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Tank 49H Solids Disturbance Analysis

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EXECUTIVE SUMMARY

Tank 49H serves as the feed tank for the Salt Waste Processing Facility (SWPF). Transfers into Tank 49H may disturb any solids that have settled to the bottom of the tank, resulting in feed that may exceed the insoluble solids content limit of 1,200 mg/L of the SWPF Waste Acceptance Criteria (WAC). During a transfer into Tank 49H, material that free falls into Tank 49H through a downcomer could potentially disturb any solids on the bottom of the tank and scour or suspend solids from a settled solids layer or turbid region. A previous analysis and report evaluated the potential to disturb solids when transferring into Tank 49H through the B4 riser and recommended a minimum tank level of 120 inches to prevent disturbing any solids in the bottom of the tank. The scope of this task is to perform additional fluid flow analysis to determine whether accounting for disturbed particle settling and particle mixing and dispersion during transfer could allow the minimum liquid level to be reduced below 120 inches.

The analysis utilized models from the technical literature to calculate the size and shape of the "plunging jet" as a function of input parameters such as initial velocity, initial jet diameter, elevation of the initial jet, liquid level in the tank, and solids depth. The analysis relied on the M-Star® simulations performed for the previous analysis to provide bounding estimates of the amount of solid particles disturbed and used the M-Star® software to calculate the dispersion and mixing of the disturbed solids with other liquid in the tank as the solids are transported to the transfer pump.

The analysis showed that with a solid particle size of 5 micron or less, a liquid level of 120 inches should be maintained to prevent significant disturbance of the solid layer at the bottom of Tank 49H.

If liquid is added to Tank 49H with a liquid level less than 120 inches, particle disturbance is expected to occur. Once the liquid level reaches 120 inches, particle disturbance will stop and particle settling will begin. In the time that the liquid level increases from 120 inches to 290 inches, significant particle settling could occur, which may prevent exceeding the SWPF WAC limit for insoluble solids, but the settling is dependent on the size of the particles at the bottom of Tank 49H.

If the disturbed particles are 1 micron or less, the particles will follow the fluid motion in the tank. As these particles are transported to the transfer pump, they will be dispersed and mixed with other liquid in the tank. The concentration of these disturbed particles in the feed to the transfer pump will likely be less than the SWPF WAC limit for insoluble solids.

Considering the settling of particles 5 micron and larger during liquid addition to Tank 49H and the dispersion and mixing of particles 1 micron and smaller during transport from the disturbed region under the B4 riser to the transfer pump, it is possible that the minimum liquid level in Tank 49H could be reduced without exceeding the SWPF WAC limit for insoluble solids. The median particle size for the actual SRS sludge samples ranged between 2.6 micron and 15.1 micron. Since an engineering analysis indicated that at least 35% of the particles should settle before reaching the transfer pump, this adds additional support for reducing the minimum liquid level in Tank 49H for additions through the B4 riser.

If the height of the settled solid particles layer in Tank 49H is greater than 1.1 inches, the mass of suspended particles and the mass of particles reaching the transfer pump should be increased proportionally. The increased insoluble solids particle layer height may lead to a smaller fraction of the particles being suspended, but that cannot be verified or quantified at this time.

In addition, if there are insoluble solid particles suspended in the supernate prior to the transfer or insoluble particles in the transfer, the concentration of these particles must be considered in determining whether the SWPF WAC limit for insoluble solids will be met.

If Savannah River Mission Completion (SRMC) wishes to maintain a lower level in Tank 49H, they should consider lowering the elevation at which the liquid enters the tank through the B4 riser, adding a device to disperse the added liquid into droplets that will not penetrate deeply below the liquid surface, or adding a nozzle to the downcomer to reduce the diameter of the jet produced by the liquid entering the tank.

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LIST OF ABBREVIATIONS

ARP	Actinide Removal Process
b	Channel half width
CFD	computational fluid dynamics
CSSX	Caustic Side Solvent Extraction
D	nozzle diameter, diameter of disturbed region
D_j	plunging jet diameter at liquid surface
D_0	diameter of jet at downcomer exit
d_p	particle density
D_z	plunging jet diameter as a function of depth
DA	Design Authority
g	gravitational acceleration
g_c	gravitational constant
H	height
H_p	plunging jet penetration depth
L	distance
LWO	Liquid Waste Operations
M	mass
MCU	Modular CSSX Unit
Q	flow rate
r	radius of converging channel
s	solid-liquid density ratio
SPF	Saltstone Production Facility
SRMC	Savannah River Mission Completion
SRNL	Savannah River National Laboratory
STP	submersible transfer pump
SWPF	Salt Waste Processing Facility
t	time
TTR	Technical Task Request
TTQAP	Task Technical and Quality Assurance Plan
v	Velocity magnitude
v_s	settling velocity
v_x	Velocity in x direction
v_y	Velocity in y direction
v_∞	Velocity downstream from channel entrance
V	volume
V_j	velocity at liquid surface

V_p	volume of a particle
V_0	downcomer discharge velocity
V_x	Dimensionless velocity in x direction
V_y	Dimensionless velocity in y direction
WAC	Waste Acceptance Criteria
x	mass fraction
X	Dimensionless x
Y	Dimensionless y
z	change in elevation
Z	Plunging jet depth
ν	kinematic viscosity
ρ	density
μ	Viscosity
ϕ	Potential function
ψ	Stream function
Φ	Dimensionless potential function
ψ	Dimensionless stream function

1.0 Introduction

Tank 49H serves as the feed tank for the Salt Waste Processing Facility (SWPF). Transfers into Tank 49H may disturb solids that have settled to the bottom of the tank, resulting in feed that may exceed the insoluble solids content limit of 1,200 mg/L of the SWPF Waste Acceptance Criteria (WAC).[1] During a transfer into Tank 49H, material that free falls from the Tank 49H B4 downcomer could potentially disturb any solids on the bottom of the tank and scour or suspend solids from a settled solids layer or turbid region. The scope of this task is to perform fluid flow analysis to determine the influence of a "plunging jet" on any solids in Tank 49H and to determine a minimum liquid level to be maintained in Tank 49H prior to transfer through the B4 downcomer that will minimize disturbing the solids and exceeding the SWPF WAC limit for insoluble solids.[2]

This analysis and report build upon previous analyses, which assessed the disturbance of solid particles when liquid was added to Tank 49H through the B4 riser and the C3 riser, along with another analysis that examined the dispersion of the disturbed solids as liquid was transported to the transfer pump.[3,4]

The Design Authority (DA) for Savannah River Mission Completion (SRMC) Tank Farm Facility Engineering provided Savannah River National Laboratory (SRNL) the information needed (inputs) to complete this task.[5] The information provided by SRMC included the following.

- The location, elevation from the tank bottom, and range of flow rates of the transfer pump from Tank 49H to SWPF
- The location, vertical distance from the tank bottom, and internal diameter of the downcomer pipe used to add liquid to the tank
- The range of flow rates for the additions to the tank
- The minimum and maximum fill levels of the tank
- The thickness of the insoluble solids layer on the tank bottom

Previous SRNL analyses showed that when liquid is added to a waste tank, a "plunging jet" can form when the liquid enters the tank.[3,6,7] This "plunging jet" entrains surrounding fluid, which is mixed with the fluid added to the tank. The "plunging jet" could have sufficient momentum to disturb any solids layer on the bottom of the tank. Fluid mechanics principles were used to determine the properties of the "plunging jet" that forms as fluid is added to Tank 49H, using the geometry and operating conditions of this tank, to determine whether the jet is likely to disturb any solids layer on the bottom of Tank 49H.

The analysis utilized models from literature[8,9,10,11] to calculate the size and shape of the "plunging jet" as a function of parameters such as initial velocity, initial jet diameter, elevation of the initial jet, liquid level in the tank, and solids depth. Some of the input parameters, such as downcomer elevation, downcomer nozzle diameter, and liquid addition rate, were provided by SRMC. The analysis varied the input parameters to determine their influence on the properties of the "plunging jet". The analysis identified liquid levels under which the plunging jet will not disturb the assumed solids on the bottom of Tank 49H.

Previous work used the M-Star® Lattice-Boltzmann Computation Fluid Dynamics (CFD) software[a] to simulate the "plunging jet" behavior and estimate the amount of solids particles disturbed as a function of liquid level.[3] The simulations showed that numerical transport occurred, which may have biased high the mass of solid particles disturbed. The mass of disturbed solids from the previous analysis will be used in some of the calculations for this report.[3]

Because of the issues with numerical transport and the long time needed to perform the "plunging jet" simulations, an alternative approach was applied in which the M-Star® software was used to simulate the transport of the disturbed solids under the B4 riser to the transfer pump. The simulations showed the blending of the disturbed solids with the liquid in the tank as the tank contents are removed by the transfer pump. The previous document[3] provided an upper bound on the mass of solids disturbed. This work uses

[a] M-Star® CFD software is licensed from M-Star® Simulations, LLC. This analysis used version 3.2.

that mass of disturbed solids and performs M-Star® simulations to calculate the concentration of insoluble solids in a transfer from Tank 49H to SWPF.

1.1 Quality Assurance

This work was performed under a Technical Task Request (TTR), which requested a functional classification of Safety Significant.[2] The work was performed under Task Technical and Quality Assurance Plan (TTQAP) SRNL-RP-2020-00320, Rev. 1.[12] The M-Star® software is classified as D, and although not sufficient for Safety Significant input, it was used to complement the other analyses performed previously. It has been benchmarked against experimental data for other tasks[13] and will be compared with an analytical solution later in this document to assess its ability to simulate the important physics in this application.

Requirements for performing reviews of technical reports and the extent of review are established in manual E7 2.60.[14] Design verification was performed by document review. This verification will be documented by the reviewer's signature on the technical report.

2.0 Analysis

Inputs:

The following input parameters were provided by SRMC and are used in the assessment.[5]

- Tank 49H Submersible Transfer Pump (STP)
  - Location: Riser B5
  - Position is 26.33 ft south of the tank center and 12.27 ft east of the tank center
  - Suction elevation: 16 inches above bottom of the tank
  - Flow Rate: 82 – 159 gpm
- Tank 49H B4 Downcomer
  - Position is 10.39 ft south of the tank center and 27.07 ft east of the tank center
  - The output of the downcomer has an elevation of 388.125 inches[b]
- Tank 49H minimum fill level
  - Nominal fill factor is 3510 gallons per inch
  - Minimum liquid level 61 inches
- Distance between downcomer riser (B4) and STP riser (B5)
  - 22 feet
- Transfer frequency to SWPF
  - 23,200 gallons every 21.6 hours
- Addition rate of liquid from Tank 41H to Tank 49H
  - 100 – 120 gpm
  - Maximum flow rate 200 gpm
- Addition rate of liquid from Tank 42H to Tank 49H
  - 70 – 198 gpm
  - Maximum flow rate 200 gpm
- Gibbsite density
  - 2.42 g/mL
- Sodium aluminosilicate density
  - 2.34 – 2.60 g/mL

[b] The original input document provided (X-ESR-H-01041, Rev. 0) listed the downcomer elevation at 388.125 inches. This elevation was used to perform the M-Star computer simulations, which are an input to the calculations in this report. A later input document (X-ESR-H-01041, Rev 3) changed the downcomer elevation to 388.625 inches. This change in elevation is not expected to have a significant impact on the results in this report. Because 388.125 inches was used for the M-Star computer simulations, that value is used in the inputs for this report.

- Tank 49H solids level
    - 1.1 inches
- Particle size
    - 1 – 100 micron

SRMC provided an estimated particle size of 1 – 100 micron in the inputs document, but the actual size, composition, and density of the solid particles is unknown. Previous work by SRNL collected data on the particle size of simulated sludge and actual sludge. Figure 1 shows particle size data. The median particle size for the actual SRS sludge samples ranged between 2.6 micron and 15.1 micron.[15] Figure 2 shows the fraction of particles less than 10 micron measured in samples of Tank 5, Tank 13, and Tank 15 sludge. The data show that ~60% of the Tank 15 sample particles, ~45% of the Tank 13 sample particles, and ~35% of the Tank 5 sample particles were less than 5 micron. This data will be used later in the document to discuss settling of disturbed particles.

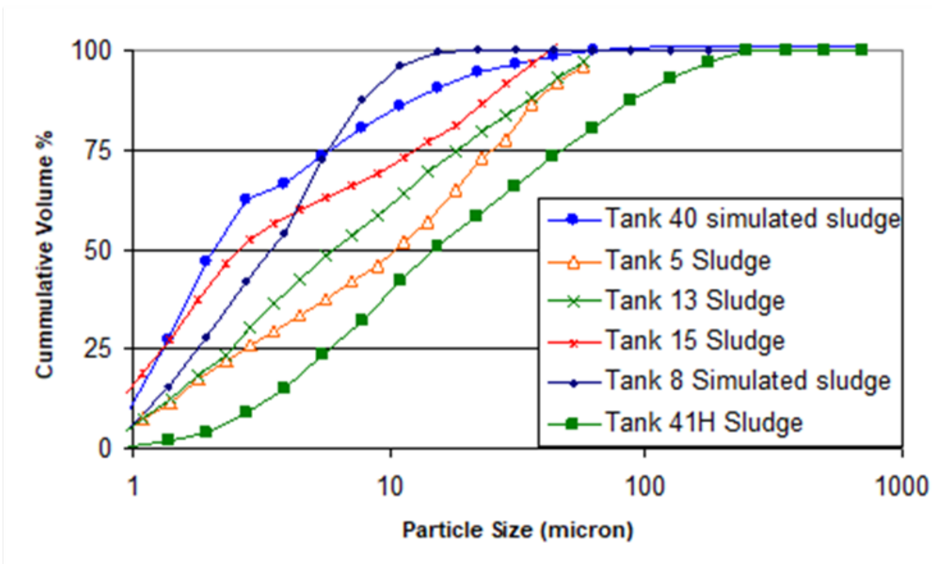

Figure 1. Particle Size of Simulated SRS Sludge and Actual SRS Sludge

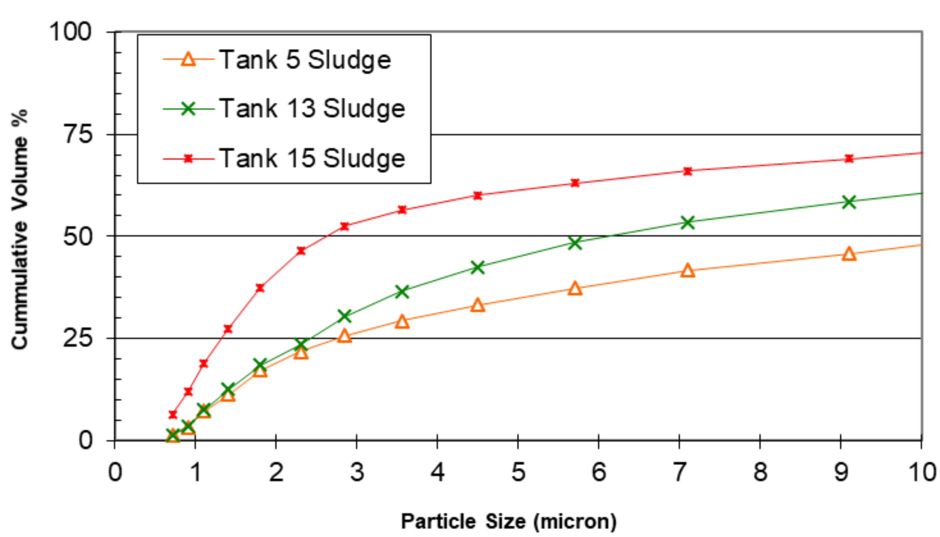

Figure 2. Fraction of Particles Less than 10 Micron in SRS Sludge Samples

In addition to the particle size data discussed above, SRNL performed a statistical analysis of sample data from Tank 48H in 1995.[16] In this study, the tank contained monosodium titanate (MST), a small concentration of entrained sludge, and no tetraphenyl borate. One of the analyses performed was for titanate, which would have come from the MST. The highest sampling points were at 126 inches, and most of the solid particles dropped below 42 inches within 2 hours after stopping agitation. Based on settling data, the authors calculated a particle size of approximately 14 micron, which is approximately equal to the median particle size of 15.1 micron measured in the Tank 41H sample. The work also observed a 75 – 90% reduction in the measured insoluble solids concentration occurring over 5 hours after stopping agitation.

Analysis of the samples collected from Tank 49H to qualify Salt Batch 1 for feed to the Actinide Removal Process (ARP)/Modular Caustic Side Solvent Extraction (CSSX) Unit (MCU) after settling overnight (13.5 hours), showed a dense particle layer at the bottom of the vessel indicating that significant particle settling occurred during this time.[17]

Figure 3 shows a view of the top of Tank 49H to show the positions of the risers B4 and B5 in the tank.

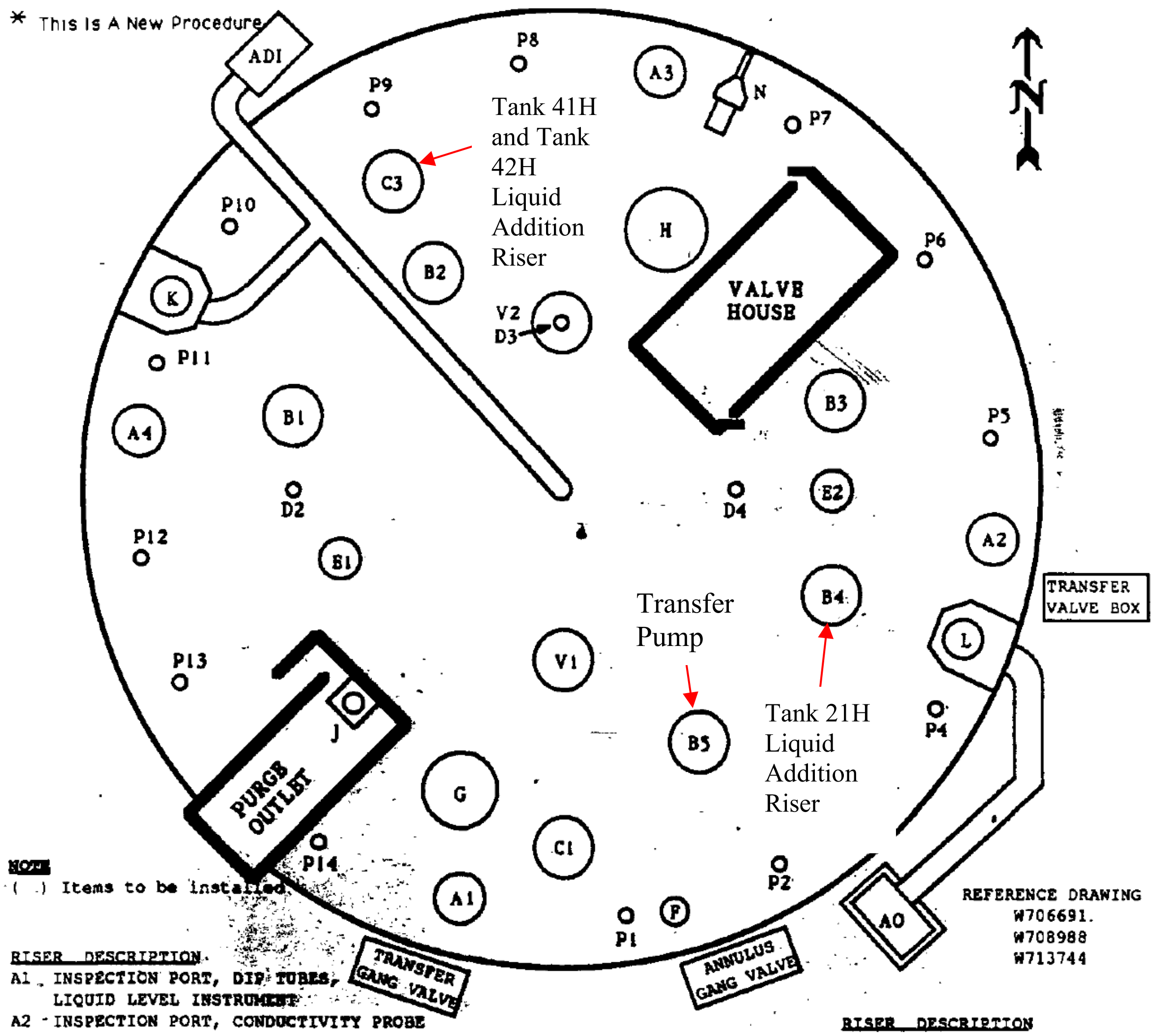

Figure 3. Tank 49H Tank Top

Assumptions:

The authors made the following assumptions to perform this analysis.

- The liquid added to the tank can be modeled as a "plunging jet". The behavior of the jet entering the tank and reaching the liquid surface follows the behavior of a "plunging jet".
- The jet is assumed to be a cylindrical column as it moves through the tank headspace. Because of turbulence and interactions with the air in the headspace, the jet will likely start to take on a non-cylindrical shape as it descends into the tank. This non-cylindrical shaped jet will entrain more air and penetrate less into the liquid.
- A liquid density of 1.26 g/mL was selected based on SRS average salt solution and would be representative of the expected density of the liquid added to Tank 49H.[18]
- A liquid viscosity of 2.5 cP was selected based on SRS average salt solution and would be representative of the expected viscosity of the liquid added to Tank 49H.[18]
- There are no insoluble solid particles in the liquid added to Tank 49H or in the Tank 49H supernate prior to the addition of liquid. If insoluble solid particles are present in the liquid added to Tank 49H or in the Tank 49H supernate prior to the addition of liquid, this mass of solid particles must be included in the calculation of the insoluble solids transferred to SWPF.
- The density of the solid particles on the bottom of the tank is 2.25 g/mL or 2.6 g/mL. The 2.25 g/mL density is less than the minimum described in the inputs above, and it was selected to be conservative for calculating solid particle settling and suspension. The 2.6 g/mL is the maximum described in the inputs above, and it was selected to be conservative when calculating the mass of particles suspended in the previous analysis and in calculating the concentration of insoluble solids in the transfers from Tank 49H to the SWPF.[3]
- The solids layer on the tank bottom is 30 vol % insoluble solids. The Safety Analysis Input document specifies the maximum insoluble solids concentration in settled sludge to be 30 vol %.[19]
- The solid particles that are suspended by the "plunging jet" are assumed to be suspended into a cylindrical volume that is 10 ft in diameter. The 10 ft diameter was selected to be much larger than the diameter of the jet reaching the liquid surface (~1 – 1.5 inches) and the maximum diameter of the plunging jet (~ 20 inches).
- In the M-Star® simulations of the transport of disturbed solids to the transfer pump, the solid particles are assumed to be suspended into a cylindrical volume that is 10 ft in diameter and 24 inches high. The previous simulations of the plunging jet showed the disturbed solids to be suspended to a height of approximately 24 inches.[3] This assumption is used to place the disturbed particles at the start of the M-Star® simulations of the transport of the disturbed solids to the transfer pump.
- This calculation assumes the transfer pump starts as soon as all the solid particles are disturbed. There may be a delay between particles being suspended (i.e., end of transfer into the tank) and the transfer pump starting. Some particles may begin to settle once they move from the disturbed region below the downcomer.
- In the M-Star® simulations of the transport of disturbed solids to the transfer pump, there is no delay between batches. During the time between transfers, particle settling and particle dispersion will occur making the simulation results conservative.
- In the M-Star® simulations of the transport of disturbed solids to the transfer pump, there are no cooling coils present. The addition of cooling coils would increase the dispersion of the solid particles as the fluid moves toward the transfer pump. This assumption makes the calculations conservative.
- These calculations assume no hindered settling behavior – i.e., particle-particle interactions – which is a reasonable assumption for dilute slurries of non-cohesive particles.
- The particle size distribution of the solid particles on the bottom of Tank 49H may be represented by the particle size data collected from Tanks 5, 13, and 15. This assumption must be used with caution. Tanks 5, 13, and 15 are sludge tanks and the particle size data were collected years ago. It may not be representative of the current material in Tank 49H.

2.1 Plunging Jet

The authors addressed this problem by treating the added salt solution as a "plunging liquid jet".[8,9,11] The following input parameters were used for the analysis.

- Downcomer pipe diameter = 3.068 inches
- Liquid flow rate = 70 gpm, 95 gpm, and 200 gpm
- Downcomer elevation = 388.125 inches[b]
- Liquid level = 80 - 120 inches
- Liquid density = 1.26 g/mL[18]
- Liquid viscosity = 2.5 cP[18]

The exit velocity of the downcomer is calculated with equation [1]

$$V_0 = \frac{4Q}{\pi D^2} \qquad [1]$$

where Q is the flow rate and D is the downcomer internal diameter. For a flow rate of 95 gpm, the exit velocity is 4.12 ft/s. For a flow rate of 200 gpm, the exit velocity is 8.68 ft/s. Because the jet is moving vertically downward, its velocity will increase due to gravity. The velocity at the liquid surface can be calculated with equation [2]

$$V_j = \sqrt{V_0^2 + 2gL} \qquad [2]$$

where V_0 is the downcomer exit velocity, g is gravitational acceleration, and L is the distance between the downcomer exit and the liquid surface (with a liquid level of 100 inches, L = 388.125 – 100 = 288.125 inches = 24 feet). For a downcomer exit velocity of 4.12 ft/s, the velocity at the surface is 39.5 ft/s. For a downcomer exit velocity of 8.68 ft/s, the velocity at the surface is 40.3 ft/s. Because the jet is accelerating, its diameter will decrease to conserve mass. The diameter of the jet at the surface is described by equation [3].

$$D_j = \sqrt{\frac{4Q}{\pi V_j}} \qquad [3]$$

With a downcomer discharge flow rate of 95 gpm, the jet diameter at the liquid surface is 0.99 inches. With a downcomer discharge flow rate of 200 gpm, the jet diameter at the liquid surface is 1.42 inches.

The penetration depth of the jet is described by equation [4]

$$H_p = 2.1\ V_j^{0.775}\ D_0^{0.67} \qquad [4]$$

where V_J is the jet velocity at the liquid surface (in m/s) and D_0 is the jet diameter at the exit of the downcomer (in m).[8,9] With a flow rate of 95 gpm out of the downcomer, the penetration depth is 103 inches. If the flow rate is increased to 200 gpm, the penetration depth is 104 inches. This distance is greater than the minimum liquid level in the tank (61 inches). Since the "plunging jet" penetration depth is greater than the liquid depth in the tank, the depth may need to be adjusted to account for the effects of the tank bottom.

After the jet enters the liquid, it will expand at an angle of ~22°. Equation [5] describes the diameter of the jet as a function of depth

$$D_z = Z\tan(\theta/2) = Z\tan(22^\circ/2) = Z\tan(11^\circ) \qquad [5]$$

where Z is the depth below the liquid surface.[6,7]

Table 1 and Figure 4 summarize the results of the analysis. Table 1 shows "plunging jet" properties at three liquid levels using two flow rates. Figure 4 shows the penetration depth as a function of inlet flow rate and tank level for additional conditions. The analysis shows that between a liquid level of 100 inches and 120 inches, the penetration depth of the "plunging jet" is approximately 100 inches and that the penetration depth is a weak function of the input flow rate. Over a range of liquid levels between 60 and 170 inches, Figure 4 shows little effect of inlet flow rate (70, 95, and 200 gpm) on the depth of the "plunging jet". This analysis does not allow for a determination of the mass of solid particles suspended.

Table 1. Behavior of Plunging Jet in Tank 49H at 100, 110, and 120 inch Liquid Level[c]

Liquid Level (inches);	100	100	110	110	120	120
Downcomer flow rate (gpm)	95	200	95	200	95	200
Downcomer exit velocity (ft/s)	4.1	8.7	4.1	8.7	4.1	8.7
Downcomer exit diameter (inches)	3.068	3.068	3.068	3.068	3.068	3.068
Jet velocity at liquid surface (ft/s)	39.5	40.3	38.9	39.6	38.2	38.9
Jet diameter at liquid surface (inches)	0.99	1.42	1.00	1.44	1.01	1.45
Penetration depth (inches)	103	104	102	103	100	102
Penetration Depth with 10% conservatism (inches)	113	114	112	113	110	112
Penetration Depth with 20% conservatism (inches)	124	125	122	124	120	122

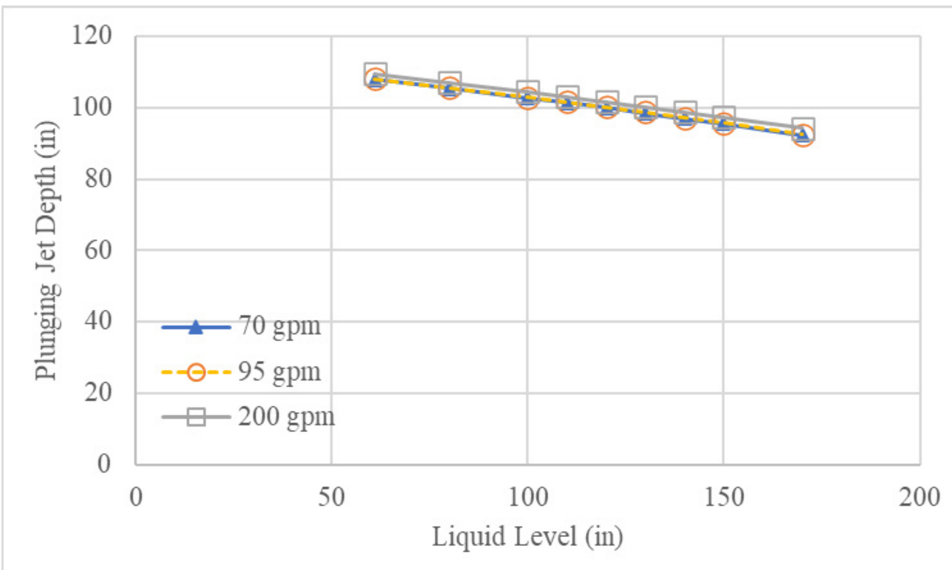

Figure 4. Influence of Inlet Flow Rate and Liquid Level on Depth of Plunging Jet

With a liquid level of 120 inches, the calculated "plunging jet" depth is 100 - 102 inches, so minimal solids disturbance should occur. With a liquid level of 100 inches, the calculated "plunging jet" depth is 103 - 104 inches, so solids disturbance is likely. With a liquid level of 110 inches, the calculated "plunging jet" depth is 102 - 103 inches. While this penetration depth is less than the 110-inch liquid level, a higher liquid level should be maintained to account for uncertainty in the correlation (equation [4]), include conservatism in the recommendation, and because even if the "plunging jet" does not reach the tank bottom, it may impart a pressure force on the tank bottom, which will disturb the solid particles.

Reviewing Figure 30 from reference 11 (see Figure 5) shows only a few of the experimental data points are more than 20% above the prediction. Most of the data are not more than 10% above the prediction. Equation [4] was derived using the same data that are plotted in Figure 5. Assuming that the uncertainty in Figure 5 is valid for equation [4], it can be applied to the results in Table 1. Adding 10% uncertainty to the calculated "plunging jet" penetration depth with a liquid level of 120 inches provides a depth of 110 – 112 inches. Adding 20% uncertainty to the calculated "plunging jet" penetration depth with a liquid level of

[c] The table only shows the results for 95 and 200 gpm. Additional calculations were performed for a flow rate of 70 gpm.

120 inches provides a depth of 120 – 122 inches. Figure 6 shows the results for other liquid levels in Tank 49H at an addition rate of 95 gpm.

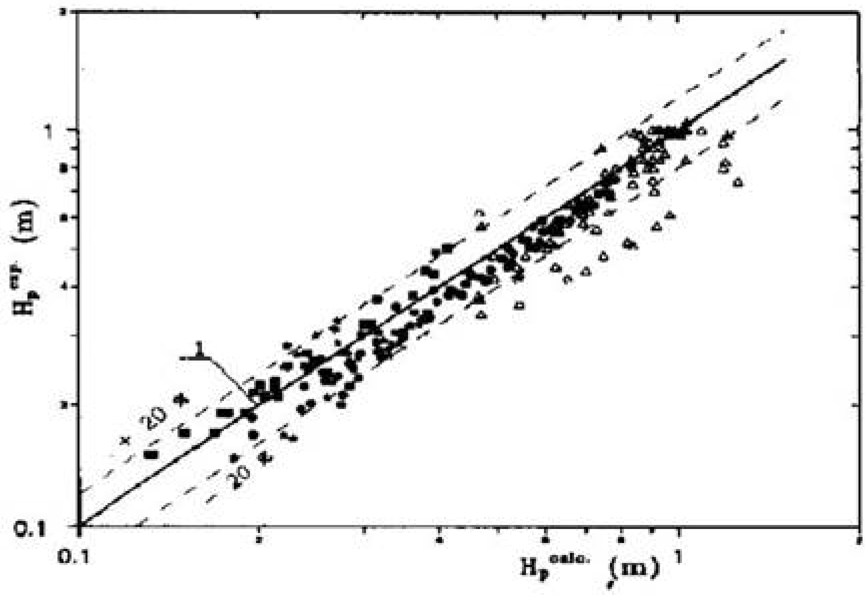

Fig. 30. Parity plot for testing eq. (55). The symbols are explained in Fig. 29: 1, line of perfect agreement.

Figure 5. Uncertainty in "Plunging Jet" depth Correlation

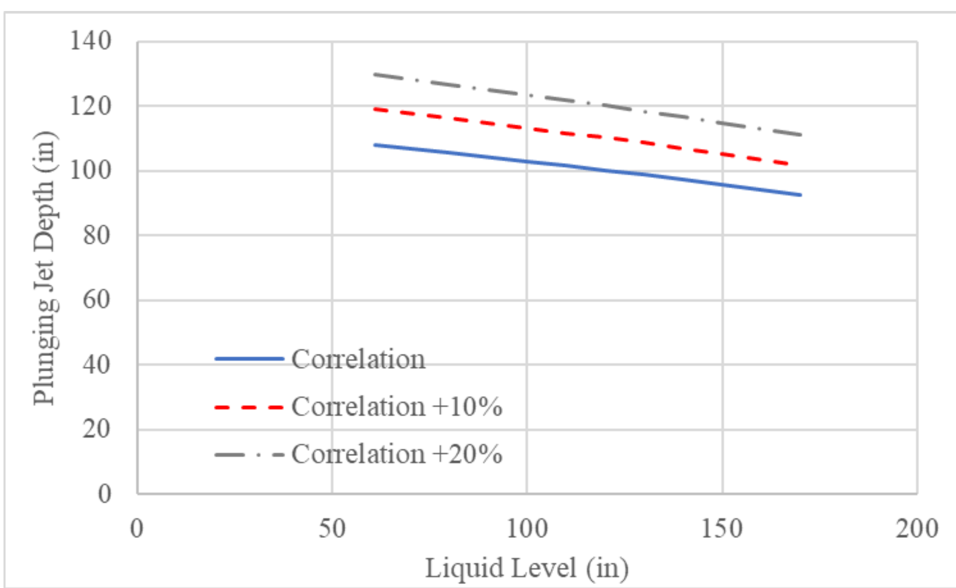

Figure 6. "Plunging Jet" Penetration Depth as a Function of Liquid Level at 95 GPM

Based on Table 1, Figure 4, and Figure 6, a minimum liquid level of 120 inches is recommended in Tank 49H to prevent any solid particles being suspended.

2.2 M-Star® CFD Simulations

To try to improve the estimate of the liquid level at which solid particles are disturbed by the "plunging jet", to attempt to quantify the mass of solids disturbed, and to examine the effect of the disturbed solids on the concentration of insoluble solids in the liquid transferred to the SWPF, CFD simulations were performed using the M-Star® Lattice-Boltzmann software.

M-Star® CFD software is used at SRNL to support Liquid Waste Operations (LWO) and other projects. The software is used to model processes that involve fluid mixing, pipe flow, gas retention and release, and non-Newtonian fluids. M-Star® CFD is a multi-physics modeling package used to simulate fluid flow, heat transfer, species transport, chemical reactions, particle transport, and rigid-body dynamics. M-Star® CFD is developed, maintained, and supported by M-Star® Simulations, LLC ("M-Star"), based in Maryland, USA.

The M-Star® software is not classified as Safety Significant software. It is classified as Class D software in X-SWCD-A-00011.[20] However, its simulation results have been compared favorably with data for other SRS applications such as impeller mixing of tanks and jet mixing of miscible liquids.[21,22] It is a tool to complement the analysis performed in the previous section and to evaluate alternative approaches to preventing added liquid in Tank 49H from disturbing the solid particles on the bottom of the tank. In addition, the M-Star® software provides a method to quantify the mass of solid particles that are disturbed by the "plunging jet" and a method to estimate the rate at which the disturbed solids are transported to the transfer pump.

To complete the additional analysis in this report, the M-Star® simulation results from a previous analysis will be used.[3] Table 2 shows the results.

Table 2. Amount of Solids Disturbed by "Plunging Jet" using M-Star® Software

Liquid Level	Region Diameter (ft)	Coils	Particle Size (μm)	Fraction Disturbed	Volume Disturbed (L)	Mass Disturbed (kg)
120 in	10	N	10	0.04	7.9	6.2
100 in	10	N	10	1.00	204	159
80 in	10	N	10	1.00	204	159
80 in	10	N	100	1.00	204	159
120 in	10	Y	10	0.04	8.1	6.4
110 in	10	Y	10	0.24	49	38
100 in	10	Y	10	0.23	46.6	33.5
100 in	15	Y	10	1.00	459	358

In the M-Star® simulations, when the region diameter was increased from 10 feet to 15 feet, the mass of solid particles disturbed increased, and the bulk concentration in the transfer to SWPF exceeded the WAC limit for insoluble solids. This result is unexpected and cannot be explained. It could be the result of numerical transport, which would bias the mass of disturbed solids high, the coarser lattice spacing in that simulation, or could be due to another factor that is not understood.

Because of the numerical transport observed in the previous M-Star® simulations, a different approach was taken in this report. The results in Table 2 were used as an input for a simulation of transport of the disturbed solids (under the B4 riser) to the transfer pump located in the B5 riser. These simulations will be discussed in Section 2.3.4.

2.3 Solids Concentration in Transfer to SWPF

A previous SRNL report looked at solids disturbance from liquid being added to Tank 49H through the B4 riser.[3] That report estimated the mass of solid particles disturbed as a function of liquid level.

The current approach employed three approaches to use this information to calculate the solid particle concentration in the liquid feed to the SWPF. These approaches are (1) performing a mass balance and calculating the maximum bulk concentration in the entire volume of liquid transferred to the SWPF, (2) accounting for particle settling during the addition of liquid to Tank 49H, and (3) performing M-Star® simulations of the transfer process to calculate the concentration of disturbed solid particles in the liquid that reaches the transfer pump in Tank 49H.

2.3.1 Solids Concentration in Transfer to SWPF

The maximum bulk solid particle concentration in the liquid transferred to the SWPF is calculated by taking the mass of solid particles suspended and dividing it by the liquid volume transferred to SWPF in a single batch (23,200 gallons or 87,812 L).

With a liquid level of 120 inches, no cooling coils, and a particle size of 10-micron, 6.2 kg of solid particles would be suspended (see Table 2). Given a transfer volume of 23,200 gallons (87,812 Liters) and assuming all the suspended particles are transferred to SWPF, the bulk solid particle concentration for the transfer would be 0.071 g/L (71 mg/L), which is below the SWPF WAC insoluble solids limit. When solid particles are transported in a liquid, there is often a "slip velocity" in which the solid particles move at a slower velocity than the liquid because of their higher density. This phenomenon will decrease the mass of disturbed solid particles transported to the transfer pump and make this calculation conservative. However, if there are insoluble solid particles suspended in the Tank 49H supernate prior to the transfer or insoluble particles in the transfer to Tank 49H, the concentration of these particles must be considered in determining whether the SWPF WAC insoluble solids limit will be met. The concentration of insoluble solids was 39.3 mg/L in the Tank 21H SWPF Batch 2 qualification sample and 107 mg/L in the Tank 21H Batch 4 qualification sample, which are less than the 1,200 mg/L SWPF WAC limit.[23,24]

With a liquid level of 80 - 100 inches (no cooling coils) and a particle size of 10-micron, 159 kg of solid particles would be suspended (see Table 2 and Table 3). Given a transfer volume of 23,200 gallons (87,812 Liters) and assuming all suspended particles are transferred to SWPF, the bulk solid particle concentration for the transfer would be 1.8 g/L (1,800 mg/L), which is above the SWPF WAC insoluble solids limit. This calculation was repeated for the other operating conditions, and the results are described in Table 3.

The table shows that with a liquid level of 100 – 120 inches and the presence of cooling coils, the bulk concentration of insoluble solids in the entire transfer to SWPF is less than the SWPF WAC insoluble solids limit. The table shows no significant difference in the mass of solids disturbed between liquid levels of 100 and 110 inches with cooling coils. This result is surprising, as more disturbance would be expected with lower liquid levels.

Without cooling coils, the mass of disturbed solids may be affected by the 10-foot diameter of the simulation model. With cooling coils, the 10-foot diameter should be sufficient to not affect the mass of solids disturbed. When the diameter of the simulation model was increased to 15 feet, the lattice spacing was increased, which may have led to the increase in the mass of solid particles suspended.

Table 3. Bulk Concentration of Disturbed Solids in Transfer to SWPF

Liquid Level	Region Diameter (ft)	Coils	Particle Size (μm)	Fraction Disturbed	Volume Disturbed (L)	Mass Disturbed (kg)	Bulk Concentration in Transfer to SWPF (mg/L)
120 in	10	N	10	0.04	7.9	6.2	71
100 in	10	N	10	1.00	204	159	1,800
80 in	10	N	10	1.00	204	159	1,800
80 in	10	N	100	1.00	204	159	1,800
120 in	10	Y	10	0.04	8.1	6.4	73
110 in	10	Y	10	0.24	49	38	430
100 in	10	Y	10	0.23	46.6	33.5	380
100 in	15	Y	10	1.00	459	358	4,100

If there are insoluble solid particles suspended in the supernate prior to the transfer or insoluble particles in the transfer, the concentration of these particles must be considered in determining whether the SWPF WAC insoluble solids limit will be met.

2.3.2 Particle Settling During Transfer of Liquid into Tank 49H

Once the liquid level reaches 120 inches during addition into the tank, the plunging jet will not reach the tank bottom and disturb solids. As the liquid level increases above 120 inches, the depth and influence of the "plunging jet" will move farther away from the solid particles on the tank bottom and the disturbed solids. The disturbed solids should begin to settle.

The settling that will occur as liquid is added to Tank 49H is a function of solid particle size. A particle density of 2.25 g/mL is chosen for conservatism in calculating the settling rate. The liquid density is 1.26 g/mL, and the liquid viscosity is 2.5 cP. The particle settling rate is calculated with Stokes Law, and is described by equations [6] – [9]

$$v_s = g(s-1)d_p^2/18\nu \qquad \text{for } Re_p < 1.4 \qquad [6]$$

$$v_s = 0.13[g(s-1)]^{0.72}d_p^{1.18}\nu^{-0.45} \qquad \text{for } 1.4 < Re_p < 500 \qquad [7]$$

$$v_s = 1.74[g(s-1)\,d_p]^{0.5} \qquad \text{for } Re_p > 500 \qquad [8]$$

$$Re_p = d_p v_s/\nu \qquad [9]$$

where v_s is the settling velocity, g is the acceleration due to gravity, s is the ratio of particle and fluid densities (s = particle density/fluid density), d_p is the particle diameter, and ν is the fluid kinematic viscosity ($\nu = \mu/\rho$).[25]

At a flow rate of 120 gpm into Tank 49H, the liquid level will increase from 120 inches to 290 inches in a minimum of 3.4 days. The 3.4 day time assumes a continuous transfer into Tank 49H. If the transfer consists of multiple transfers into the tank, the time for the liquid level to increase from 120 inches to 290 inches will be longer.

Figure 7 shows the estimated vertical distance the various particle sizes will settle as the liquid level increases above 120 inches during a transfer into Tank 49H. (These calculations assume no hindered settling behavior – i.e., particle-particle interactions – which is a reasonable assumption for dilute slurries of non-cohesive particles.) The figure shows that particles 5 micron and larger will settle at least 5 ft as the liquid level increases from 120 inches to 290 inches and should be at the tank bottom when the liquid level reaches 290 inches. The figure shows that particles 3 micron and larger will settle approximately 2 ft as the liquid level increases from 120 inches to 290 inches and may be at the tank bottom when the liquid level reaches 290 inches. Particles less than 3 micron may not settle to the tank bottom. These results are consistent with the results from the Tank 48H sampling analysis conducted in 1995.[17] This particle settling may prevent exceeding the SWPF WAC limit for insoluble solids but is dependent on the size of the particles at the bottom of Tank 49H.

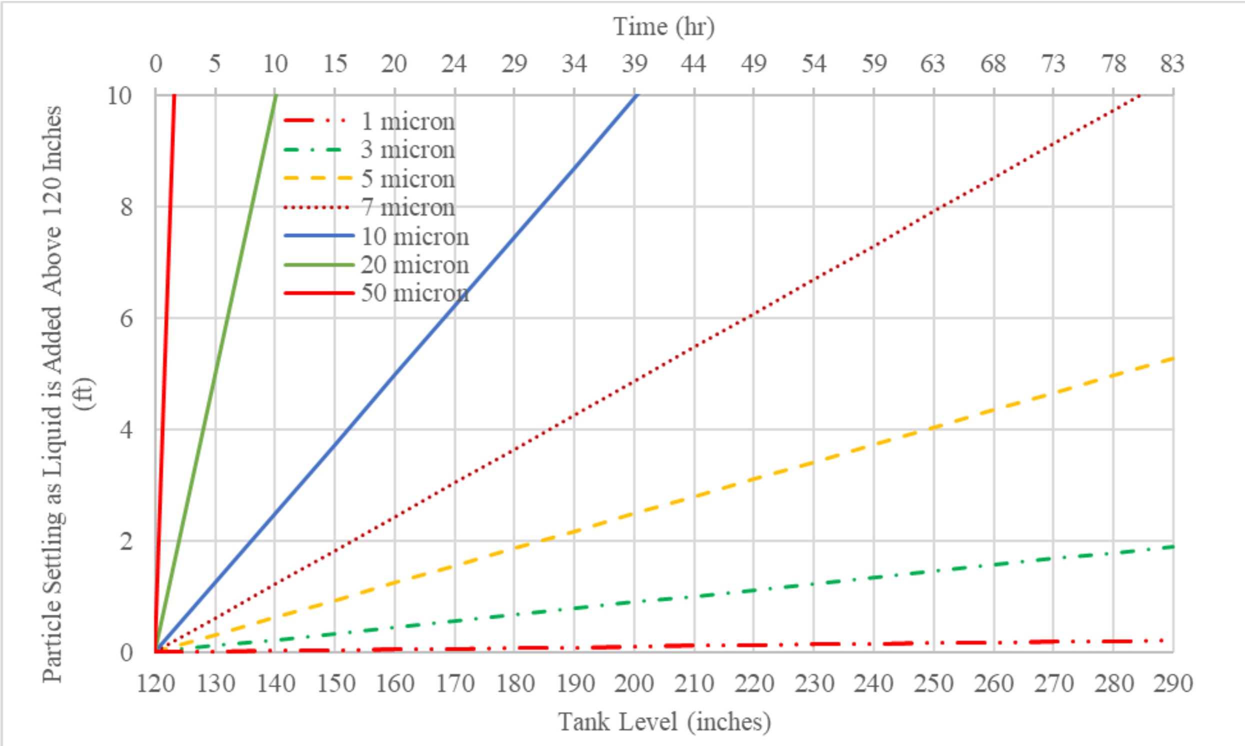

Figure 7. Particle Settling as Liquid is Added to Tank 49H

2.3.3 M-Star® Simulations of Transport of the Disturbed Solids to the Transfer Pump

After solids are disturbed by the "plunging jet", they will either settle or be transported to the transfer pump. As discussed above, particles larger than 5 microns in diameter will settle during liquid addition to Tank 49H. Particles smaller than 1 – 3 microns in diameter are unlikely to settle and could reach the transfer pump and be transferred to SWPF. These smaller particles are likely to follow the fluid flow and be blended/diluted by mixing with the liquid in the tank.

The following approach was employed to simulate the movement of the small, disturbed solid particles from under the B4 riser to the transfer pump:

- The transfers were continuous with no down time between transfers. The down time would allow for additional particle settling and dispersion, which makes these simulations conservative.
- The flow rate of the transfer pump is 159 gpm.
- All particles in a 10-foot diameter circle under the B4 riser are disturbed. Although not all of the particles in the 10-foot diameter circle were suspended in the previous M-Star® simulations, a large fraction of them were suspended and we assumed that all were suspended for conservatism. To quantify the mass of particles suspended for additional calculations, all particles were assumed to be suspended, which would be bounding.[3]
- The disturbed particles are contained in a 10-foot diameter, 2 foot (24 inch) high cylinder located at the tank bottom under the B4 riser.
- The particles are 1 micron in diameter. The 1-micron particles will settle minimally during liquid addition and transfer. They will follow the liquid fluid motion and represent particles 1 micron and smaller.
- Since the solids level is 1.1 inches and the volume fraction of solid particles is 0.3, the volume of solid particles is

  $V = 0.3\ \pi\ D^2\ H/4 = (0.3)\ (3.14)\ (120\ \text{in})^2\ (1.1\ \text{in})\ (1\text{m}\ /39.37\ \text{in})^3/4 = 0.0612\ \text{m}^3$ of particles

  The volume of a single 1-micron particle is

$V_p = (4/3)\,\pi\,(d_p/2)^3 = (4/3)\,\pi\,(0.5 \times 10^{-6}\ m)^3 = 5.236 \times 10^{-19}\ m^3$/particle

The number of 1-micron particles occupying this volume is

V_p/V = (0.0612 m^3 of particles)/($5.236 \times 10^{-19}\ m^3$/particle) = 1.17×10^{17} particles

- Using the upper bound for the particle density (2.6 g/mL or 2,600 kg/m^3), the total mass of suspended particles is

  Mass = (0.0612 m^3) (2,600 kg/m^3) = 159 kg of disturbed particles

- The cooling coils were not included in the tank for the simulations. Including the cooling coils would increase the dispersion of solid particles as fluid was transported to the transfer pump, making this simulation conservative.

The density of the liquid was 1.26 g/mL, and the viscosity was 2.5 cP.[18] In the simulation, the liquid removed by the transfer pump is added back at the top of the liquid in the tank. This return of liquid keeps the level in the tank constant and simulates the presence of the liquid above 120 inches in the tank. A 120-inch liquid level was used for the simulations, which will bound higher liquid levels. The simulation modeled all of the solid particles.

Figure 8 shows the relative positions of the B4 riser, transfer pump, and center column in the tank.

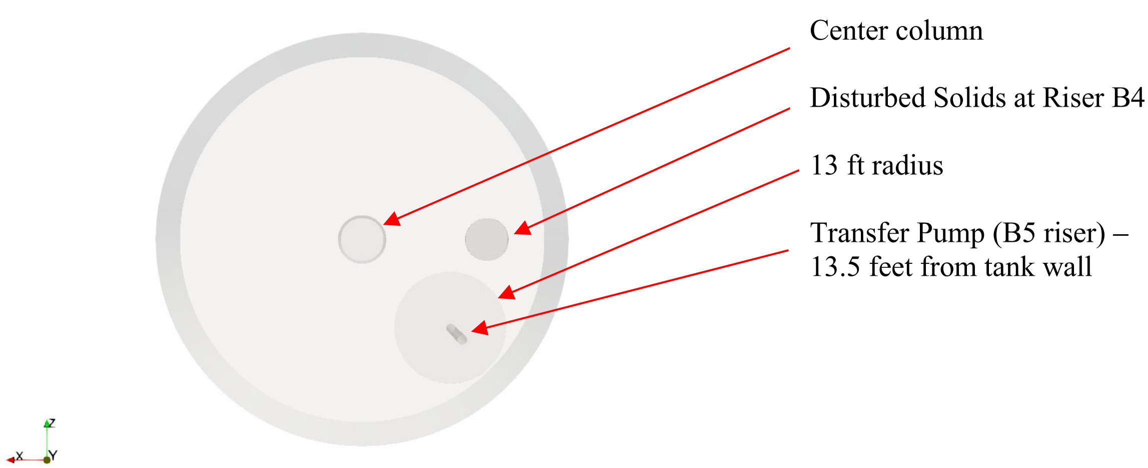

Figure 8. Location of Disturbed Solids and Transfer Pump in Tank 49H

Figure 9 shows the concentration of 1-micron insoluble solids in the transfer from Tank 49H to SWPF as a function of time and the normalized particle concentration in Tank 49H as a function of time. The results show that the maximum concentration of small particles (1-micron or less in diameter) in the material leaving Tank 49H is less that the waste acceptance criteria (WAC) limit of 1.2 g/L. In addition, the results show that it takes over 58,000 seconds (16 hours) for half of the disturbed solid particles (1-micron or less) to reach the transfer pump. Since a typical transfer takes ~ 2.5 hours, it would take at least 6 transfers to remove half of the disturbed particles from the tank. As stated above, particles 5-micron and larger will settle during liquid addition to the tank.

Table 4 shows the average insoluble solids concentration in each of the first 11 transfers from Tank 49H to SWPF. They are all much less than the WAC insoluble solids limit of 1.2 g/L.

Appendix - A shows screen shots from the M-Star® simulations at select times. The screen shots provide a view from the side and from the top of the tank. They show the particles accumulating near the bottom of the tank and spreading out over the entire tank cross section.

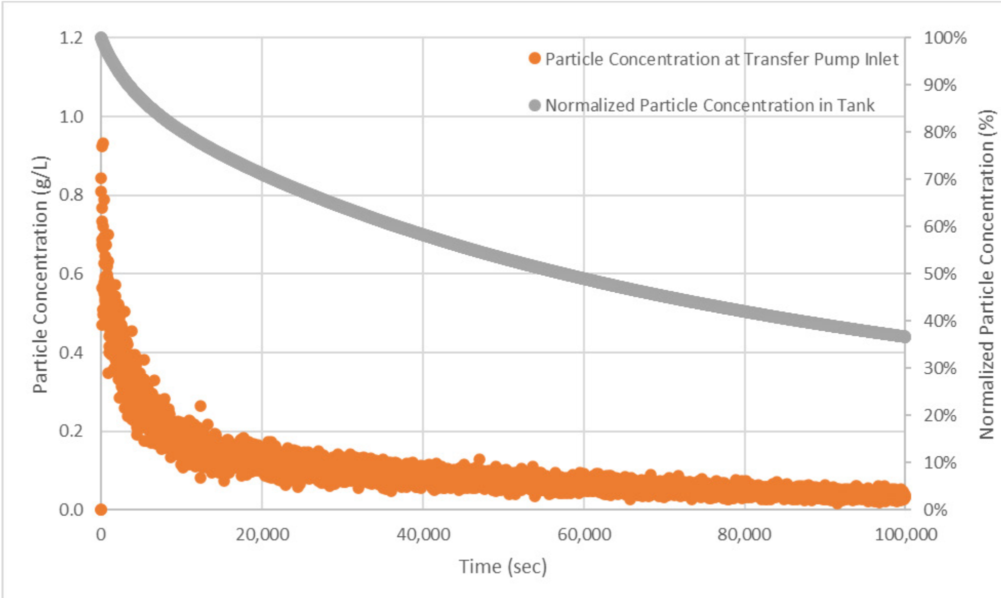

Figure 9. Particle Concentration in Transfer from Tank 49H to SWPF and in Tank 49H with a 120 Inch Liquid Level

Table 4. Average Insoluble Solids Concentration in a Transfer from Tank 49H to SWPF with a 120 Inch Liquid Level

Transfer #	Particle Conc (g/L)
1	0.33
2	0.15
3	0.12
4	0.10
5	0.09
6	0.08
7	0.07
8	0.06
9	0.05
10	0.05
11	0.04

2.3.3.1 Benchmarking of the Ability of M-Star® to Model Fluid Flow into a Pump Suction

To benchmark the ability of the M-Star® software to simulate the flow of liquid into a pump suction, a simulation was performed of flow into a rectangular channel and compared with the analytical solution in reference 26. The two-dimensional velocity field of an inviscid fluid flowing into a rectangular channel can be determined by using a stream function and a potential function.

The continuity equation in two dimensional flows can be solved by writing the velocity components in terms of a stream function (ψ), where the x and y velocities are defined by equations [10] and [11]

$$v_x = - \partial \psi / \partial y \quad [10]$$

$$v_y = \partial \psi / \partial x \quad [11]$$

For inviscid, irrotational flow, a potential function (ϕ) can be used and the x and y velocities defined by equations [12] and [13]

$$v_x = \partial \phi / \partial x \quad [12]$$

$$v_y = \partial \phi / \partial y \quad [13]$$

Figure 10 describes the two-dimensional flow into a rectangular channel. To solve the problem, the following dimensionless variables are introduced

$X = \pi x/b$
$Y = \pi y/b$
$\Phi = \pi\phi/bv_\infty$
$\psi = \pi\psi/bv_\infty$

where b is the half width of the rectangular channel and v_∞ is the velocity downstream from the channel entrance. The relationships between these dimensionless variables are described by equations [14] and [15]

$$X = \Phi + \exp(\Phi) \cos(\psi) \quad [14]$$

$$Y = \psi + \exp(\Phi) \sin(\psi) \quad [15]$$

The solution to the problem is described by equations [16] and [17]

$$v_x v_\infty / v^2 = -[1 + \exp(\Phi) \cos(\Psi)] \quad [16]$$

$$v_x v_\infty / v^2 = -[\exp(\Phi) \cos(\Psi)] \quad [17]$$

where v is the velocity magnitude.

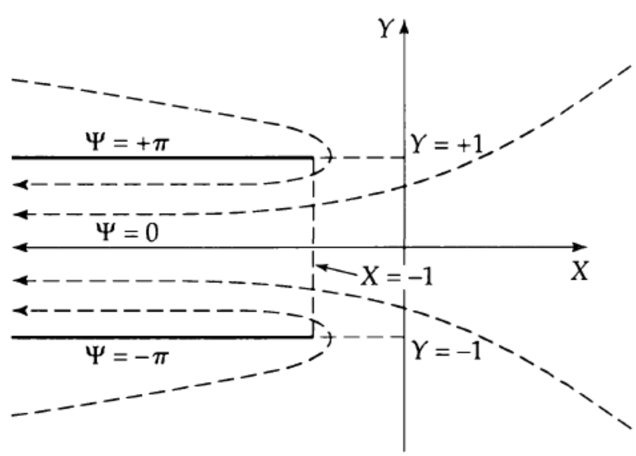

Figure 10. Flow into a Rectangular Channel Using a Stream Function and a Potential Function[25]

An M-Star® simulation was performed with a rectangular box that was 1 meter wide (x direction), 1 meter tall (y direction), and 0.02 meters thick (z direction). The small z dimension was selected to attempt to approximate a two-dimensional flow field with the M-Star® software. The box contained a rectangular channel that was 0.02 meter wide, 0.02 meter thick, and 0.7 meter tall. The half width of the channel is 0.01 meter. The boundaries of the box had free slip boundary conditions. The x boundaries of the channel were no slip boundaries, while the z boundaries were free slip boundaries. A constant velocity of 1 m/s was set at the inlet to the channel (flowrate of 0.0004 m^3/sec).[d] To conserve volume and mass, an equal flow rate of liquid was added back to the top of the box.

The horizontal velocity was measured at select locations between the channel centerline and the wall at a distance 0.01 m below the bottom of the channel. The velocity profile (i.e., velocity as a function of vertical position) was measured at a horizontal distance of 0.2 meters from the channel centerline. Figure 11 shows the layout of the channel in the M-Star® simulation.

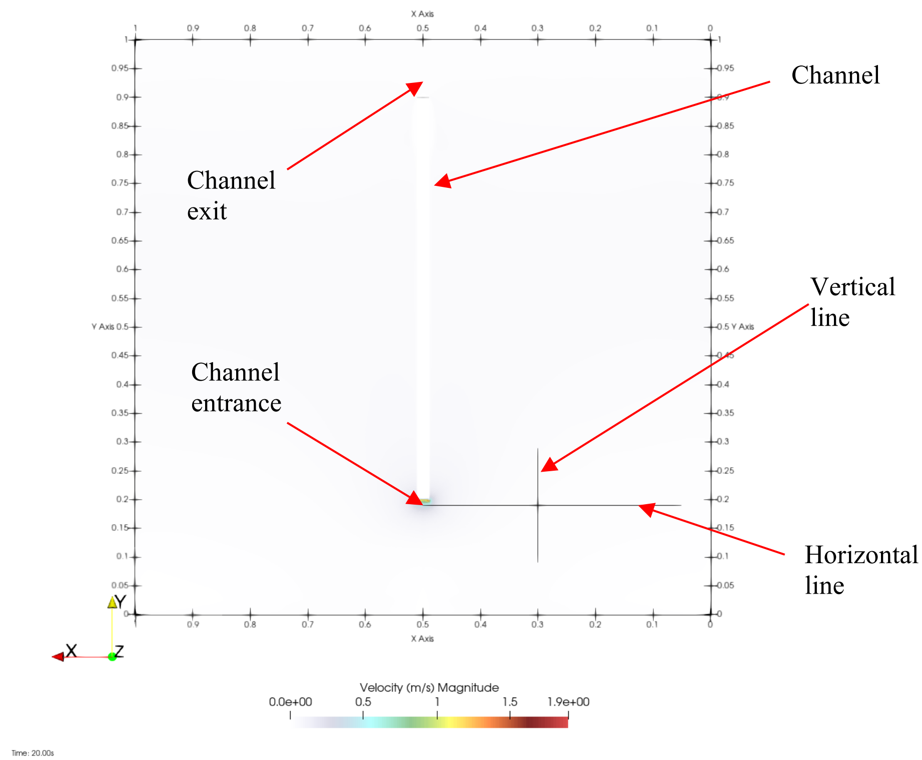

Figure 11. Layout of Channel for M-Star® Simulations

Figure 12 shows velocity vectors generated by the M-Star® software. These vectors are consistent with the velocity vectors in the analytical solution. Figure 13 shows the horizontal velocity at select positions along the horizontal line. Zero on the horizontal axis is defined as the channel centerline. The velocities are compared with the analytical solution (in which the equivalent velocity is v_y) and agree well. Figure 14 shows the horizontal velocity profile at a distance of 0.2 m from the channel centerline. Zero on the horizontal axis is defined as the elevation of the channel inlet. These velocities agree well with the analytical solution (again, the equivalent velocity would be v_y).

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[d] The x and y directions are different in reference 26 and the M-Star® simulation. In reference 26, the inlet to the channel is in the x direction, and the y direction is normal to the inlet. In the M-Star® simulation, the inlet to the channel is in the y direction (vertical direction), and the x direction is horizontal.

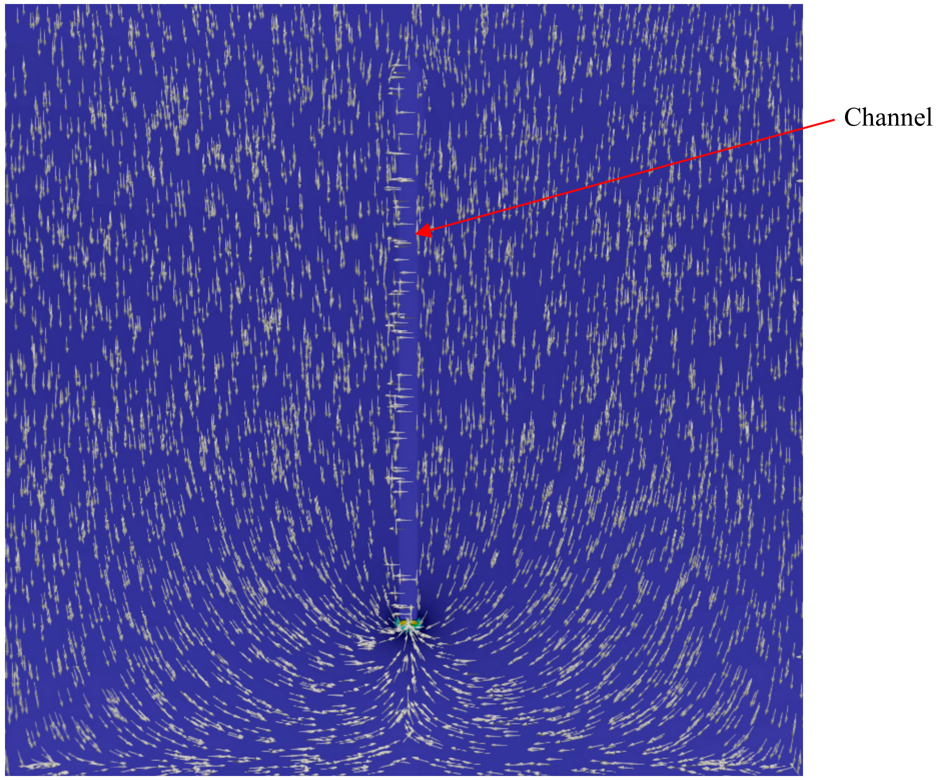

Figure 12. Velocity Vectors

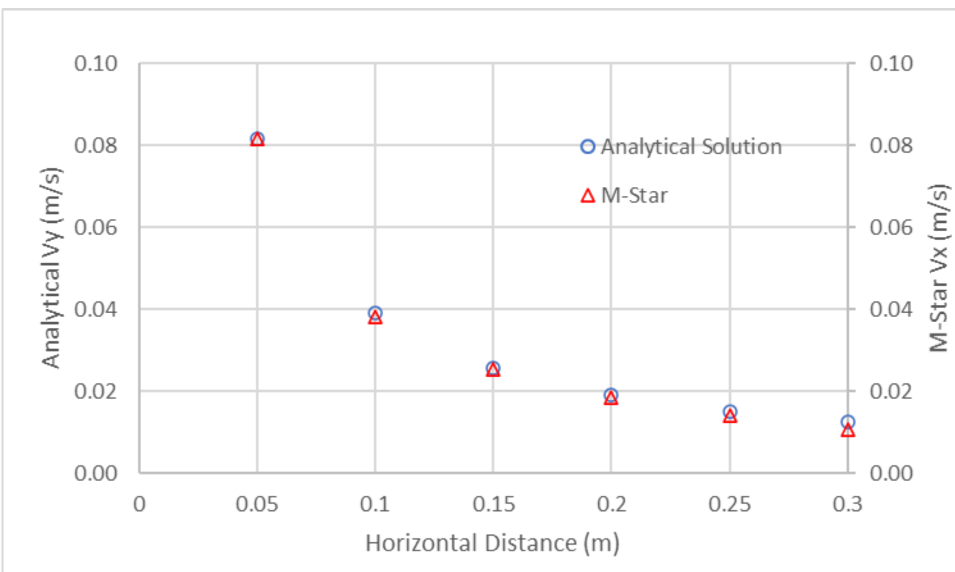

Figure 13. Comparison of M-Star® Simulation with Analytical Solution along Horizontal Line

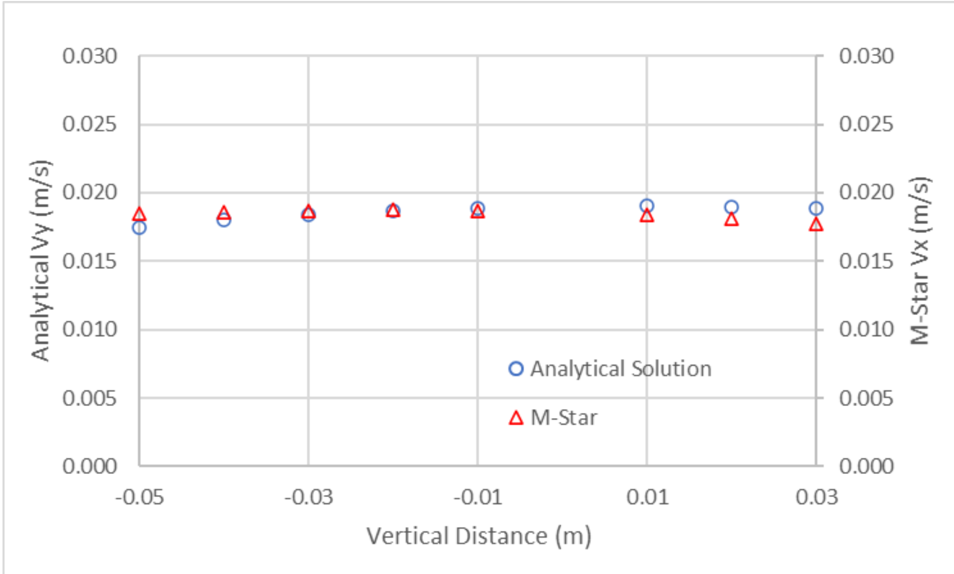

Figure 14. Comparison of M-Star® Simulation with Analytical Solution along Vertical Line

2.4 Discussion of Results

Based on the "plunging jet" analysis in Section 2.1, a minimum liquid level of 120 inches is recommended in Tank 49H. If the liquid level in Tank 49H is 120 inches or more, minimum solids disturbance will occur.

If the liquid level is less than 120 inches, significant solids disturbance could occur. Estimating the mass of solid particles disturbed, the dilution that will occur with other liquid in Tank 49H, and the settling that will occur, it may be possible to meet the SWPF WAC insoluble solids limit at a lower liquid level in Tank 49H. However, the results of the simulations performed suggest that additional work is needed to optimize the geometry of the simulation as well as the simulation parameters if the simulations are to be used to quantify the solids disturbance. If the particles are greater than 5 microns in diameter, any disturbed particles are likely to settle before being transported to the transfer pump. If the disturbed particles are less than 3 - 5 micron in diameter, a large fraction of these disturbed particles may be transported to the transfer pump, and then transferred to SWPF.

Particle settling will occur during liquid addition to Tank 49H. At a nominal liquid addition rate to Tank 49H through the B4 riser (120 gpm), the time for the liquid level to increase from 120 inches to 290 inches is (290 – 120 inches) (3510 gallons/inch)/120 gal/min = 4,973 minutes.

Given the time for particle settling during liquid addition (4,973 minutes), Figure 15 shows the volume fraction of disturbed solids that will settle a specified height during this time based on the average particle size distribution of Tanks 5, 13, and 15. Approximately 50% of the particles will settle 3 ft in this time, and approximately 60% of the particles will settle 2 ft in this time. However, Tanks 5, 13, and 15 are sludge tanks, and may not represent the particle size distribution of the particles at the bottom of Tank 49H.

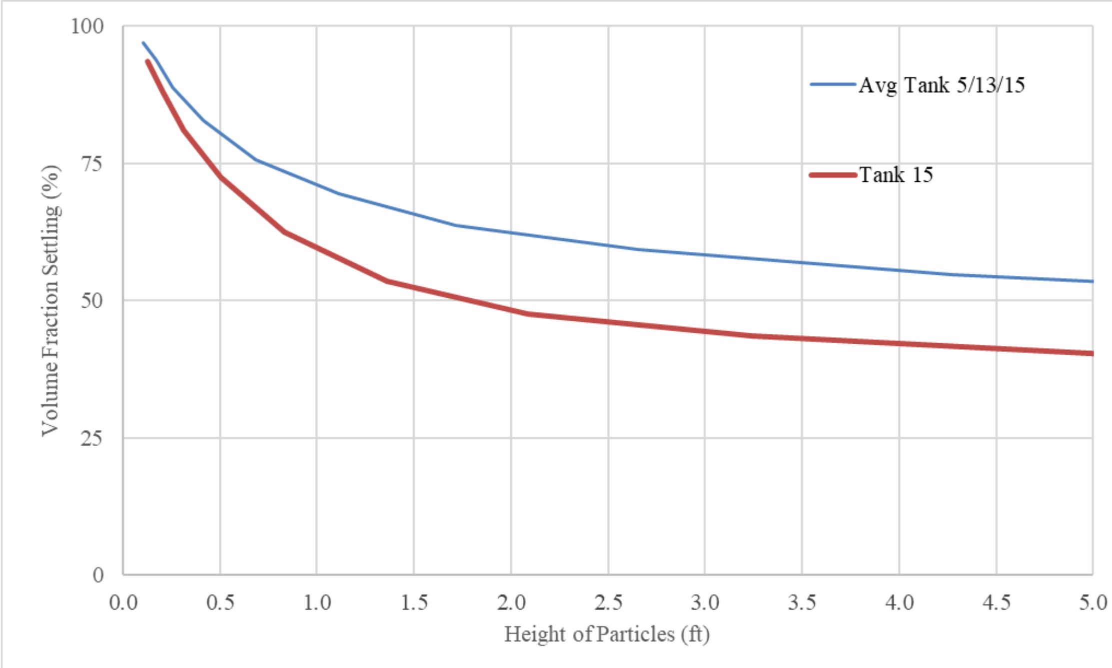

Figure 15. Volume Fraction of Disturbed Particles Settling during Liquid Addition to Tank 49H

In addition to looking at the behavior of the large particles (> 5 micron) disturbed during liquid addition to Tank 49H and transfer to SWPF, the authors looked at the behavior of small particles (1 micron) disturbed during liquid addition to Tank 49H during the transfers to SWPF. Figure 16 and Table 5 summarize the results. Using a liquid level of 120 inches with all particles represented, the concentration of insoluble solids at the transfer pump inlet is below the SWPF WAC insoluble solids limit. These calculations are likely conservative given that many of the disturbed particles are likely to be larger than 1 micron and particle settling will occur during liquid addition and between transfers.

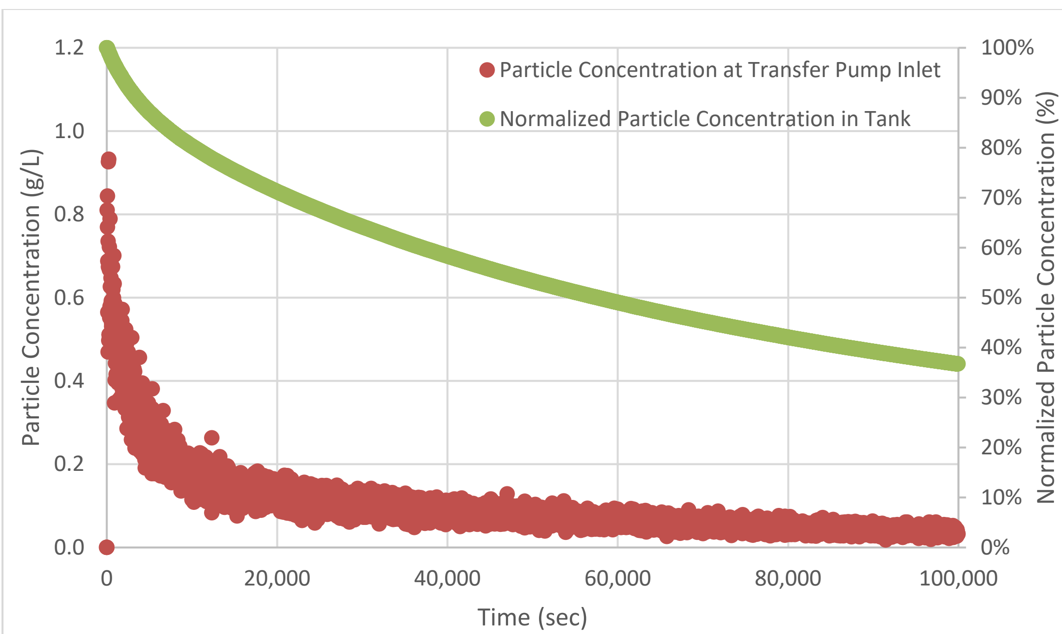

Figure 16. Particle concentration in Transfer from Tank 49H to SWPF

Table 5. Average Insoluble Solids Concentration in a Transfer from Tank 49H to SWPF

Transfer #	Part. Conc. (g/L)
1	**0.33**
2	0.15
3	0.12
4	0.10
5	0.09
6	0.08
7	0.07
8	0.06
9	0.05
10	0.05
11	0.04
WAC limit	1.20

^ *Highest concentration shown in bold*

The analysis in this document shows that with a liquid level of 120 inches and higher, minimal particle disturbance will occur from adding liquid to Tank 49H through the B4 riser. If the liquid level is between 80 and 120 inches, significant particle disturbance could occur. If the disturbed particles are 5 micron and larger, they are likely to settle during liquid addition to the tank. Smaller particles (represented by 1 micron diameter particles) are unlikely to settle during liquid addition to the tank. However, during transport to the transfer pump, they will be dispersed and mix with other liquid in the tank. The concentration of disturbed solids in the feed to the transfer pump will be less than the SWPF WAC insoluble solids limit.

This analysis showed that the penetration depth of the 'plunging jet" is a function of the diameter of the jet exiting the downcomer. If the diameter of this jet could be reduced, its penetration depth into the liquid would be reduced such that it does not disturb the solid particles on the tank bottom. Figure 17 shows a comparison of the depth of a "plunging jet" coming from a 1-inch downcomer compared with a 3-inch downcomer. The results show a significant decrease in the penetration depth with the smaller diameter downcomer, keeping the inlet flow rate constant at 95 gpm.

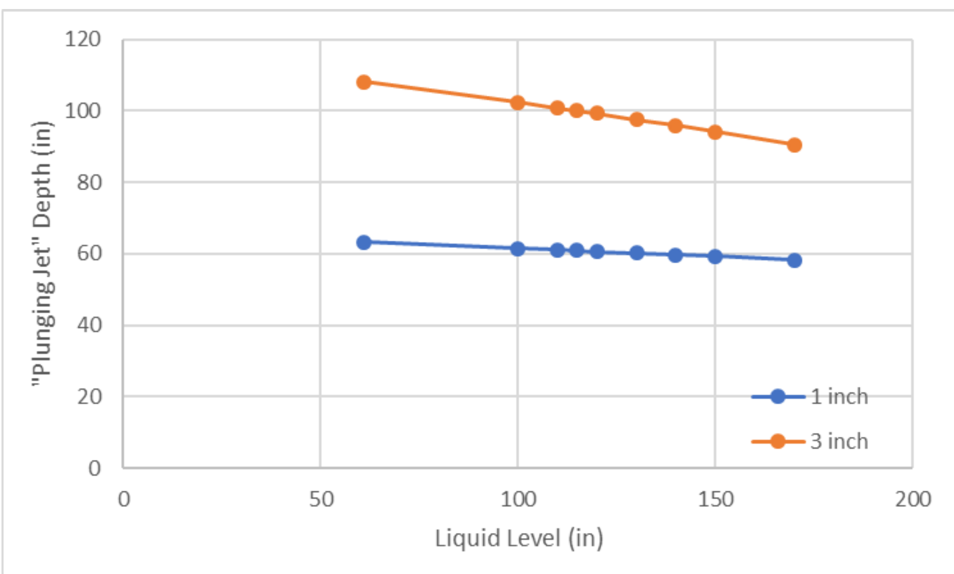

Figure 17. "Plunging Jet" Depth as a Function of Downcomer Diameter

Other approaches that SRMC should consider if they wish to maintain a lower level in Tank 49H are to lower the elevation at which the liquid enters the tank, adding a device to disperse the added liquid into droplets that will not penetrate deeply below the liquid surface, or adding a nozzle to the downcomer to reduce the diameter of the jet produced by the liquid entering the tank.

Lowering the addition level will reduce liquid momentum entering the tank due to the acceleration by gravity. If the added liquid could be dispersed into liquid droplets rather than a jet stream with a large diameter, they are likely to penetrate less into the liquid in the tank and would be unlikely to disturb the solid particles on the tank bottom.

SRMC could measure the particle size, bed height and/or concentration of critical species (Pu, Sr-90, etc.) below the plunging jet to reduce conservatism.

3.0 Conclusions

The analysis showed that with a solid particle size of 5 micron or less, a liquid level of 120 inches should be maintained to prevent significant disturbance of the solid layer at the bottom of Tank 49H.

If liquid is added to Tank 49H with a liquid level less than 120 inches, particle disturbance will occur. Once the liquid level reaches 120 inches, particle disturbance will stop and particle settling will begin. In the time that the liquid level increases from 120 inches to 290 inches, significant particle settling could occur, which may prevent exceeding the SWPF WAC limit for insoluble solids, but the settling is dependent on the size of the particles at the bottom of Tank 49H.

If the disturbed particles are 1 micron or less, the particles will follow the fluid motion in the tank. As these particles are transported to the transfer pump, they will be dispersed and mixed with other liquid in the tank. The concentration of these disturbed particles in the feed to the transfer pump will likely be less than the SWPF WAC insoluble solids limit.

Considering the settling of particles 5 micron and larger during liquid addition to Tank 49H and the dispersion and mixing of particles 1 micron and smaller during transport from the disturbed region under the B4 riser to the transfer pump, it is possible that the minimum liquid level in Tank 49H could be reduced without exceeding the SWPF WAC insoluble solids limit. The median particle size for the actual SRS sludge samples ranged between 2.6 micron and 15.1 micron. Since an engineering analysis indicated that at least 35% of the particles should settle before reaching the transfer pump, this adds additional support for reducing the minimum liquid level in Tank 49H for additions through the B4 riser. The actual size, composition, and density of the solid particles is unknown.

If the height of the solid particles in Tank 49H is greater than 1.1 inches, the mass of suspended particles and the mass of particles reaching the transfer pump should be increased proportionally. The increased solid particle height may lead to a smaller fraction of the particles being suspended, but that cannot be verified or quantified at this time.

In addition, if there are insoluble solid particles suspended in the supernate prior to the transfer or insoluble particles in the transfer, the concentration of these particles must be considered in determining whether the SWPF WAC insoluble solids limit will be met.

If SRMC wishes to maintain a lower level in Tank 49H, they should consider lowering the elevation at which the liquid enters the tank, adding a device to disperse the added liquid into droplets that will not penetrate deeply below the liquid surface, or adding a nozzle to the downcomer to reduce the diameter of the jet produced by the liquid entering the tank.

4.0 References

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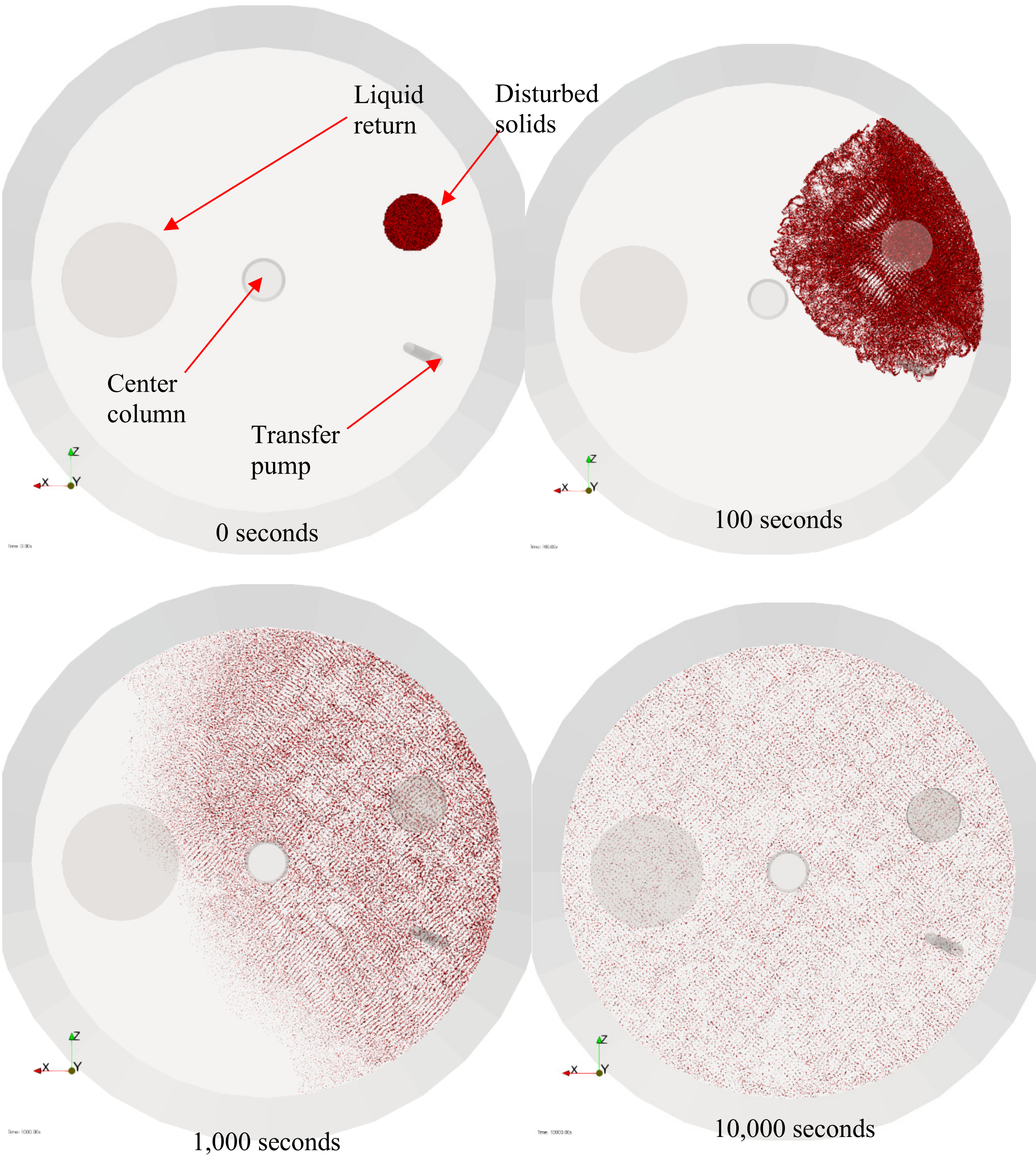
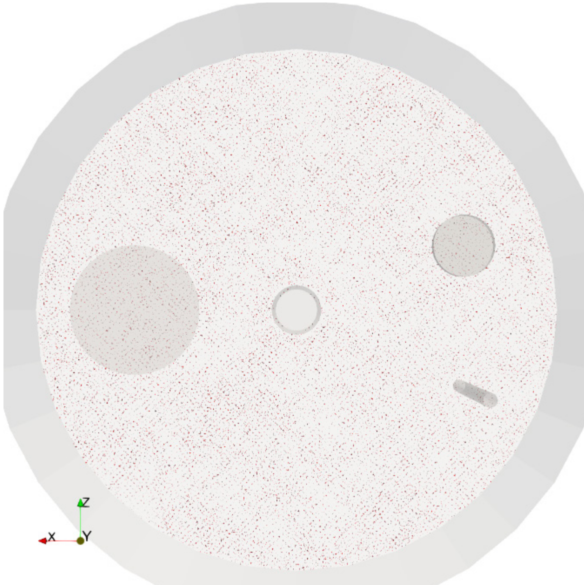
5.0 Appendix A: M-Star® Simulation Screenshots

5.1 Transfer from Tank 49H to SWPF with 120 Inch Liquid Level





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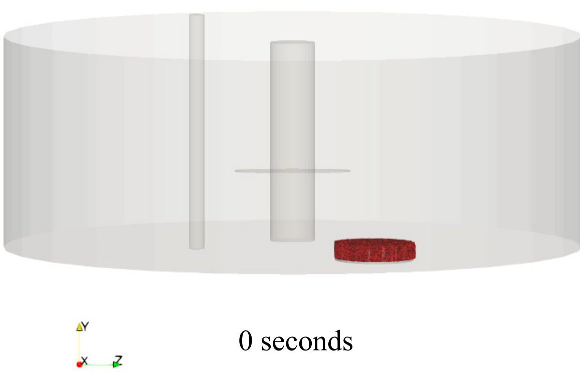

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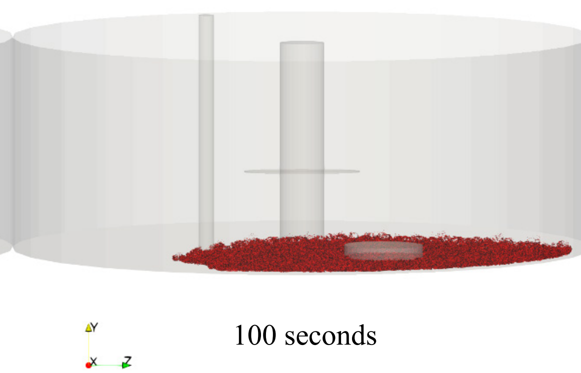

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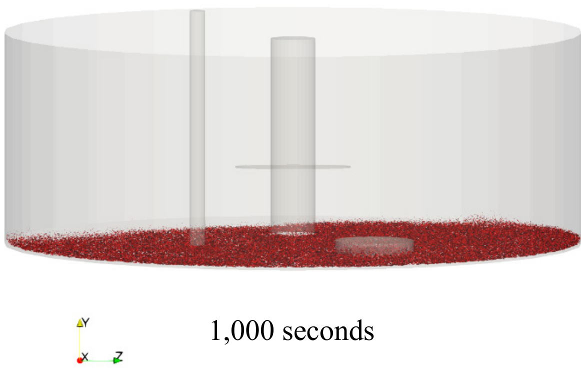

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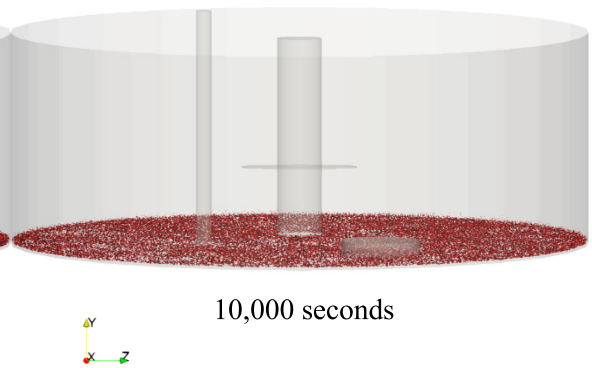

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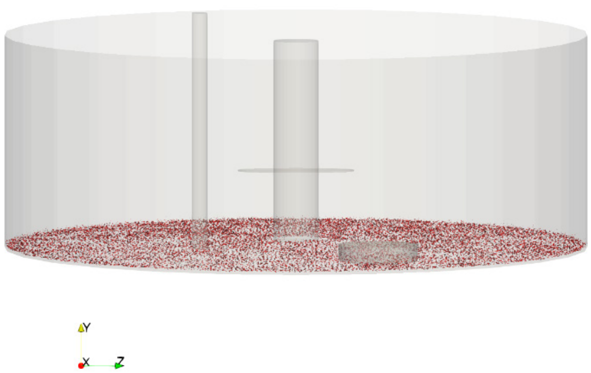

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