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Mixing, Scaling,
MST, SCIX

Retention:
Permanent

Scaling Solid Resuspension and Sorption for the Small Column Ion Exchange (SCIX) Processing Tank

Michael R. Poirier
Zafar H. Qureshi

December 14, 2010

Savannah River National Laboratory
Savannah River Nuclear Solutions
Aiken, SC 29808

**Prepared for the U.S. Department of Energy Under
Contract Number DE-AC09-08SR22470**



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LIST OF ACRONYMS

ARP	Actinide Removal Process
CFD	Computational Fluid Dynamics
CST	Crystalline Silicotitanate
DWPF	Defense Waste Processing Facility
LWO	Liquid Waste Organization
MST	Monosodium titanate
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
RMF	Rotary Microfilter
SCIX	Small Column Ion Exchange
SDIP	Salt Disposition Integration Project
SMP	Submersible Mixer Pumps
SRNL	Savannah River National Laboratory
SRR	Savannah River Remediation
SRS	Savannah River Site

NOMENCLATURE

A	constant
a	exponent
a_s	surface area
B	constant
b	exponent
C	constant
C_L	liquid phase concentration
C_S	solid phase concentration
c_f	drag coefficient
D	Jet nozzle diameter
D	tube diameter
D	molecular diffusivity
d_H	hydraulic diameter
d_p	particle diameter
ECR	effective cleaning radius
g	gravitational acceleration
h	liquid level
k	mass transfer coefficient
N_A	mass transfer rate
n	exponent
P	power
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
St	Strouhal number
T	tank diameter
U	velocity
U_j	jet nozzle velocity
u_t	terminal velocity
V	volume
X_t	ratio of transverse tube pitch to tube diameter
x	axial distance from pump
z	scour hole dimension
δ	boundary layer thickness
ε	power per unit mass
ρ	density
τ_c	critical shear stress
τ_s	shear strength
τ_w	wall shear stress
τ_y	yield stress
ν	kinematic viscosity
ω	rotation rate

Subscripts

full	full-scale tank
j	jet
pilot	pilot-scale tank

1.0 SUMMARY

The Small Column Ion Exchange (SCIX) process is being developed to remove cesium, strontium, and actinides from Savannah River Site (SRS) Liquid Waste using an existing 1.3 million gallon waste tank (i.e., Tank 41H) to house the process. Savannah River National Laboratory (SRNL) is conducting pilot-scale mixing tests to determine the pump requirements for suspending and resuspending Monosodium Titanate (MST), Crystalline Silicotitanate (CST), and simulated sludge. In addition, SRNL will also be conducting pilot-scale tests to determine the mixing requirements for the strontium and actinide sorption. As part of this task, the results from the pilot-scale tests must be scaled up to a full-scale waste tank. This document describes the scaling approach.

The pilot-scale tank is a 1/10.85 linear scale model of Tank 41H. The tank diameter, tank liquid level, pump nozzle diameter, pump elevation, and cooling coil diameter are all 1/10.85 of their dimensions in Tank 41H. The pump locations correspond to the proposed locations in Tank 41H by the SCIX Program (Risers B5 and B2 for two pump configurations and Risers B5, B3, and B1 for three pump configurations). MST additions are through Riser E1, the proposed MST addition riser in Tank 41H.

To determine the approach to scaling the results from the pilot-scale tank to Tank 41H, the authors took the following approach. They reviewed the technical literature for methods to scale mixing with jets and suspension of solid particles with jets, and the technical literature on mass transfer from a liquid to a solid particle to develop approaches to scaling the test data. SRNL assembled a team of internal experts to review the scaling approach and to identify alternative approaches that should be considered.

The conclusions from this analysis follow.

- For solids suspension/resuspension, the nozzle discharge velocity in the full-scale tank must be 30% greater than the nozzle discharge velocity in the pilot-scale tank. This approach is the most conservative scaling relationship for the solids suspension/resuspension process.
- The time to resuspend the particles in the full-scale tank could be up to 10.85 times longer than the resuspension time in the pilot-scale tests.
- For strontium/actinide sorption the nozzle discharge velocity in the full-scale tank must be at least 2.2 times greater than the nozzle discharge velocity in the pilot-scale tank. The time for strontium sorption should be the same in the pilot-scale and full-scale tanks.
- The cooling coils will cause less drag and less reduction in jet velocity in the full-scale tank compared with the pilot-scale tank. Neglecting a correction for the cooling coils will under predict the jet velocity in the full-scale tank and provide conservatism in scale-up.
- The pump rotation rate in the pilot-scale tests should be 10.85 times the pump rotation rate in the full-scale tank. The actual difference between the full-scale and pilot-scale tanks could be less, but the authors selected the 10.85 factor since a faster rotation rate may produce less effective mixing in the pilot-scale tank.

The authors make the following recommendations to improve the scaling of these test results.

- Perform testing at another scale. Having different scales of testing provides additional data points for the analysis and allows one to better support the proposed scaling method(s). Additional data would allow the authors to refine the scaling relationships and allow the SCIX Program to reduce the conservatism in their design, as well as reduce the program risk.
- Perform Computational Fluid Dynamics (CFD) modeling. CFD would allow us to conduct tests at several scales and compare fluid velocities in different size tanks. With CFD, we could determine the nozzle velocities needed to obtain equivalent fluid velocities at equivalent points in the tank. Knowing these nozzle velocities would reduce the conservatism needed to size the SCIX mixer pumps. In addition, the CFD analysis could quantify the impact of the cooling coils on scale up. SRNL is currently performing CFD modeling to support the design of pumps for the Salt Disposition Integration Project (SDIP). A minimal effort would be needed to apply the results to this task.
- Conduct additional strontium sorption tests with varying pump rotation rates to verify the impact of pump rotation rate on the strontium sorption rate. This data, along with previous SRNL strontium sorption data and solid-liquid mass transfer data in the technical literature, can be used to strengthen the conclusion that the strontium sorption rate is not sensitive to the pump rotation rate and reduce the uncertainty surrounding the impact of pump rotation rate.

2.0 INTRODUCTION

Savannah River Remediation (SRR) is developing the SCIX process to remove cesium, strontium, and select actinides from SRS Liquid Waste using an existing waste tank (i.e., Tank 41H) to house the process, (see Figure 1 below). The process initially adds MST as a slurry to the waste tank (i.e., Tank 41H) to chemically sorb the soluble strontium and select actinides in the supernate using the installed jet mixer pumps to provide the necessary mixing. After the MST has completed the sorption cycle, it is allowed to settle. The resulting supernate in the tank is then pumped through an in-riser rotary microfilter (RMF) unit. The RMF unit provides a solids free stream to two ion-exchange columns in series containing CST to remove the cesium. After the stream has been processed through the CST columns, it is sent directly to another salt waste tank for final disposition. Once the CST columns are loaded with cesium, the CST is transferred to an in-riser grinder to reduce its size and transferred into a waste tank (e.g., Tank 40H or Tank 41H - baseline is Tank 40H) as a slurry. The MST, sludge, and CST (if transferred to Tank 41H) in the waste tank will be periodically transported to a sludge tank, and ultimately to the Defense Waste Processing Facility (DWPF) for final disposition.

To assist SRR in designing the SCIX process, SRNL is conducting pilot-scale testing to determine the number, type, and size of pumps needed to mix Tank 41H. As part of the testing, SRNL will also estimate the MST sorption time needed in Tank 41H, and the ability of the pumps to resuspend MST, CST, and sludge slurries.¹ The maximum time that solid particles (i.e., MST, CST, and sludge) can settle in Tank 41H and be resuspended is being determined currently.

The objectives of this task are to use pilot-scale tests

- To determine the pump requirements (i.e., number, size, discharge velocity, rotation rate and mixing times) to resuspend settled solids after sitting in the tank for an extended period of time.
- To determine the strontium sorption by MST as a function of time.
- To relate the results from these tests to full-scale expectations using the scaling methodology provided in this document.

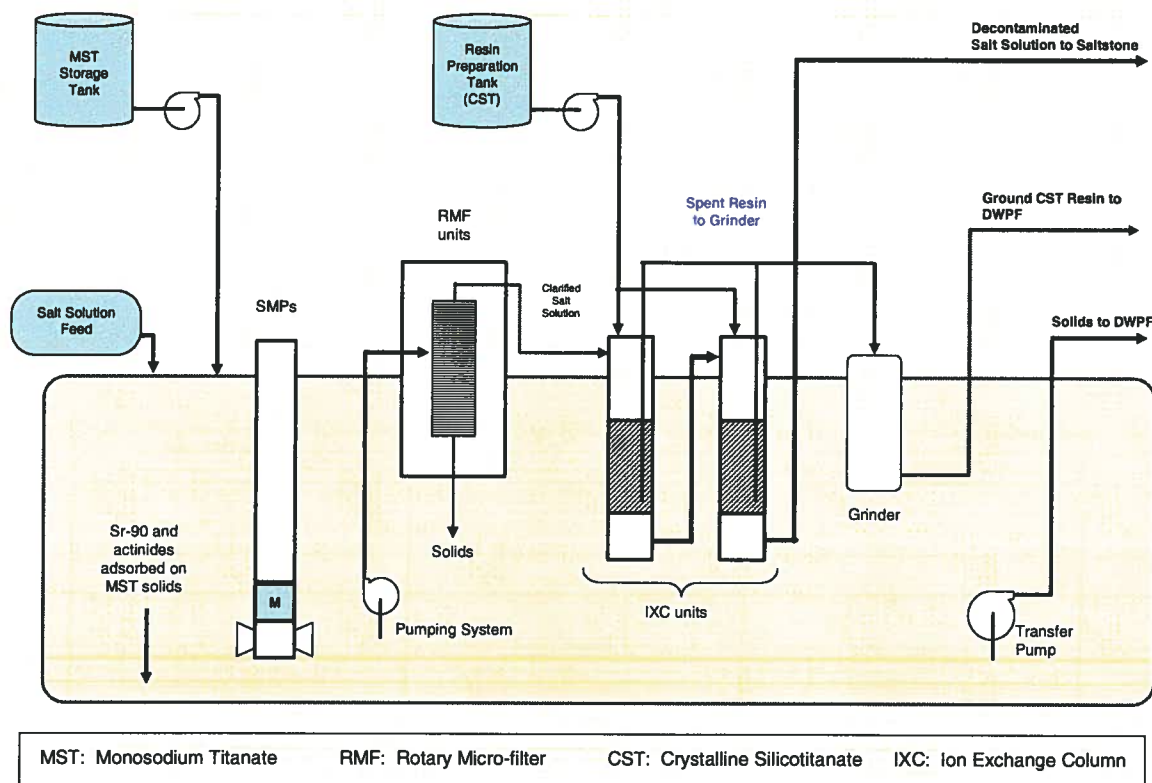


Figure 1. Small Column Ion Exchange (SCIX) Concept

The purpose of this mixing application is for the MST to adequately contact the strontium and actinide containing liquid and to remobilize the settled solid particles so they can be removed from the tank. There are no requirements for the MST to be homogeneous in the tank during either mixing activity.

These tests are being conducted in a nominal 8 foot diameter pilot-scale mixing tank (see Figure 2). Figure 3 illustrates a top view of the pilot-scale tank with the riser locations corresponding to Tank 41H. The black, green, and red line segments show the cooling coils. The tank and cooling coils are approximately 1/10 linear scaled (actual scale is 1/10.85). The cooling coils are based on the cooling coil design in Tank 41H. Researchers originally designed and built two rotating mixer pumps. The pumps were placed in Risers B5 and B2. Because of the initial results obtained, SRR and SRNL decided to increase the number of pumps to three.^a These pumps were placed in Risers B5, B3, and B1. The maximum cleaning radius needed is 47.1 inches in the pilot-scale tank (42.6 feet in Tank 41H). The liquid volume in the pilot-scale

^a Resuspension tests showed that two SMPs would not have sufficient power to suspend MST particles that settled for four weeks at 45 °C.

tank is 800 gallons, which is geometrically-scaled to the expected volume in Tank 41H [$1,000,000 \text{ gallons} / (10.85)^3 = 780 \text{ gallons} \sim 800 \text{ gallons}$]. The pumps have discharge nozzles that simulate standard slurry pumps, quad volute slurry pumps, and submersible mixer pumps (SMP). The nozzle diameters are linearly scaled to the actual pumps. Figure 4 shows the dimensions of the pilot-scale SMP. Table 1 shows the properties of mixer pumps that are commonly used in SRS waste tanks.

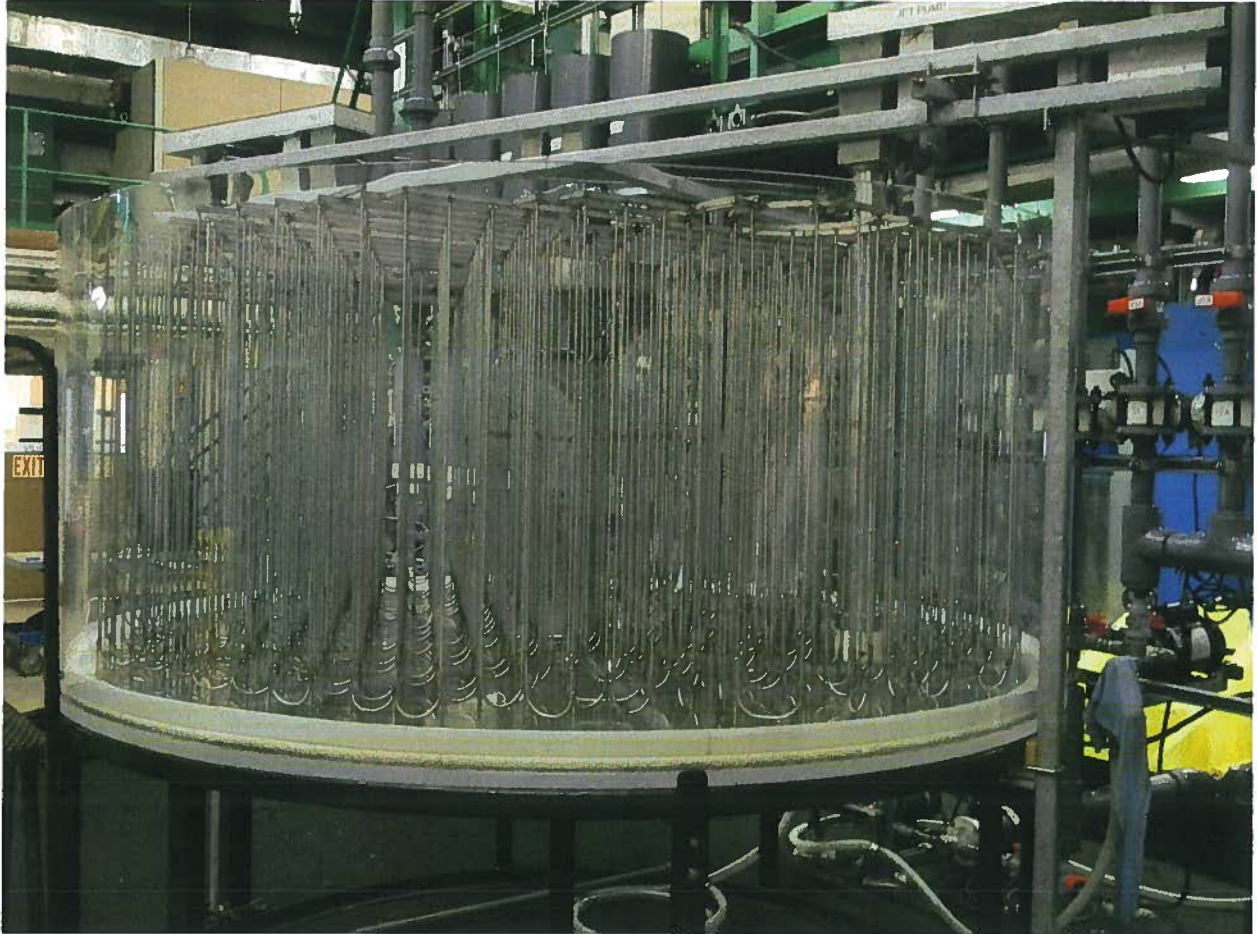


Figure 2. Pilot-Scale Waste Tank

The solid particles used in the tests are MST, CST, and sludge. The MST used in this testing is from the same lot currently being used at the Actinide Removal Process (ARP). It has a median particle size of $\sim 15 \mu$ and it is cohesive. The CST used in the testing was obtained from UOP (the CST manufacturer) and ground by the equipment SRR plans to use in the process (median particle size $2.5 - 8.2 \mu$). The sludge used in the testing will be simulated Sludge Batch 6. It has a median particle size of less than 5μ and it is cohesive. The shear strength and yield stress of slurries containing MST, CST, and/or simulated sludge are being measured concurrently.¹

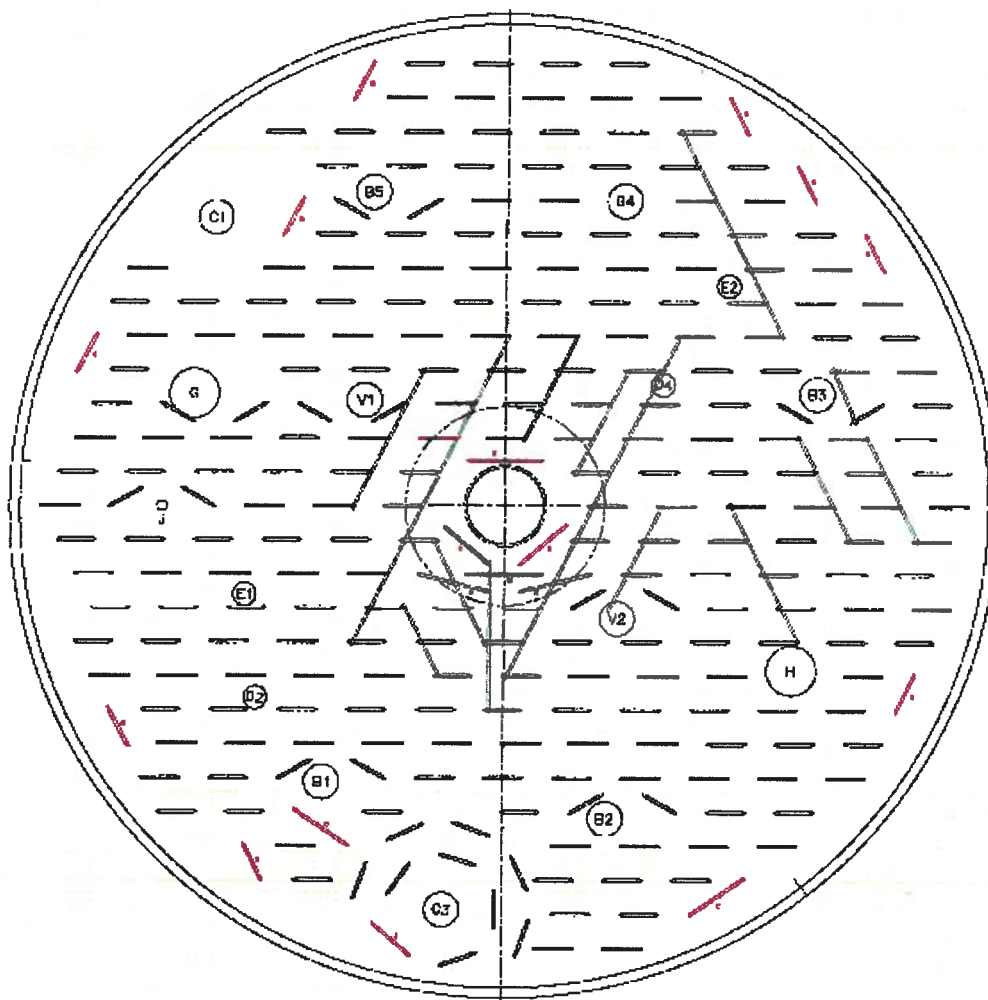


Figure 3. Pilot-Scale Tank Top

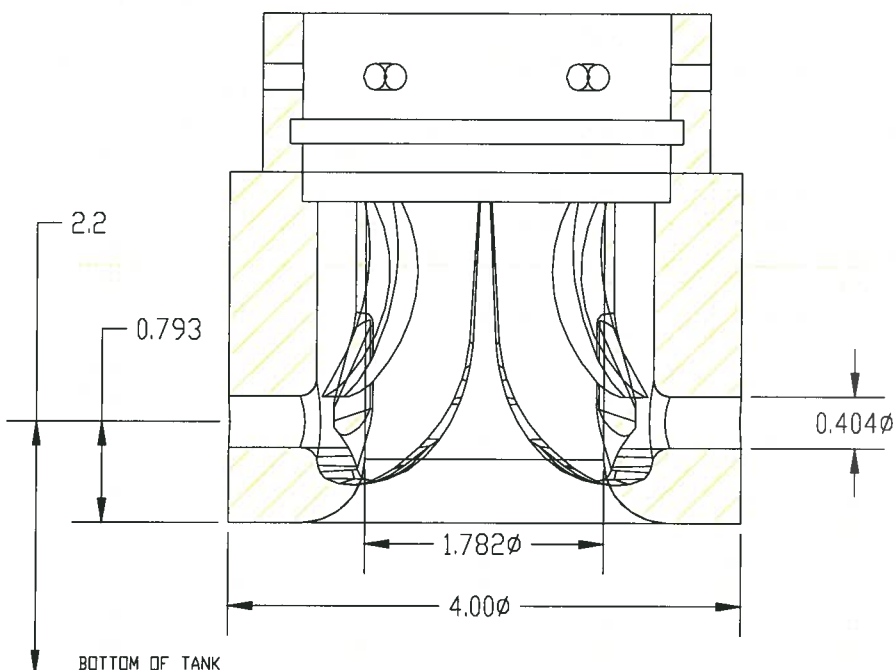


Figure 4. Pilot-Scale SMP Head

Table 1. Properties of Proposed SCIX Mixing Pumps

Pump	D_i (in)	V_i (ft/s)	$D_i V_i$ (ft ² /s)	Power (HP)	Nozzles
Standard Slurry Pump	1.5	109	13.6	70	2
Quad Volute Slurry Pump	3.62	72	21.7	118	2
Submersible Mixer Pump	4.4	79	29.4	230	2

3.0 ANALYSIS

Geometric similarity is maintained, where the ratio of lengths, such as tank diameter, jet nozzle diameter, nozzle height, liquid level, and cooling coil diameter and length, is 10.85:1 between the full-scale tank and the pilot-scale tank.

To determine the method for scaling the results from the pilot-scale tank to Tank 41H, the authors took the following approach. They reviewed the technical literature for methods to scale mixing with jets and suspension of solid particles with jets (Section 3.1), reviewed the technical literature on mass transfer from a liquid to a solid particle (Section 3.2), reviewed the technical literature for methods to scale mixing with impellers (Section 3.5), and reviewed scaling approaches developed for the pulsed jet mixers at the Hanford Waste Treatment Plant (Section 3.6).

The goal of this analysis is to develop an equation, like equation [1], to describe the relationship between the nozzle discharge velocity in the pilot-scale tank and the nozzle discharge velocity in the full-scale tank that leads to equivalent performance in both tanks

$$U_{j\text{-pilot}} = U_{j\text{-full}} (D_{\text{pilot}}/D_{\text{full}})^n \quad [1]$$

where $U_{j\text{-pilot}}$ is the nozzle discharge velocity in the pilot-scale tank, $U_{j\text{-full}}$ is the nozzle discharge velocity in the full-scale tank, D_{pilot} is the diameter of the pilot-scale pump nozzle, D_{full} is the diameter of the full-scale pump nozzle, and n is an exponent. The exponent in equation [1] is a function of the mixing application.

In this analysis, when the literature review indicated that a range of possible values for the scaling parameter might be appropriate, the authors identified bounds on scaling and selected a value that produced the least effective mixing in the pilot-scale tests and was applicable to the process of interest.

In addition, SRNL assembled a team of internal experts to review the scaling approach and to identify alternative approaches that should be considered.

3.1 SCALING SOLIDS RESUSPENSION

A solid particle or group of particles that have settled on the tank bottom are influenced by the fluid velocity or the shear stress in the vicinity of the particles rather than by the fluid velocity or shear stress further away. Matching the local fluid velocity or local shear stress is an approach to obtain comparable results for suspending particles in the pilot-scale and full-scale tanks.

One approach to scaling the pilot-scale test results is to look at turbulent jet theory. The mixer pumps produce two opposing jets. In a very large tank away from boundaries with no internal structures, the discharge behaves as a turbulent free jet. Because the pump discharge nozzles are located near the tank bottom and the tank contains walls and cooling coils, a free turbulent jet does not completely describe the process. Because the jet is not located at the tank bottom, the turbulent wall jet theory does not completely describe the process. However, both theories can provide insight into the fluid mechanics in the tank. David and Winarto investigated jet diffusion from a circular nozzle above a solid plane and found that the velocity profile did not vary significantly from a free jet.²

Equation [2] describes the velocity of an axisymmetric turbulent free jet

$$U = C \frac{D_j U_j}{x} \exp \left[-B \left(\frac{r}{x} \right)^2 \right] \quad [2]$$

where U is the velocity as a function of position, B is a constant, C is a constant, D_j is the pump nozzle diameter, U_j is the average pump nozzle velocity, x is the distance from the nozzle along the jet centerline, and r is the distance from the jet centerline.^{3,4} Equation [3] describes the velocity at equivalent points in the two tanks.

$$U_{full} = U_{pilot} \frac{C \frac{D_{j-full} U_{j-full}}{x_{full}} \exp \left[-B \left(\frac{r_{full}}{x_{full}} \right)^2 \right]}{C \frac{D_{j-pilot} U_{j-pilot}}{x_{pilot}} \exp \left[-B \left(\frac{r_{pilot}}{x_{pilot}} \right)^2 \right]} \quad [3]$$

Since the tanks are geometrically-scaled, at equivalent points in the tanks, D_j/x and r/x are equal and equation [3] reduces to

$$U_{full} = U_{pilot} \frac{U_{j-full}}{U_{j-pilot}} \quad [4]$$

For equal fluid velocity at equivalent locations in turbulent free jets in the full-scale and pilot-scale tanks, the nozzle discharge velocity needs to be the same in both tanks.

The jets produced are not “free jets”. They have a boundary below them and cooling coils throughout the tank. In addition, the fluid motion at the solid-liquid interface will affect the solid particle suspension. Equation [5] describes the velocity profile of a plane wall jet

$$U = C \frac{D_j^{0.5} U_j}{x^{0.5}} \exp \left[-0.693 \left(\frac{y - \delta}{D_j} \right)^2 \right] \quad [5]$$

where C is a constant, D_j is the nozzle diameter, U_j is the nozzle discharge velocity, y is the vertical distance from the tank bottom, x is horizontal distance from the nozzle along the jet centerline, and δ is the boundary layer thickness ($\delta = 0.014x$).³ Equation [6] compares the velocity in the full-scale tank to the velocity in the pilot-scale tank.

$$U_{full} = U_{pilot} \frac{C \frac{D_{j-full}^{0.5} U_{j-full}}{x_{full}^{0.5}} \exp \left[-0.693 \left(\frac{y_{full} - \delta_{full}}{D_{j-full}} \right)^2 \right]}{C \frac{D_{j-pilot}^{0.5} U_{j-pilot}}{x_{pilot}^{0.5}} \exp \left[-0.693 \left(\frac{y_{pilot} - \delta_{pilot}}{D_{j-pilot}} \right)^2 \right]} \quad [6]$$

Since the tanks are geometrically scaled, D_j/x and $[(y - \delta)/D_j]$ are constant for equivalent positions in the tanks, and equation [6] reduces to equation [7].

$$U_{full} = U_{pilot} \frac{U_{j-full}}{U_{j-pilot}} \quad [7]$$

To produce the equivalent wall jet velocity profile in the pilot-scale tank and in the full scale tank, the nozzle discharge velocity should be the same in both tanks (i.e., the exponent in equation [1] is 0).

Equation [8] describes the wall shear stress of a turbulent wall jet

$$\tau_w = c_f \frac{\rho U_j^2}{2} = \frac{0.2}{(x/D_j)(U_j D_j / \nu)^{1/12}} \frac{\rho U_j^2}{2} \quad [8]$$

where τ_w is the shear stress at the tank bottom, c_f is the drag coefficient, ρ is density, U_j is the nozzle discharge velocity, x is axial distance, D_j is the nozzle diameter, and ν is kinematic viscosity.⁵ Solving equation [8] for U_j produces equation [9].

$$U_j = \frac{\left(\frac{x}{D_j}\right)^{12/23} \left(\frac{D_j}{\nu}\right)^{1/23} \tau_w^{12/23}}{0.3 \rho^{12/23}} \quad [9]$$

If the shear stress at the tank bottom controls the suspension of cohesive particles, then the shear stress at the tank bottom needs to be equal in both tanks. Equation [10] describes the relationship between the nozzle velocities in both tanks (neglecting cooling coils) when the shear stress at the tank bottom is the same at equivalent points.

$$U_{j\text{-full}} = U_{j\text{-pilot}} (D_{j\text{-full}}/D_{j\text{-pilot}})^{1/23} \quad [10]$$

According to equation [10], the jet nozzle velocity in the full-scale tank will be larger than the nozzle velocity in the pilot-scale tank. However, because of the small exponent (1/23) and the scale factor (10.85), the ratio of the nozzle velocities is 1.11, which is close to 1.

Pacific Northwest National Laboratory (PNNL) investigated the jet erosion of Hanford K-basin sludge.⁶ They looked at modeling the process as a turbulent wall jet. They found the amount of cohesive sludge suspended to be related to an excess shear parameter. The excess shear is the shear stress above a critical shear stress, which is the minimum shear stress needed for solid particles to be suspended. Since these tests are using MST from the same lot as ARP, CST that is ground by the same equipment planned for the SCIX process, and simulated sludge that was selected to match Sludge Batch 6, the authors assumed that the settled particles will have a comparable critical shear stress to the solid particles expected in Tank 41H (The real sludge properties are likely to show some variability from tank to tank). We will assume the excess shear is matched when the applied shear stress is matched.

To match the suspension of cohesive solids, we need to match the excess shear (and therefore, the shear applied to the sludge by the pumps). If we use the same expression for skin friction (c_f) as equation [8], this scaling is described by equation [10].

An alternative expression for skin friction is $c_f = C/Re^{0.2}$, where C is a constant.⁷ Using this expression in equation [8] and solving for U_j produces equation [11].

$$\tau_w = \frac{C}{(U_j D_j / \nu)^{1/5}} \frac{\rho U_j^2}{1} \quad [11]$$

Solving equation [11] for U_j produces equation [12].

$$U_j = \frac{C D_j^{1/9} \tau_w^{1/1.8}}{\nu^{1/9}} \quad [12]$$

If the shear stress at the tank bottom controls the suspension of cohesive particles, then the shear stress at the tank bottom needs to be equal in both tanks. Equation [13] describes the relationship between the nozzle velocities in both tanks when the shear stress at the tank bottom is the same.

$$U_{j\text{-full}} = U_{j\text{-pilot}} (D_{j\text{-full}}/D_{j\text{-pilot}})^{1/9} \quad [13]$$

According to equation [13], the jet nozzle velocity in the full-scale tank will be larger than the nozzle velocity in the pilot-scale tank. With an exponent of 1/9 and a scale factor of 10.85, the ratio of the nozzle velocities is 1.30, which is significant.

Mazurek et. al investigated scouring of cohesive soils by submerged turbulent wall jets.⁸ They found that the dimensions of the hole (defined as z) produced in the solids by the jet is a function of nozzle diameter, fluid density, nozzle discharge velocity, fluid viscosity, and a critical shear stress, and it could be described by equation [14]

$$z = D_j f(\rho U_j^2 / \tau_c) \quad [14]$$

where τ_c is the critical shear stress. The fluid density is the same in both scales and equivalent solids are used in both scales.^b The critical shear stress should be the same at both scales for equivalent solids mobilization. For the ratio of the depth of the scour hole to the nozzle diameter to be the same at both scales, the nozzle jet velocity must be the same at both scales (i.e., the exponent in equation [1] is 0).

Ade and Rajaratnam investigated erosion by circular horizontal jets.⁹ They found the ratio of the depth of the scour hole to the jet nozzle diameter to be a function of the densimetric Froude number and the relative downstream fluid depth, which is described by equation [15]

^b The MST used in testing is the same MST being used in ARP. The CST being used was ground at Hockmeyer using a grinder like the one planned for the SCIX process. The simulated sludge was selected to represent a slow settling sludge, with high aluminum typically seen in HM sludge, like that observed in Sludge Batch 6.

$$\frac{z}{D_j} = f \left[\frac{U_j}{\sqrt{\frac{gd_p \Delta \rho}{\rho}}}, \frac{hd_p}{D_j} \right] \quad [15]$$

where h is the liquid level and g is gravitational acceleration. Since the pilot-scale tank is geometrically scaled, h/D_j is constant. The particle size and fluid density are the same in both tanks. Therefore, the ratio of the scour hole depth to the nozzle diameter will be the same in both scales if the jet nozzle velocity is the same (i.e., the exponent in equation [1] is 0).

SRNL and PNNL performed full-scale and pilot-scale testing to evaluate the pump operating parameters to suspend and mobilize settled sludge in SRS and Hanford waste tanks.^{10,11} In both instances, the settled sludge level was above the pump discharge nozzles (In these tests, the settled solids are below the pump discharge nozzles). SRNL developed a model for the effective cleaning radius (ECR) as a function of pump and sludge properties. Equation [16] describes the effective cleaning radius

$$ECR \propto D_j U_j (\rho/\tau_y)^{1/2} \quad [16]$$

where ECR is the cleaning radius, D_j is the jet nozzle diameter, U_j is the average jet nozzle discharge velocity, ρ is fluid density, and τ_y is the sludge yield stress. PNNL developed a similar model, which is described by equation [17]

$$ECR \propto D_j U_j \tau_s^{-0.46} \quad [17]$$

where τ_s is the sludge shear strength. Both models show the ECR to be proportional to $D_j U_j$. The ECR needs to equal the tank diameter, T , for complete suspension. If the pilot-scale and full-scale tanks are geometrically scaled, T/D_j is the same in both tanks and the pump nozzle velocity required for complete solids suspension in the pilot-scale tank is equal to the pump nozzle velocity required for complete solids suspension in full-scale tank (assuming the solids have the same yield stress or shear strength in both tanks). The exponent in equation [1] is zero. This model assumes the solid suspension is caused by the normal force produced by the jet impacting the sludge rather than a shear force created by the jet passing over the top of the sludge.

These approaches indicate that the exponent in equation [1] is in the range of 0 to 1/9 (0, 1/23, or 1/9) for this application. In all of these cases, the jet nozzle velocity in the pilot-scale tank is close to the jet velocity in the full-scale tank. The exponent of 1/9 produces the lowest jet nozzle velocity in the pilot-scale tank, and therefore, provides a lower bound on jet nozzle velocity for the tests.

3.1.1 Impact of Cooling Coils

The pilot-scale and full-scale tanks contain cooling coils, which will reduce the velocity of the turbulent jets produced by the pumps. Pilot-scale testing conducted by SRNL to measure liquid blending times as a function of pump parameters showed the cooling coils increased the blending time by approximately two fold.¹² While the coils are geometrically scaled between the two tanks, their impact could be different in the full-scale tank and the pilot-scale tank.

The authors looked at two approaches to assess the impact of the cooling coils on scaling the test data: turbulent channel flow and turbulent flow across tube banks. When liquid flows in a channel between two parallel plates, the shear stress between the plates and the fluid causes a decrease in pressure or a decrease in velocity. The decrease in pressure is described by equation [18]

$$-\Delta P = \frac{0.158 \nu^{0.25} \rho U^{1.75} x}{d_h^{1.25}} \quad [18]$$

where P is pressure, x is axial distance in the pilot-scale tank, ν is kinematic viscosity, ρ is density, U is velocity, and d_h is the hydraulic diameter in the pilot-scale tank, which is equal to 4 times the channel width for channel flow.^{13,14} Since the tanks are geometrically scaled, the ratio of axial distance to hydraulic diameter is constant, and the pressure drop is proportional to hydraulic diameter raised to the negative one fourth power ($-\Delta P \propto d_h^{-0.25}$). This approach to determining the impact of the cooling coils on scaling indicates that as the tank size increases, the cooling coils cause less of a reduction in jet velocity. With a scale factor of 10.85, the pressure drop in the larger tank is 45% less than the pressure drop in the smaller tank.

An alternative approach to assessing the impact of the cooling coils on scale up is to consider the coils to be a tube bank. Research investigating pressure drops in the shell side of heat exchangers has developed correlations to predict the pressure drop across tube banks. Donahue developed the following correlation

$$f = 0.99 (D U/\nu)^{-0.2} \propto D^{-0.2} \quad [19]$$

where f is the Fanning friction factor, D is the tube (i.e., cooling coil) diameter, U is velocity, and ν is kinematic viscosity.¹⁵

Dwyer et. al developed the following correlation

$$f = [0.23 + 0.11/(X_t - 1)^{1.06}](DU/\nu)^{-0.15} \propto D^{-0.15} \quad [20]$$

where X_t is the ratio of transverse tube pitch to tube diameter (the same in both tanks).¹⁶

Gunter and Shaw developed the following correlation.¹⁷

$$f = 1.92 (D U/\nu)^{-0.145} \propto D^{-0.145} \quad [21]$$

These correlations show the friction factor is inversely proportional to the tube diameter raised to an exponent n , where n is between 0.145 and 0.2. Given a scale factor of 10.85 and an exponent of 0.2, the friction factor would decrease by 38% in going from the pilot-scale tank to the full-scale tank. If the exponent is 0.145, the friction factor would decrease by 29%.

Both approaches to determine the impact of the cooling coils on scale up give similar results. The cooling coils will cause less of decrease in the jet velocity in the full-scale tank than in the pilot-scale tank, making the pilot-scale mixing results bounding. Because of the complexity of the fluid motion in these tanks and the lack of test results at another scale, equations [18] – [21] should not be used to quantitatively predict the impact of the cooling coils on scale up. The present work did not attempt to correct for the impact of the cooling coils as the tank becomes larger. Ignoring this correction leads to additional pump jet power for solids suspension than would exist if the impact of the coils was the same at both scales.

To better quantify the impact of the coils on scale up, testing should be conducted at another scale or computational fluid dynamics (CFD) modeling should be performed in a jet mixed tank with and without cooling coils to determine the impact of the coils on jet velocity on scale up.

The authors are conducting pilot-scale solids suspension tests in the following manner. They add solid particles (MST, CST, and/or simulated sludge) to the tank and allow the particles to settle for a specified time at a specified temperature.¹ They start the pilot-scale pumps at a low flow rate and measure the cleaning radius. They increase the flow rate, measuring cleaning radius as a function of $U_j D$, until all solid particles are suspended or the maximum pump flow rate is reached.

3.2 LIQUID-PARTICLE MASS TRANSFER

SRS uses impellers to suspend and mix the MST in the ARP. Previous work describing solid-liquid mass transfer in tanks mixed with impellers has shown the mass transfer rate to increase with impeller speed until all of the particles are suspended. After the particles are suspended, the increase in mass transfer rate with increasing impeller speed is much smaller.¹⁹ Therefore, a key to successful strontium sorption in the pilot-scale and full-scale tanks is to ensure all MST particles are suspended.

The rate controlling step in the sorption process must be determined to properly scale the strontium sorption tests. Plausible rate controlling steps in solid-liquid mass transfer are bulk transport, film diffusion, pore diffusion, or sorption. SRNL work has determined the rate controlling step is film diffusion.¹⁸ Previous mixing and mass transfer work in the technical literature has shown that agitation affects film diffusion.¹⁹

Correlations have been developed for mass transfer between a flowing fluid and a solid sphere. Many of the correlations are of the form described by equation [22]

$$Sh = A + BRe^a Sc^b \quad [22]$$

where Sh is the Sherwood number ($Sh=k d_p/D$), Re is the Reynolds number, Sc is the Schmidt number ($Sc=\nu/D$), k is the mass transfer coefficient, d_p is the particle size, ν is the kinematic viscosity, D is the molecular diffusivity, and A , B , a , and b are constants.^{20,19} Two expressions have been used for the Reynolds number, a Reynolds number based on the Kolmogoroff theory and a Reynolds number based on the particle slip velocity. Equation [23] describes the Reynolds number based on the Kolmogoroff theory and equation [24] describes the Reynolds number based on the slip velocity

$$Re = \epsilon d_p^4 / \nu^3 \quad [23]$$

$$Re = d_p u_t / \nu \quad [24]$$

where ϵ is the power per unit mass (power per unit volume when multiplied by density) and u_t is the slip velocity.^{19,21,22,23} Since the materials (supernate and solid particles) in the pilot-scale test have the same properties (density, viscosity, diffusivity, particle size) as the materials in the full-scale tank, the only parameter that can vary between the tanks is the power per unit mass (equation [23]) or the particle slip velocity (equation [24]). When the slip velocity is small, $<<0.1$ ft/min, equation [23] should be used to determine the Reynolds number.¹⁹ For a particle size of 15μ , a particle density of 1.8 g/cm^3 , a fluid density of 1.3 g/cm^3 , and a fluid viscosity of 3 cp , the particle settling velocity (and slip velocity) is $5.2 \times 10^{-3} \text{ ft/min}$.^c Therefore, equation [23] should be used to determine the Reynolds number for particles such as MST.

If the power per unit mass is intentionally held constant in both tanks, then the mass transfer coefficient should be the same in both tanks (see equation [23]). This scaling is described below. Equation [25] describes the power produced by a turbulent jet

$$P = (\pi/8) \rho D_j^2 U_j^3 \quad [25]$$

where P is power, ρ is fluid density, D_j is the jet diameter, and U_j is the jet discharge velocity. Equation [26] describes the volume of the tanks

$$V = \pi T^2 H / 4 = \pi T^3 (H/T) / 4 \quad [26]$$

where H is the liquid height. Equation [27] describes the power per unit volume in a tank.

$$P/V = [\pi \rho D_j^2 U_j^3 4] / [8 \pi T^3 (H/T)] = \rho D_j^2 U_j^3 / 2 T^3 (H/T) \quad [27]$$

If the tanks are geometrically scaled, the ratio of power per unit volume in the two tanks is described by equation [28]

$$\frac{(P/V)_{full-scale}}{(P/V)_{pilot-scale}} = \frac{D_{j-full-scale}^2 U_{j-full-scale}^3 T_{pilot-scale}^3}{D_{j-pilot-scale}^2 U_{j-pilot-scale}^3 T_{full-scale}^3} \quad [28]$$

^c Measured particle size of MST following resuspension test with two SMPs was 15μ .

Since the tanks are geometrically-scaled, the ratio of jet diameter to tank diameter is constant, and equation [28] reduces to equation [29].

$$\frac{(P/V)_{full-scale}}{(P/V)_{pilot-scale}} = \frac{U_{j-full-scale}^3 T_{pilot-scale}}{U_{j-pilot-scale}^3 T_{full-scale}} \quad [29]$$

Since the power per unit mass is held constant at both scales, the power per unit volume is also the same, and equation [29] reduces to equation [30]

$$U_{j-full-scale}^3 T_{pilot-scale} = U_{j-pilot-scale}^3 T_{full-scale} \quad [30]$$

and equation [31]

$$U_{j-full-scale} = U_{j-pilot-scale} (T_{full-scale}/T_{pilot-scale})^{1/3} \quad [31]$$

Therefore, for equal mass transfer in the pilot-scale tank and Tank 41H, the jet velocity in Tank 41H should be equal to the nozzle velocity in the pilot-scale tank multiplied by the cube root of the scale factor (10.85), or by 2.2. Using equation [31] for scale up produces a greater jet nozzle velocity in the full-scale tank.

For equal mass transfer between the pilot-scale and full-scale tanks, the exponent in equation [1] would be 1/3. To ensure that all particles are suspended, the exponent in equation [1] should be 0, 1/23, or 1/9. Exponents of 0 and 1/3 bound the scaling of the strontium sorption. The authors selected an exponent of 1/3 to provide a lower bound on the jet nozzle velocity for the pilot-scale tests.

The authors plan to conduct the pilot-scale strontium sorption tests in the following manner. Strontium nitrate will be added to the tank to produce a strontium concentration of ~ 2 mg/L. After the strontium is added, they will operate the mixer pumps to blend the tank, stop the pumps, and allow the tank contents to equilibrate for at least 24 hours. They will start the pumps with a nozzle discharge velocity such that $U_{j-pilot-scale} = U_{j-full-scale}/2.2$. Samples will be collected and filtered to determine the soluble strontium concentration. MST will be added to the tank to produce a concentration of 0.4 g/L. After the MST addition, samples will be collected and filtered to measure the soluble strontium concentration as a function of time. The pilot-scale strontium sorption tests will use the same power per unit volume as the full-scale process.

3.3 SCALING OF PUMP ROTATION

In addition to scaling the pump nozzle discharge velocity, the pump rotation rate must be scaled to obtain equivalent solids suspension and strontium sorption in both tanks. The SRS Tank Farm pumps rotate at 1/3 – 1/5 rpm (3 – 5 minutes for one complete rotation). The SMP pump planned for use in the SCIX process has a nozzle diameter of 4.4 inches and a discharge velocity of 79 ft/s. Equation [32] describes the centerline velocity of the pump discharge (neglecting cooling coils) as a function of position

$$U(x) = 6D_j U_j / x \quad [32]$$

where D_j is the nozzle diameter, U_j is the nozzle discharge velocity, and x is the distance from the pump. The maximum required cleaning radius in Tank 41H is 42.6 ft. The flight time for the fluid leaving the pump to travel 42.6 ft (assuming no obstructions) is 5.15 sec. If the cooling coils increased this time by a factor of 2, the time would be 10.3 sec.^d This time is significantly less than the time required for one rotation of the pump (i.e., 180 – 300 sec). Therefore, the rotation rate of the pump should not have a significant effect on the properties of the jet produced in the full-scale tank [In the pilot-scale tank, the flight time is 0.5 sec (at the same nozzle discharge velocity)].

3.3.1 Impact on Solids Suspension

In 1981, SRNL conducted full-scale testing with kaolin clay and SRS slurry pumps.¹⁰ The tests measured the pump cleaning radius as a function of nozzle diameter, nozzle discharge velocity, fluid density, and slurry yield stress for standard slurry pumps and quad volute pumps. The researchers conducted tests at 1/3 rpm and 1/5 rpm rotation rates. Initial studies of the effect of pump rotation speed indicate the cleaning radius is larger at lower rotation rates and is a factor in the ability of the jet to erode away the settled bed of solids, given that the jet has more time for a given location at the slower rotational speed. This result indicates that faster rotation rates are likely conservative for pilot-scale testing.

One approach to scaling the pump rotation rate is to compare the particle settling time with the time of a pump rotation. The MST mixing tests were conducted with the same MST that SRR uses in ARP. The supernate simulant was selected to have the same density and viscosity as the expected feed to the SCIX process. Therefore, the particle settling velocity in the pilot-scale tank should be the same as the particle settling velocity in the full-scale tank. However, the suspended particles have a shorter distance to fall in the pilot-scale tank than in the full-scale tank. The ratio of the distances is 1/10.85. Since the equivalent distance for a particle to fall in the pilot-scale tank is 1/10.85 the distance in the full-scale tank, the pumps should rotate 10.85 times faster in the pilot-scale tank, so the particles that are suspended have the same time to fall before the pump jet passes them on the next rotation.

Another approach to scaling the pump rotation rate was developed by PNNL during testing of the Advanced Design Mixer Pump.²⁴ The relevant scaling parameter is the product of the angular rotation rate and the residence time, which is described by equation [33]

$$(\omega_{\text{pilot}} h_{\text{pilot}} T_{\text{pilot}}^2 / D_{j-\text{pilot}}^2 U_{j-\text{pilot}}) = (\omega_{\text{full}} h_{\text{full}} T_{\text{full}}^2 / D_{j-\text{full}}^2 U_{j-\text{full}}) \quad [33]$$

where ω is the pump rotation rate, h is the tank fluid level, T is the tank diameter, D_j is the nozzle diameter, and U_j is the nozzle discharge velocity. Since the tanks are geometrically scaled, T/D_j is constant. If the nozzle discharge velocity is the same at both scales, equation [33] reduces to equation [34].

^d Factor of two based on difference in blend time measured by SRNL in pilot-scale testing in tanks with and without cooling coils [SRNL-STI-2010-00054].

$$\omega_{\text{pilot}} h_{\text{pilot}} = \omega_{\text{full}} h_{\text{full}} \quad [34]$$

According to equation [34], the pump rotation rate in the pilot-scale tank should be 10.85 times the pump rotation rate in Tank 41H (assuming constant jet nozzle velocity). If the jet nozzle velocity is 30% larger in the full-scale tank, the pump rotation rate would be 8.35 times faster in the pilot-scale tank.

The Strouhal number compares the time scale of steady flow with the time scale of oscillating flow, and is described by equation [35]

$$St = T \omega / U_j \quad [35]$$

where T is the tank diameter, ω is the pump rotation rate, and U_j is the pump nozzle discharge velocity. If the nozzle discharge velocity is the same in both scales, the pump rotation rate is inversely proportional to the tank diameter, and would be 10.85 times faster in the pilot-scale tank than in the full-scale tank. If the nozzle discharge velocity is 1.3 times larger in the full-scale tank than in the pilot-scale tank, the pump rotation rate is 8.35 times faster in the pilot-scale tank than in the full-scale tank.

PNNL conducted pilot-scale testing of sludge mobilization by rotating jet pumps.¹¹ The pilot-scale tanks were geometrically scaled. They maintained equal centerline jet velocities at geometrically similar points in the pilot-scale and full-scale tanks by maintaining the same jet nozzle velocity at both scales. They rotated the pumps at a faster rate in the pilot-scale tests ($\omega_{\text{pilot-scale}} = \omega_{\text{full-scale}} T_{\text{full-scale}} / T_{\text{pilot-scale}}$) in order to mobilize a scaled quantity of sludge corresponding to the quantity of sludge that is mobilized by a pump rotation in the full-scale tank. Following this approach, the pilot-scale pumps should rotate 10.85 times faster than the full-scale pumps.

Based upon these approaches for scaling the pump rotation rate, the authors make the following recommendation for this testing (see Table 2). If the nozzle jet velocity is the same in the full-scale tank as the pilot-scale tank, the pilot-scale pump rotation rate should be 10.85 times the full-scale pump rotation rate. If the nozzle jet velocity in the full-scale tank is 1.3 times the nozzle jet velocity in the pilot-scale tank, the pilot-scale pump rotation rate should be 8.35 times the full-scale pump rotation rate. If the nozzle jet velocity in the full-scale tank is 2.2 times the nozzle jet velocity in the pilot-scale tank, the pilot-scale pump rotation rate should be 4.93 times the full-scale pump rotation rate. Since a faster pump rotation rate may reduce the range the jet can penetrate with sufficient shear to suspend solids, the authors selected a pilot-scale pump rotation rate 10.85 times faster than the full-scale pump rotation rate.

Table 2. Scaling Pump Rotation Rate

<u>Approach</u>	<u>Pilot-Scale Pump Rotation Rate</u>	<u>Full-Scale Pump Rotation Rate</u>
Equal Jet Velocity	X	10.85X
Equal Shear Stress	X	8.35X
Equal Power per Volume	X	4.93X
Recommendation	X	10.85X

3.3.2 Impact on Strontium Sorption

As the pumps rotate, the fluid and particles in the tank will experience increases and decreases in fluid motion, turbulence, and shear stress. These changes could lead to changes in the mass transfer coefficient, which could be different in the two scales.

Strontium sorption is a slow process, typically taking approximately 12 - 24 hours for completion. The time for one complete pump rotation in SRS waste tanks is 3 – 5 minutes. The time for a complete rotation in the pilot-scale tank is approximately 17 seconds. Because the strontium sorption process is several orders of magnitude slower than a pump rotation, the rotation rate should not have a significant effect on the strontium sorption rate.

SRNL work has shown film diffusion to be the rate limiting step for strontium sorption on MST.¹⁸ Based on bench-scale tests¹⁸, the strontium sorption rate is 2.4 - 47 $\mu\text{g/Lhr}$.^e If we assume the volume of the film on a single MST particle is V_f and the strontium sorption rate is 47 $\mu\text{g/Lhr}$, the rate of strontium transport across the film is 47 $V_f \mu\text{g/hr}$. Since film diffusion is slower than bulk transport across the tank, as soon as a strontium molecule crosses the film and enters the MST pores, a new strontium molecule replaces it. Therefore, the strontium concentration in the film equals the strontium concentration in the bulk. Given a film volume of V_f and a liquid strontium concentration of 90 $\mu\text{g/L}$, the amount of strontium in the film is 90 $\mu\text{g/L} * V_f = 90 V_f \mu\text{g}$.^f At a pump rotation rate of 1/3 rpm, the jet sweeps by a section of the tank every 1.5 minutes (0.025 hours). The amount of strontium sorbed during a single jet pass is approximately 1.2 $V_f \mu\text{g}$ (47 $V_f \mu\text{g/h} * 0.025 \text{ hr}$), which is 1.3% of the strontium in the film. This calculation shows minimal change in the strontium concentration in the film as the pump completes one rotation. If the pump rotated at 3.6 rpm rather than 1/3 rpm, the time between jet sweeps would be 0.0023 hours, and the amount of strontium sorbed would be 0.11 $V_f \mu\text{g}$ (0.12%). Again, a minimal change in film strontium concentration during one jet sweep. In addition to this calculation, the SRNL testing shows the variation in strontium sorption rate between mixed and unmixed slurries to be less than 20%.¹⁸

In addition to the above calculation, work in the technical literature describing mass transfer between a liquid and a solid particle in impeller agitated tanks and fluidized beds shows that when the particles are suspended, changes in Reynolds number produce small changes in the mass transfer coefficient.^{25,26,27} Therefore, changes in the particle Reynolds number as the pumps rotate should not produce significant changes in the mass transfer coefficient and the strontium sorption.

The authors recommend conducting additional strontium sorption tests with varying pump rotation rates to confirm the assumption that the pump rotation rate does not significantly impact the strontium sorption rate.

^e Based on maximum rate in Table 1 in SRNL-STI-2010-00438.

^f Strontium concentration in the bulk is based on supernate strontium concentration prior to the start of High Activity Salt Solution Test in SRNL-STI-2010-00438.

3.4 SCALING OF SOLIDS SUSPENSION AND STRONTIUM SORPTION TIME

Given that the local velocity or local shear stress at the fluid-solid interface is the same in the pilot-scale and full-scale tanks, the rate of solid particle suspension should be the same in both tanks. Since the volume (i.e., depth) of solid particles is 10.85 times larger in the full-scale tank, the time to suspend the equivalent amount of particles in the full-scale tank is 10.85 times longer than in the pilot-scale tank.

In their scaled testing of sludge mobilization, PNNL looked at the effect of scale on the sludge mobilization time.¹¹ If the fluid velocities are the same in both tanks, the time for a fluid particle to be transported between equivalent points is reduced by the scale factor (10.85 in this work). As a result, the mixing rate scales linearly with tank size, and the time for equivalent solids suspension is increased in the full-scale tank by the scale factor (i.e., 10.85). Based on this analysis, the time required for solids suspension should be increased by a factor of 10.85 in the full-scale tank compared with the pilot-scale tank. If the ratio of jet nozzle velocities is 1.3 rather than 1.0, the increase in time for solids suspension becomes 8.35.

The impact of scaling on the strontium sorption time is different from the impact on solids suspension. The strontium sorption tests have been scaled to produce equal solid-liquid mass transfer coefficients between the pilot-scale and full-scale tanks. The rate of mass transfer of strontium (or an actinide) between the bulk liquid and the MST particles is described by equation [36]

$$N_A = k a_s (C_S - C_L) \quad [36]$$

where N_A is the rate of mass transfer, k is the mass transfer coefficient, a_s is the MST surface area, C_S is the strontium concentration on the MST and C_L is the strontium concentration in the bulk liquid. The tests were performed to produce the same mass transfer coefficient in both tanks. The initial bulk liquid and MST strontium concentrations will be the same in both tanks. The MST surface area per volume is the same in both tanks. Since the full-scale tank contains $10.85^3 = 1277$ times the MST as the pilot-scale tank, the surface area will be 1277 times larger in the full-scale tank. Therefore, the rate of strontium transfer will be 1277 times faster in the full-scale tank. Since the full-scale tank will contain 1277 times the strontium as the pilot-scale tank, the time required to reach the same reduction in strontium concentration will be comparable in both tanks assuming that the scaled concentration gradient of the strontium matches at both scales.

The SCIX Program is investigating the impact of scaling on the strontium sorption by conducting comparable tests on the bench-scale and comparing the rate of strontium sorption.¹

3.5 SCALING IMPELLER MIXING

Significant work exists in the technical literature describing the scaling of mixing tanks with impellers. While impeller mixing is different from mixing with rotating jets, scaling of impeller mixing was reviewed.^{28,29} After reviewing this information, the authors decided to use the

scaling approaches described in Sections 3.1 and 3.2, because they are more applicable to the SCIX process than the impeller approaches.

3.6 SCALING PULSED JET MIXERS

Dr. Dave Dickey, a recognized mixing expert, looked at scaling pulsed jet mixers for the Hanford Waste Treatment Plant.³⁰ While the mixing device in this analysis is different from the slurry pumps, there are similarities in the physics of mixing with the two devices. After reviewing this information, the authors decided to use the scaling approaches described in Sections 3.1 and 3.2, because they are more applicable to the SCIX process than the pulsed jet mixer approaches.

4.0 RESULTS

Since the scale ratio of Tank 41H to the pilot-scale tank is 10.85:1, equation [1] becomes

$$U_{\text{full-scale}} = U_{\text{pilot-scale}} (10.85)^n \quad [37]$$

When describing the suspension of MST, CST, and/or sludge in the SCIX process, the appropriate exponent in equation [1] is 0, 1/23, or 1/9. For scaling of solids suspension, the authors recommend using an exponent of 1/9 in equation [37], which leads to the nozzle discharge velocity being 30% larger in the full-scale tank than in the pilot-scale tank. Other scaling approaches suggest less of a difference in velocity between the two scales, but this approach provides a lower bound on the pilot-scale pump nozzle discharge velocity, and is applicable to this process.

When describing the sorption of strontium on MST, the appropriate exponent is 1/3. For scaling of strontium sorption, the authors recommend using an exponent of 1/3 in equation [37], which leads to the nozzle discharge velocity in the full-scale tank being 2.2 times the nozzle discharge velocity in the pilot-scale tank. Other scaling approaches suggest less of a difference in velocity between the two scales, but this approach provides a lower bound on jet nozzle velocity and is most applicable.

The cooling coils will cause less drag and less reduction in jet velocity in the full-scale tank compared with the pilot-scale tank. With less drag, the required pump nozzle velocity in the full-scale tank might be less than predicted from pilot-scale testing. This phenomenon leads to more pump jet power being available for solids suspension and strontium sorption than if the effect was the same at both scales.

The pumps will rotate faster in the pilot-scale tank than in the full-scale tank. The increase will be 4.9 – 10.85 times. Since a faster pump rotation rate may be less effective at suspending solid particles and the particles will settle an equivalent distance in 1/10.85 the time in the pilot-scale tank, the authors selected a pilot-scale pump rotation rate 10.85 times faster than the full-scale pump rotation rate.

The mixing rate scales with tank size, and the time for equivalent solids suspension is increased in the full-scale tank by a factor of 8.35 – 10.85. The time required to reach the same reduction in strontium concentration will be the same in both tanks. Testing is being performed as part of this task to verify this conclusion.

Table 3 summarizes the change in process variables between the pilot-scale and full-scale tanks.

Table 3. Comparison of Mixing Parameters in Pilot-Scale and Full-Scale Tanks

Parameter	Pilot-Scale Tank	Full-Scale Tank (Strontium sorption)	Full-Scale Tank (suspension/resuspension)
Power/Volume	1	1	0.09
Nozzle diameter (D_j)	1	10.85	10.85
Nozzle velocity (U_j)	1	2.2	1.3
$U_j D_j$	1	23.9	14.1
Reynolds number	1	23.9	14.1
Flow Rate	1	259	153
Mixing Time	1	1	8.35
Rotation Rate	1	0.2	0.12
Wall shear stress	1	2.6	1

The authors selected simulated supernate solution and solid particles to match the expected feed to the SCIX process. The simulated supernate was selected to match Tank 37H supernate. Other feeds to the SCIX process could have different ionic strength, density, viscosity, and composition. An increase in solution viscosity would cause a more rapid decay of the turbulent jet produced by the pumps. However, that effect is expected to be small.

The authors selected the solid particles to match the solid particles expected in the SCIX process. The MST is from the same lot as the MST currently in use at ARP. The CST is from UOP (the CST manufacturer) and is being ground by the same process planned for SCIX. The sludge is simulated Sludge Batch 6, and was chosen because it is slow settling and has a high yield stress. An increase in particle size could increase the pump nozzle velocity needed to suspend the solid particles. However, given the small size of the particles expected (1 – 15 μ), a very large increase would be needed for the effect to be significant. An increase in rheology (i.e., yield stress or shear strength) could have a significant effect on the pump nozzle velocity needed to suspend the solid particles.

5.0 CONCLUSIONS

The conclusions from this analysis follow.

- For solids suspension/resuspension, the nozzle discharge velocity in the full-scale tank must be 30% greater than the nozzle discharge velocity in the pilot-scale tank. This approach is the most conservative scaling relationship for the solids suspension/resuspension process.
- The time to resuspend the particles in the full-scale tank could be up to 10.85 times longer than the resuspension time in the pilot-scale tests.

- For strontium/actinide sorption the nozzle discharge velocity in the full-scale tank must be at least 2.2 times greater than the nozzle discharge velocity in the pilot-scale tank. The time for strontium sorption should be the same in the pilot-scale and full-scale tanks.
- The cooling coils will cause less drag and less reduction in jet velocity in the full-scale tank compared with the pilot-scale tank. Neglecting a correction for the cooling coils will under predict the jet velocity in the full-scale tank and provide conservatism in scale-up.
- The pump rotation rate in the pilot-scale tests should be 10.85 times the pump rotation rate in the full-scale tank. The actual difference between the full-scale and pilot-scale tanks could be less, but the authors selected the 10.85 factor since a faster rotation rate may produce less effective mixing in the pilot-scale tank.

6.0 RECOMMENDATIONS

The authors make the following recommendations to improve the scaling of these test results.

- Perform testing at another scale. Having different scales of testing provides additional data points for the analysis and allows one to better support the proposed scaling method(s). Additional data would allow the authors to refine the scaling relationships and allow the SCIX Program to reduce the conservatism in their design, as well as reduce the program risk.
- Perform Computational Fluid Dynamics (CFD) modeling. CFD would allow us to conduct tests at several scales and compare fluid velocities in different size tanks. With CFD, we could determine the nozzle velocities needed to obtain equivalent fluid velocities at equivalent points in the tank. Knowing these nozzle velocities would reduce the conservatism needed to size the SCIX mixer pumps. In addition, the CFD analysis could quantify the impact of the cooling coils on scale up. SRNL is currently performing CFD modeling to support the design of pumps for the Salt Disposition Integration Project (SDIP). A minimal effort would be needed to apply the results to this task.
- Conduct additional strontium sorption tests with varying pump rotation rates to verify the impact of pump rotation rate on the strontium sorption rate. This data, along with previous SRNL strontium sorption data and solid-liquid mass transfer data in the technical literature, can be used to strengthen the conclusion that the strontium sorption rate is not sensitive to the pump rotation rate and reduce the uncertainty surrounding the impact of pump rotation rate.

7.0 REFERENCES

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- ¹ K. M. L. Taylor-Pashow, M. R. Poirier, Z. Qureshi, F. F. Fondeur, T. B. Peters, D. T. Hobbs, and S. D. Fink, "Task Technical and Quality Assurance Plan for Testing to Support Modular Salt Processing Project – Monosodium Titanate Studies", SRNL-RP-2010-00686, Rev. 1.
 - ² M. R. David and H. Winarto, "Jet Diffusion from a Circular Nozzle above a Solid Plane", J. Fluid Mech., vol. 101, pp. 201-221, 1980.
 - ³ R. D. Blevins, Applied Fluid Dynamics Handbook, New York: Van Nostrand Reinhold, 1984.
 - ⁴ B. Cushman-Roisin, Environmental Fluid Mechanics, New York: Wiley, 2010.

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- ⁵ N. Rajaratnam, "Turbulent Mixing and Diffusion of Jets", in N. P. Cheremisinoff and R. Gupta, Eds., Handbook of Fluids in Motion, Boston: Butterworths, 1983.
- ⁶ B. E. Wells, C. W. Enderlin, P. A. Gauglitz, and R. A. Peterson, "Assessment of Jet Erosion for Potential Post-Retrieval K-Basin Settled Sludge", PNNL-18831, September 2009.
- ⁷ C. O. Bennett and J. E. Myers, Momentum, Heat, and Mass Transfer, 3rd Ed., New York: McGraw-Hill, 1982.
- ⁸ K. A. Mazurek, N. Rajaratnam, and D. C. Sego, "Scour of a Cohesive Soil by Submerged Plane Turbulent Wall Jets", J. Hydraulic Res., Vol. 41, No. 2, pp. 195-206, 2003.
- ⁹ F. Ade and N. Rajaratnam, "Generalized Study of Erosion by Circular Horizontal Jets", J. Hydraulic Res., Vol. 36, No. 4, pp. 613-636, 1998.
- ¹⁰ B. V. Churnetski, "Effective Cleaning Radius Studies", DPST-81-282, February 19, 1981.
- ¹¹ M. R. Powell, Y. Onishi, and R. Shekarritz, "Research on Jet Mixing of Settled Sludges in Nuclear Waste Tanks at Hanford and Other DOE Sites: A Historical Perspective", PNNL-11686, September 1997.
- ¹² R. A. Leishear, M. R. Poirier, and M. D. Fowley, "SDI Blend and Feed Blending Study Tank 50H Scale Modeling for Blending Pump Design Phase I", SRNL-STI-2010-00054, June 2010.
- ¹³ F. M. White, Viscous Fluid Flow, New York: McGraw-Hill, 1974, p. 487.
- ¹⁴ C. O. Bennett and J. E. Myers, Momentum, Heat, and Mass Transfer, 3rd Ed., New York: McGraw-Hill, 1982, p. 168.
- ¹⁵ D. A. Donahue, "Heat Transfer and Pressure Drop in Heat Exchangers", Ind. Eng. Chem., Vol. 41, No. 11, pp. 2499-2511, 1949.
- ¹⁶ O. E. Dwyer, T. V. Sheehan, J. Weisman, F. L. Horn, and R. T. Schomer, "Cross Flow of Water through a Tube Bank at Reynolds Numbers up to a Million", Ind. Eng. Chem., 48, no. 10, pp. 1836-1846, 1956.
- ¹⁷ A. Y. Gunter and W. A. Shaw, "A Generalized Correlation of Friction Factors for Various Types of Surfaces in Crossflow", trans. ASME, Nov. 1945, pp. 643-660.
- ¹⁸ D. T. Hobbs, "Review of Experimental Studies Investigating the Rate of Strontium and Actinide Adsorption by Monosodium Titanate", SRNL-STI-2010-00438, October 2010.
- ¹⁹ V. A. Atiemo-Obeng, W. R. Penney, and P. Armenante, "Solid-Liquid Mixing", in Paul E.L.; Atiemo-Obeng, V. A.; and Kresta, S. M., Eds., Handbook of Industrial Mixing, Wiley, Hoboken, 2004.
- ²⁰ C. O. Bennett and J. E. Myers, Momentum, Heat, and Mass Transfer, 3rd Ed., New York: McGraw-Hill, 1982.
- ²¹ D. M. Levins and J. R. Glastonbury, "Application of Kolmogoroff's Theory to Particle-Liquid Mass Transfer in Agitated Vessels", Chem. Eng. Sci., vol 27, pp. 537-543, 1972.
- ²² A. W. Nienow, "Agitated Vessel Particle-Liquid Mass Transfer: A Comparison between Theories and Data", The Chem. Eng. J., Vol. 9, pp. 153-160, 1975.
- ²³ V. G. Pangarkar, A. A. Yawalkar, M. M. Sharma, and A. A. C. M. Beenackers, "Particle-Liquid Mass Transfer Coefficient in Two/Three Phase Stirred Tank Reactors", Ind. Eng. Chem. Res., Vol. 41, pp. 4141-4167, 2002.
- ²⁴ C. W. Enderlin, G. Terrones, C. J. Bates, B. K. Hatchell, and B. Adkins, "Recommendations for Advanced Design Mixer Pump Operation in Savannah River Site Tank 18F", PNNL-14443, October 2003.

-
- ²⁵ S. Boon-Long, C. Laguerie, and J. P. Couderc, "Mass Transfer from Suspended Solids to a Liquid in Agitated Vessels", Chem. Eng. Sci., Vol. 33, pp. 813-819, 1978.
- ²⁶ R. V. Chaudhari and P. A. Ramachandran, "Three Phase Slurry Reactors", AIChE J., vol. 26, No. 2, pp. 177-201, 1980.
- ²⁷ A. W. Nienow and D. Miles, "The Effect of Impeller/Tank Geometry on the Fluid-Particle Mass Transfer", Chem. Eng. J., vol. 15, pp. 13-24, 1978.
- ²⁸ R. R. Tautzen, R. R. Corpstein, and D. S. Dickey, "How to use Scale-up Methods for Turbine Agitators", Chemical Engineering, October 25, 1976.
- ²⁹ C. M. Garrison, "How to Design and Scale Mixing Pilot-Plants", Chemical Engineering, February 7, 1983.
- ³⁰ D. S. Dickey, "Scaling of PJM Vessels Containing Settling Solids in Newtonian Slurries" Attachment to CCN 210455, March 4, 2010.