaled. The velocities at the pump discharge nozzles were equal to blender pump nozzle velocities at full-scale. Transfer pump suction inlet velocities were scaled from full scale (130 gpm at full-scale). Pump model dimensions were approximated while vendor design was in process, and modeling scale-up issues will be considered in follow up papers. Details of the pump designs, equipment setup, and fluids follow.

Pump Model Details
The flow through the full-scale blender pump can be visualized using Figure 2.E. A cross section is shown on the left side of the figure, and an exploded view is shown on the right hand side. The flow path through the pump is followed from numbers 1 through 6 on the figure. The flow enters all around the suction screen at points labeled (1), passes up into the pump suction inlet at point (2), to the eye of the pump impeller (3), through the rotating vanes of the impeller as the fluid velocity increases (4), down through circuitous vertical passages to a directional cone (5), and out through the pump nozzles into the tank (6). The final pump model is shown in Figure 2.F. To represent the pump, a suction pipe was installed parallel to the supply pipe attached to the nozzle assembly. Photos of the nozzle assembly and blender suction inlet model are also shown in Figure 2.F. As sludge testing progressed, different versions of the nozzles shown in Figure 2.F were used at different orientations with respect to the nozzle center line. Initially, simple tee junction nozzles and a drilled pipe cap suction were used for sludge testing, as shown in Figure 3.B (D = 0.209"). The transfer pump suction inlet was similar to the blender suction inlet. For the transfer pump, tests were performed with a bottom plate, which was both removed and installed for different tests. Pump models were attached to the superstructure above the tank.

Experimental Setup
A schematic for the test system is shown in Figure 3.A. A data acquisition system (DAS) recorded and calculated variables, such as pH, concentration, turbidity, flow rates, temperature, horsepower, motor speed, density, nozzle diameter, nozzle velocity, and *UoD* during testing. Shop temperatures during tests were typically 70º F during tests. An external centrifugal pump recirculated the fluid into the tank through two diametrically opposed nozzles and back to the recirculation pump through the pump model suction. A variable frequency drive (VFD), and PID controller (proportional, integral, derivative controller) were used to control the motor speed and pump flow rates.

Fluid Properties
Fluids included the SB6 sludge layer, and a nearly transparent supernate layer above the sludge. Although a single non-Newtonian sludge simulant was used, different Newtonian supernate simulants were used for testing. One simulant was a sodium nitrite and sodium hydroxide solution, and the other was water with sodium hydroxide. These two solutions were selected to investigate the effects of supernate properties on sludge disturbance (i.e., density and viscosity).

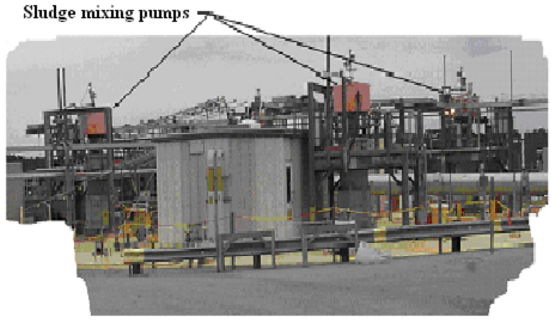

Figure 1.A: Nuclear Waste Tank

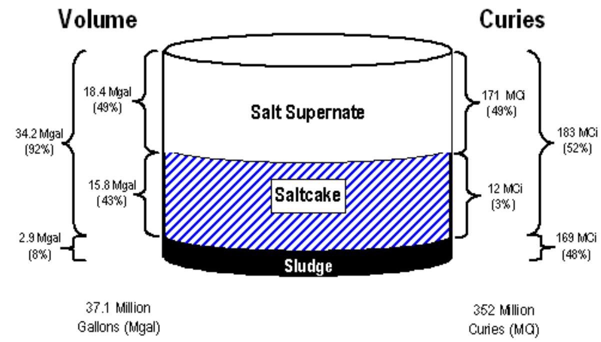

Figure 1.B: Nuclear Waste at SRS

Figure 1.C: Saltstone Production Facility

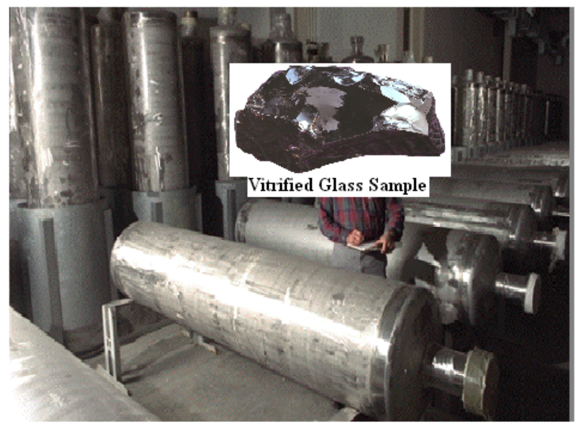

Figure 1.D: Radioactive Glass Strorage Containers, DWPF

Figure 1.E: SWPF Facility

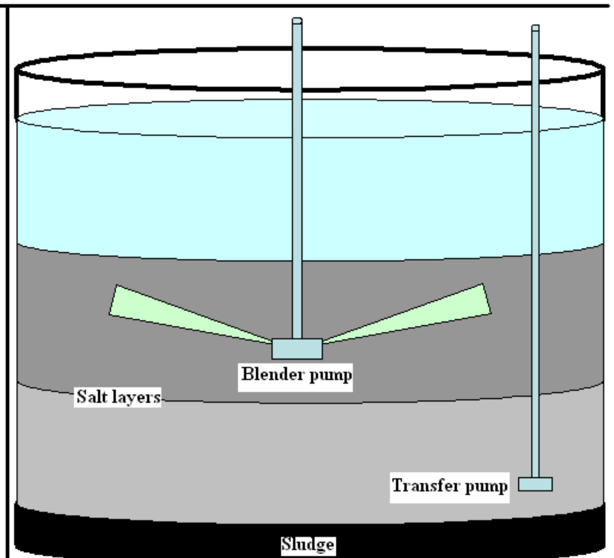

Figure 1.F: Stratified Salt and Sludge Layers

Figure 1: SRS radioactive liquid waste processing

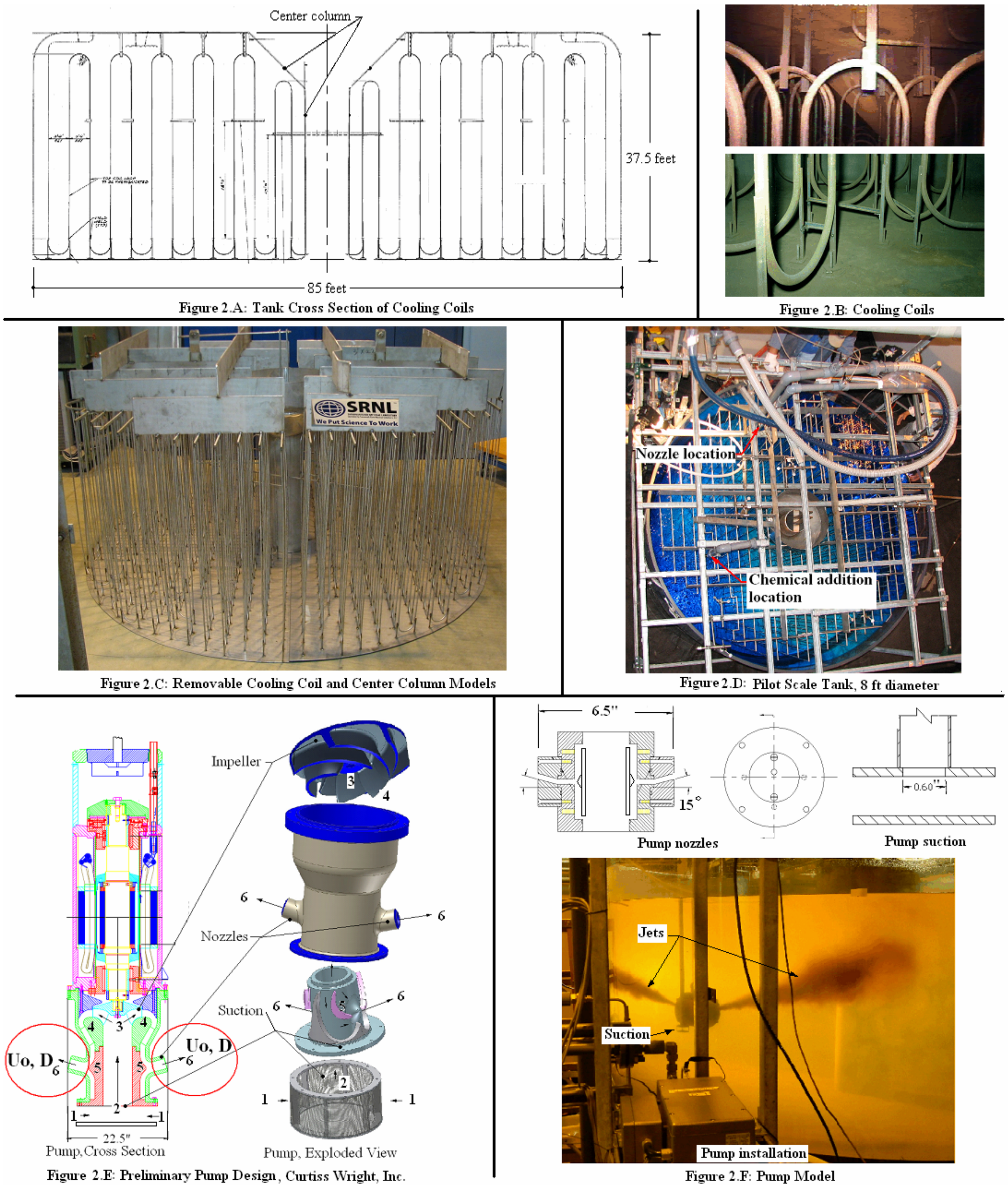

Figure 2.A: Tank Cross Section of Cooling Coils

Figure 2.B: Cooling Coils

Figure 2.C: Removable Cooling Coil and Center Column Models

Figure 2.D: Pilot Scale Tank, 8 ft diameter

Figure 2.E: Preliminary Pump Design, Curtiss Wright, Inc.

Figure 2.F: Pump Model

Figure 2: Full scale equipment and scale modeling

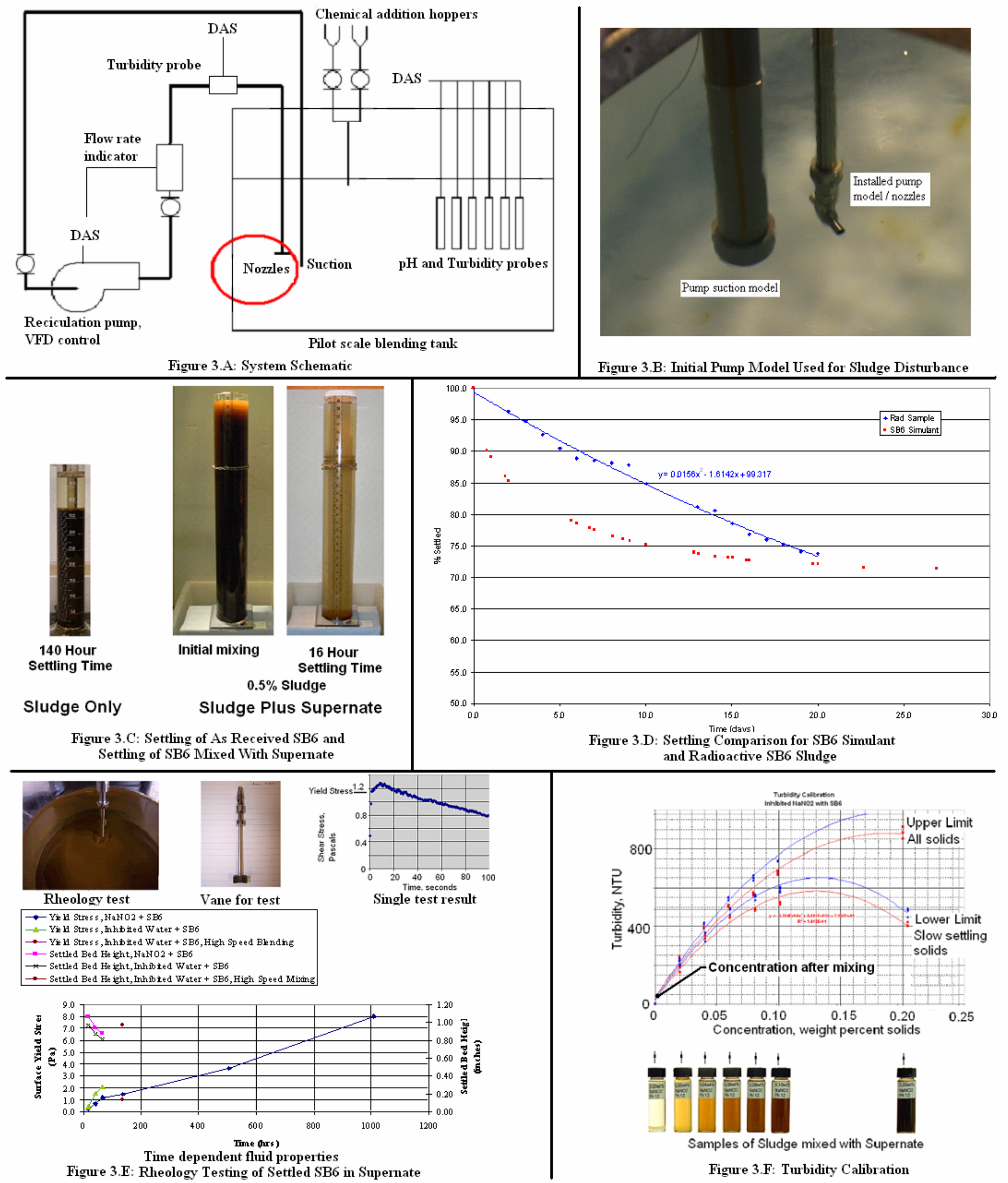

Figure 3: Pilot scale testing and material properties

Newtonian Fluids / Supernate

Newtonian fluids consisted of the supernate simulants. Due to chemistry issues, NaOH addition to the $NaNO_2$ was required to prevent rag formation, which is a gelatinous layer that forms on the sludge surface where the required NaOH concentration was less than pH ≈ 12.

Table 1: Newtonian supernate properties

Fluid	Density, gram/cm^3	Kinematic Viscosity, Centipoise
Supernate + Inhibited water (Deionized water + NaOH)	1.00	1.00
Supernate, NaOH + $NaNO_2$ + Deionized water	1.26	2.35
Supernate, NaOH + $NaNO_3$ + Deionized water	1.32	2.26

Non-Newtonian Fluids / SB6 Simulant

SB6 simulant was prepared (Herman, et. al. [6]), based on bench scale processing and testing of the simulant. Rheological properties were not specified and fluid properties varied widely. Three 55-gallon batches were received at SRS: Batches 1, 2, and 3. Batch 1 and 3 were similar in that they were the thinnest solution, and poured like milk. Batch 2 was much thicker, where a boat paddle stood up in the middle of the 55-gallon drum without support. Unwashed radioactive SB6 sludge was removed from a waste tank after blending several waste streams, and was measured to have a yield stress of 3.5 Pascal. Batch 1 had a yield stress of 1.55 Pascal after thorough mixing, where mixing of the 55-gallon drum was required since settling had occurred. Batch 1 was selected as the test simulant since it had the lowest yield stress of any simulant to date. The lower the yield stress, the more likely it will be disturbed during salt blending. The selection of Batch 1 provided a lower limit for sludge properties to be used in modeling. Even so, settling was observed over a few days for a sample of the simulant.

That is, non-Newtonian SB6 fluid properties varied with respect to time, and this time dependence had a significant effect on testing. The sludge simulant was prepared using a procedure for a recently qualified, SRS, sludge batch simulant, referred to as Sludge Batch 6 (SB6). This particular sludge is referred to as a slow settling sludge, since the sludge settles slowly after mixing into suspension in a full scale waste tank. The non-radioactive SB6 simulant contained aluminum, iron, manganese, and nickel compounds. Although SB6 is referred to as slow settling, individual compounds in solution settled at different rates, and SB6 settling behavior directly affected sludge disturbance behavior during the time required to complete a test.

The general behavior of the settling sludge is observed in Figure 3.C. The as received SB6 simulant is shown on the left side of the figure after nearly six days, where water is evident above the settling sludge. Figure 3.D provides a comparison between SB6 simulant and radioactive SB6 waste. Properties are similar, but not identical. Additional full scale testing in a 30 foot tall column is in process to assess scaling. Time dependent yield stress data is unavailable for SB6 waste. However, time dependence of yield stress was considered for the SB6 simulants. Referring again to Figure 3.C, a mixture is shown for SB6 simulant with $NaNO_2$ and 0.01 molar NaOH. Overnight, most of the solids settle. In a few days, the solution became clear unless the solution was exposed to sunlight, which colored the solution with organics. Either way, sludge was nearly completely precipitated after a few days for a 32.1 inch fluid level.

During the settling of SB6 in $NaNO_2$, the yield stress of the sludge increases as it is compacted. Figure 3.D summarizes the investigation of sludge compaction during settling of salt / sludge solution of comparable depth to the pilot scale tank, where 15/16 inch of SB6 was added to obtain 32.1 inches, total, which was the same as the fluid level used in the pilot scale tank. Settling containers were fabricated, which had removable lower sections to permit testing without disturbing the settled sludge bed. Both inhibited water and $NaNO_2$ were tested with SB6 and NaOH to prevent rag formation. Samples were tested using a Haake rheometer shown in the figure. This instrument rotates at 1/5 rpm, and the torque on the submerged vane is converted to yield stress, where the yield stress is the fluid stress required to mobilize the sludge. The vane used for testing is also shown in the figure, along with a typical test result and a graph of the rheology tests performed for both simulants over a six week period. Note that results for inhibited water are different than results for $NaNO_2$ simulant. When testing was performed by slowly mixing the SB6 with simulant, the inhibited water / SB6 had higher yield stresses. For a single test, the inhibited water was mixed at the full speed of hand drill with a mixing attachment. In that case, the inhibited water / SB6 yield stress was lower than the $NaNO_2$ / SB6 yield stress. One implication is that a safety factor may need to be applied during scale-up, since settling properties are not only dependent on water content, but are dependent on previous processing and chemistry. Evaluation of a 30 foot settling column test results and post-test rheology testing are expected to provide insight into this issue.

Monitoring Concentration with Turbidity Probes

In general, density meters are inaccurate for the low concentrations considered here, and turbidity probes were used for real time monitoring of solids concentration. A Hach Solitax® turbidity probe selected for use worked on the principle that a white light source exits the probe, and reflected light from solution was measured by a connected processor. The amount of light reflected back to the sensor can provide a measure of concentration. The turbidity can be affected by particle shape, color, size, and distribution. Multiple calibrations using known concentrations of solids were performed to develop a relationship between turbidity and weight percent undissolved solids, and to demonstrate repeatability. As shown in Figure 3.F, two probes were used (indicated by red and blue lines). Consider first the lower pair of probe results. The turbidity levels off at about 0.13 weight percent, and then decreases. As more light is absorbed by the particles or scattered into the particle field within the solution, the amount of reflected light measured by the sensor decreases, in addition the accuracy of the sensor decreases. In other words, the probes are most accurate up to about 0.1 weight percent, which is above the required range of 0.09 weight percent required for this study.

Figure 3.F also describes the appearance of different concentrations of sludge. Several calibration samples are shown below the figure, where each sample is related to the weight percent undissolved solids directly above it on the graph. Of particular interest, the 0.09 weight percent acceptance criterion yields a nearly black solution. In fact, when the vessel is larger, as is the case for the pilot scale tank, the solution becomes completely opaque for concentrations above 0.13 weight percent. The concentration may be small, but the effect of entrained solids seems large.

Settling properties also affected the turbidity measurements used to monitor sludge disturbance. When calibrations were initially performed, the upper curves were obtained. These results were obtained by immersing the turbidity sensor into a container of solution with a known concentration of sludge (same sludge used for testing) and allowing the reading to stabilize. However, agitation of the turbidity sample contents during calibrations yielded different results as shown by the lower curves in Figure 3.F. This material behavior is attributed to the settling rate of solids. When more solids are agitated into solution, the turbidity is lower since more light is absorbed or scattered. The calibration sample contents were agitated continually with a peristaltic pump to obtain the lower curves for all solids. Agitation of the sample was not performed for the upper curves. In other words, stirring the sample contents changes the turbidity by suspending the heavier solids, as shown by the upper and lower sets of curves. Concentrations during pilot scale are expected between these two limits.

PILOT SCALE EXPERIMENTAL RESULTS

A total of 124 tests were performed to investigate sludge disturbance for blending and transfer pumps, i.e., 35 for sludge disturbance and 89 for blending. To support pilot scale testing, more than 300 laboratory measurements were performed for turbidity, viscosity, settling, rheology, particle size distribution, concentration, chemical analysis, and velocity. Thirty CFD models are in process for scale up analysis to apply to the test results presented here.

All of the blender pump sludge tests were performed with the nozzles installed slightly above the tank mid-elevation and parallel to the tank wall. For the blender pump, the nozzle orientation was varied with respect to the nozzle centerline. Different orientations included: 15º upward; 15º inward; 30º inward; 45º inward; and 15º up and 15º inward simultaneously. Although further testing may have optimized the nozzle orientation, the 15º upward nozzle design provided satisfactory results, based on the nozzle positions tested. The pump with an installed bottom plate below the pump suction could be operated closer to the sludge layer. Since a lower pump position increases the total transfer volume from a tank, transfer pump testing focused on a pump with a bottom plate. The transfer pump and plate were lowered to the sludge layer to observe sludge disturbance as a function of distance from the sludge. The test setup, material properties, and sludge monitoring techniques require some discussion prior to a presentation of test results.

A pump was required to blend the tank contents, and increasing the blender pump flow rate provided better blending, while decreasing the flow minimized sludge disturbance. The two requirements for a blending pump were divergent, and a determination of whether, or not, a range of flow rates could be established for adequate blending was a primary goal of the research. To that end, some pilot scale test results for blending efficiency were previously published (Leishear, et. al. [1]), and pilot scale test results for sludge disturbance due to blending are shown in Figure 4.C.

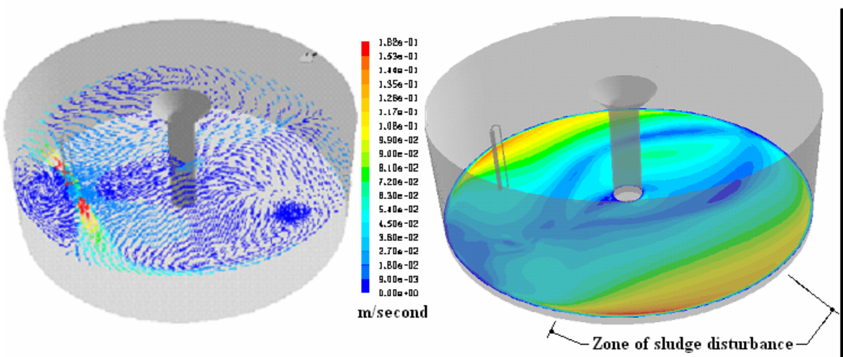

Figure 4.A: Flow Patterns for a Tee Nozzle in a Pilot Scale Tank Without Coils

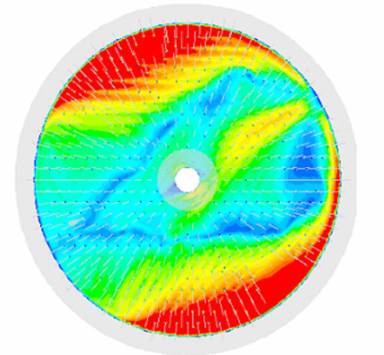

Figure 4.B: Flow in a Tank with Coils, Tee Nozzle

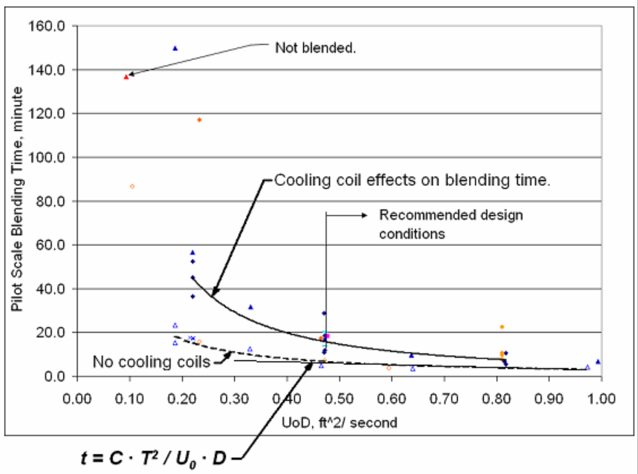

Figure 4.C: Blending Test Results for Water in a Pilot Scale Tank

Figure 4.D: Minimal Sludge Diturbance

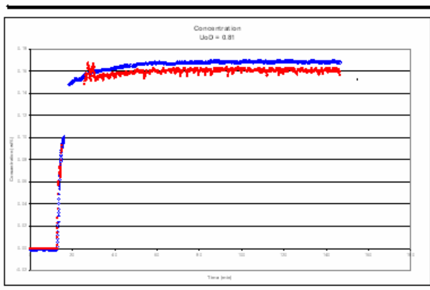

Figure 4.E: Typical Turbidity Data

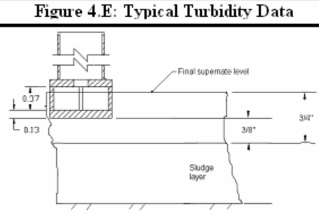

Figure 4.F:Loss of Transfer Pump Prime

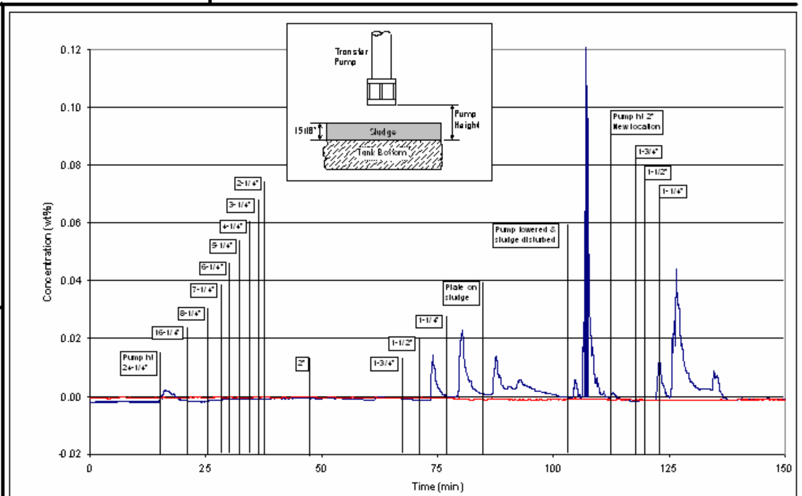

Figure 4.G: Typical Transfer Pump Turbidity Data

Figure 4: Test results

TEST RESULTS SUMMARY

Sludge disturbance blender pump test results can be separated into two parts; initial testing that scoured the tank bottom unacceptably, and final testing that blended the pilot scale tank contents without significant sludge disturbance. Initial tests were performed at *UoD* = 0.81 feet /s^2, which was a preliminary recommendation from previous testing to ensure blending. In these tests, various nozzles were used in a tank without coils and sludge was scoured down to the tank floor as the jet from the nozzle hit the tank wall and deflected down to the sludge surface. A CFD model shows the flow patterns in the pilot-scale tank during sludge disturbance. The higher velocities occur near the tank wall as the jet impacts the sludge, as shown in Figure 4.A. Figure 4.B shows similar results for a tank with coils. After modifying the nozzle design and permitting sludge to settle sufficiently, a design condition was established from the final sludge test results, where acceptable sludge disturbance was obtained during blending. Also, a transfer pump model was installed with and without a bottom plate, and lowered to determine the minimum clearance required to prevent sludge disturbance. Since blending is co-requisite to sludge disturbance, a brief summary of blending research precedes a discussion of sludge test results.

Summary of Blending Test Results

Blending test results were published earlier (Leishear, et. al. [1] but are summarized in Figure 4.C. Previous testing was performed in a tank containing water, and several observations were made.

- An empirical equation for a tank without coils agrees well with pilot scale blending test results, such that $t = (C \cdot T^2) / (Uo \cdot D)$, where t is the blending time, C = 3.08 is an experimentally determined constant, and T is the tank diameter.
- Installed cooling coils have a significant effect on blending.
- Viscosity has a significant effect on blending.
- Significant variations in blending times occur for similar test conditions.
- As *UoD* is lowered, the blending time increases until blending is incomplete.
- In the absence of additional research, a recommended pilot scale design condition was provided, which was based on linear scaling using empirical equations.
- A single, non-rotating pump is adequate to blend a full scale tank, but sludge disturbance required investigation.

Figure 4.C clearly demonstrates that increasing *UoD* improves blending performance. The recommended design conditions were lowered from previous conservative estimates, and are based on sludge disturbance test results provided in this paper. CFD modeling, additional completed testing, and statistical analysis will be used to scale up the revised *UoD* recommendation. From these test results *UoD* =0.47 ft^2/s is a recommended minimum, until further research is completed

Initial Blender Pump / Sludge Test Results

During initial tests *UoD* = 0.81 ft^2/s, and significant sludge was disturbed for all nozzle designs following 16 hour settling. Models included a tee (D = 0.209"), and various angled nozzles used with the vendor pump model design. Weekend settling tests (≈ 66 hours) were performed for a 15º upward nozzle and a horizontal nozzle. The 15º nozzle reduced the quantity of sludge suspended to an acceptable level. Although nozzle design could have been optimized, this design along with a specified settling time resolved the problem of sludge scouring. Prior to this design a significant sludge volume was scoured down to the tank floor for both ½ inch and 15/16 inch sludge depths. For the 15/16 inch sludge depth, the typical quantity of disturbed sludge scaled up to 3000 – 4000 gallons, which was considered unacceptable for sludge disturbance. An area of several feet along the tank circumference extending 12 – 18 inches inboard was typically scoured on each side of the tank.

For the initial tests, significant sludge was also mixed into solution. Turbidity probes provided significant insight into the behavior of disturbed sludge. Also, a sample was obtained and chemically analyzed, where aluminum was shown to be the primary metal compounds lifted into solution. The manganese, iron, and nickel compounds remained on the tank floor, and were either moved around the floor or remained undisturbed below settled aluminum particles. When the pump speed was rapidly increased, tan materials from the tank floor issued from the pump nozzle, and blended with the suspended black material. The overall color of settled sludge was a dark brown. For initial testing, weight percent solids were above the maximum limit of the turbidity probes (Figure 4.E).

Final Blender Pump / Sludge Test Results

Tests were performed at various values of *UoD* to find the optimum operating condition (*UoD* = 0.22, 0.34, 0.47, 0.58, 0.70, 0.81, and 0.87 ft^2/s). At *UoD* < 0.47 ft^2/s sludge was not disturbed. At *UoD* = 0.58 ft^2/s, minimal sludge was disturbed, as shown in Figure 4.D. At this limiting *UoD*, minimal sludge was lifted into solution as wisps of sludge vortexed from the surface. Once lifted into solution, the trace quantities of sludge were uniformly blended by the blender pump. Monitoring the tank for 24 hours concluded that the sludge level did not decrease. Consequently, *UoD* = 0.58 ft^2/s is the recommended maximum value at pilot scale. Again, scale up will be confirmed using CFD. Comparable velocities will be assumed to disturb the sludge at both full scale and pilot scale. Coupled with the blender pump results the recommended operating range at pilot scale is 0.47 ft^2/s < *UoD* < 0.58 ft^2/s, where negligible sludge disturbance was determined by visual observation.

Transfer Pump Test Results
The transfer pump was incrementally lowered, to determine the level at which sludge disturbance was first noticed. The lowest point at which sludge was undisturbed and the point at which sludge disturbance was first noted will be modeled using CFD, to compare equal velocities at the sludge surface for scale up. Tests were performed both with and without a bottom plate installed on the transfer pump model. For the transfer pump without a bottom plate, the minimum height was 13/16 ± 1/16 inches from the surface to the pump suction. For the pump with a bottom plate, the minimum height from the surface to the bottom of the plate was 3/8 ± 1/16 inches. By adding the bottom plate to the transfer pump, the clearance to the sludge can be cut in half. Typical test results are shown in Figure 4.G. No turbidity change occurred during the determination of these minimum operating levels.

CONCLUSIONS

Blending tests were performed to determine pump design requirements, demonstrate that waste tank contents can be uniformly blended, and investigate disturbance of a settled sludge layer on the tank bottom. To prevent the release of flammable hydrogen trapped, the sludge layer cannot be disturbed during blending. Blending tests were performed in parallel to this research to demonstrate the waste tank contents can be uniformly blended, and the research presented in this paper investigated the sludge layer expected to accumulate on the tank bottom. This sludge cannot be disturbed during blending to prevent the release of flammable hydrogen trapped in the sludge layer. Testing was performed to investigate sludge disturbance in a 1 /10.85 pilot scale tank for scale up to a 1.3 million gallon nuclear waste tank. At pilot scale, tests showed that sludge will be negligibly disturbed when *UoD* < 0.58 ft^2/s. Adequate blending is expected when *UoD* > 0.47 ft^2/s. These two limits will be investigated during CFD modeling and scale up analysis. To obtain these limits, settling was required for at least 65 hours at pilot scale, which tentatively scaled to 30 days at full scale. Scale up of settling will also be investigated and presented in later publications.

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