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Tank 49H Solids Disturbance Analysis

M. R. Poirier

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OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

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EXECUTIVE SUMMARY

Tank 49H will serve 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 1200 mg/L from the SWPF Waste Acceptance Criteria (WAC). During a transfer into Tank 49H, material that free falls from the Tank 49H B4 downcomer and passes through the supernate could potentially disturb the 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 impact of a "plunging jet" through the B4 downcomer on solids in Tank 49H and to determine a minimum liquid level to be maintained in Tank 49H prior to transfers that will minimize disturbing the solids and exceeding the SWPF WAC limits for insoluble solids carryover to SWPF.

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. In addition, the analysis included M-Star® computational fluid dynamics (CFD) simulations of the "plunging jet" to assess whether it disturbed the solids at the bottom of the tank, and to estimate the mass of solid particles that was disturbed by the "plunging jet."

The analysis showed that with a solid particle size of 10 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 the particle size is 100 micron or larger, the liquid level in the tank can be reduced to as low as 80 inches. At this level, the larger particles will be disturbed, but they will settle to the tank bottom before reaching the transfer pump. Since a large fraction of the solid particles in Tank 49 are expected to be less than 10 microns based on previous analyses of SRS sludge particle size which measured median particle sizes of 2.6, 6.1, 10.8, and 15.1 microns, the 120-inch liquid level is recommended at this time.

Calculations of the dilution that will occur with the liquid above the solid particles as they are disturbed and blending that will occur as they are transported to the transfer pump suggest that their concentration may be below the SWPF WAC with liquid levels between 100 – 120 inches. SRNL and SRR should review the details of the planned transfers to determine whether these calculations can be used to justify a lower liquid level in Tank 49H. Depending on the solid particle size, significant particle settling could occur between transfers. Following the first transfer to SWPF for each batch, the concentration of insoluble solids in the transfer will likely decrease.

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

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 (~1,000,000 gallons), significant particle settling could occur, which may prevent exceeding the SWPF WAC limits for insoluble solids, but the settling is dependent on the size of the particles at the bottom of Tank 49H.

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 will be met.

If Savannah River Remediation (SRR) 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.

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LIST OF ABBREVIATIONS

CFD	computational fluid dynamics
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	constant
H	height
H_p	plunging jet penetration depth
L	distance
LWO	Liquid Waste Operations
M	mass
Q	flow rate
r	radius of converging channel
s	solid-liquid density ratio
SPF	Saltstone Production Facility
SRNL	Savannah River National Laboratory
SRR	Savannah River Remediation
STP	submersible transfer pump
SWPF	Salt Waste Processing Facility
t	time
TTR	Technical Task Request
TTQAP	Task Technical and Quality Assurance Plan
v_s	settling velocity
V	volume
V_j	velocity at liquid surface
V_0	downcomer discharge velocity
WAC	Waste Acceptance Criteria
x	mass fraction
z	change in elevation
Z	Plunging jet depth
ν	kinematic viscosity
ρ	density
μ	viscosity

1.0 Introduction

Tank 49H will serve 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 from the SWPF Waste Acceptance Criteria (WAC).[1] During a transfer into Tank 49H, material that free falls from the Tank 49H B4 downcomer and passes through the supernate could potentially disturb the 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 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 limits for insoluble solids carryover to SWPF.[2]

The Design Authority (DA) for Savannah River Remediation (SRR) Tank Farm Facility Engineering provided Savannah River National Laboratory (SRNL) the information needed (inputs) to complete this task.[3] The information provided by SRR 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.[4,5] 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 the 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 the solids layer on the bottom of Tank 49H.

The analysis utilized models from literature[6,7,8] 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 input parameters were provided by SRR. The analysis varied the input parameters to determine their influence on the properties of the "plunging jet". The analysis identified conditions under which the plunging jet will not disturb the solids on the bottom of Tank 49H.

In addition, the analysis included M-Star® computational fluid dynamics (CFD) simulations of the "plunging jet" to assess whether it disturbed the solids at the bottom of the tank, and to estimate the mass of solid particles that was disturbed by the "plunging jet".[a] When the solids layer was impacted by the "plunging jet", the analysis estimated the size of the solids layer region impacted, and if the solids could be pumped to SWPF during the transfer of Tank 49H liquid to SWPF.

1.1 Quality Assurance

This work was performed under a Technical Task Request (TTR).[2] The recorded data, analysis, and conclusions satisfy the Safety Significant requirements in the Task Technical and Quality Assurance Plan (TTQAP) associated with this TTR.[9] The M-Star software is classified as D, and was used to complement the other analyses performed.

[a] M-Star CFD software is licensed from M-Star Simulations, LLC. This analysis used version 2.8.

Requirements for performing reviews of technical reports and the extent of review are established in manual E7 2.60.[10] SRNL documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2.[11]

2.0 Analysis

Inputs:

The following input parameters were provided by SRR and are used in the assessment.[3]

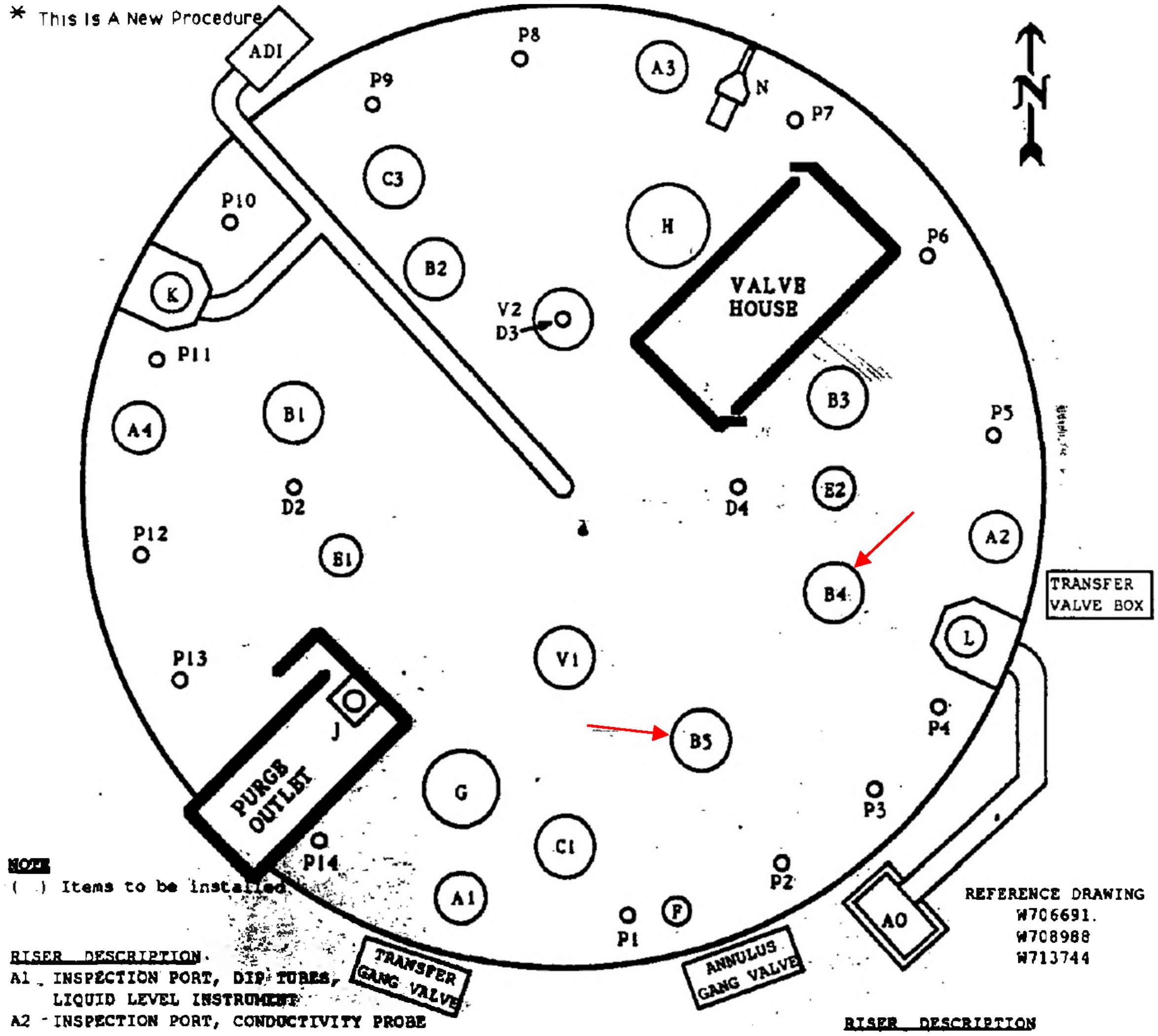
- Tank 49H Submersible Transfer Pump (STP)
  - Location: Riser B5
  - Suction elevation: 16 inches above bottom of the tank
  - Flow Rate: 82 – 159 gpm
- Tank 49H B4 Downcomer
  - Outlet elevation: 388.125 inches above the bottom of the tank
  - Outlet pipe diameter: 3-inch schedule 40 pipe – ID = 3.068 inches
- 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[b]
  - 100 – 120 gpm
  - Maximum flow rate 200 gpm
- Addition rate of liquid from Tank 42H to Tank 49H[b]
  - 95 – 115 gpm
  - Maximum flow rate 200 gpm
- Gibbsite density
  - 2.42 g/mL
- Sodium aluminosilicate density
  - 2.32 – 2.60 g/mL
- Tank 49H solids level
  - 1.1 inches
- Tank 21H to Tank 49H transfer rate
  - 75 – 100 gpm
- Particle size
  - 1 – 100 micron

No data was provided to describe the size of the solid particles on the tank bottom. Previous work by SRNL collected data on the particle size of simulated sludge and actual sludge. The median particle size for the actual SRS sludge samples ranged between 2.6 micron and 15.1 micron.[17]

Figure 1 shows a view of the top of Tank 49H to show the positions of the risers B4 and B5 in the tank.

[b] This flow rate was used to evaluate the sensitivity of the "plunging jet" depth to the inlet flow rate. It was not used to calculate the amount of solids transferred from Tank 49H to SWPF. The initial transfer will be from Tank 21H to Tank 49H. Tank 21H to Tank 49H transfers will have a maximum flow rate of 100 gpm.

Figure 1. Tank 49H Tank Top



Assumptions:

The author made the following assumptions to perform this analysis.

- The liquid added to the tank can be modeled as a "plunging jet", which is defined as an impinging rapid flow into a slower body of liquid, which may be a pool of liquid at rest. When a water jet impinges on the surface of a pool of water, air bubbles may be entrained and carried below the free surface.[19] These air bubbles slow and eventually stop the downward motion of the jet.
- 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.[12]
- 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.[12]
- 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 suspending solid particles. The 2.6 g/mL is the maximum described in the inputs above, and it was selected to be conservative for the mass of particles suspended.

- M-Star modeling of the "plunging jet" used a 10 ft diameter tank. The 10 ft diameter was selected to reduce the computational requirements and because 10 feet is much larger than the expected diameter of the plunging jet as it reaches and expands below the liquid surface (14 – 19 inches).
- The jet was added in the M-Star simulation 20 inches above the liquid surface rather than at the top of the tank to save computer memory, to reduce the simulation time, and to prevent the calculation from becoming unstable due to the large increase in velocity between the downcomer and the liquid surface. The velocity of the jet was selected based on equations describing the behavior of "plunging jets". Placing the jet above the liquid surface allowed for air entrainment, which would give the jet buoyancy and reduce its penetration depth.
- 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 %.[18]
- 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 and 16 inches high. The 16 inches is selected to equal the height of the transfer pump suction.
- The flow of fluid into the transfer pump can be modeled as a converging channel flow. The radius of the converging channel flow to the transfer pump suction is assumed to be 13 ft, which is less than the distance between the transfer pump and the wall and the distance between the transfer pump and the disturbed solids location.
- 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.
- These calculations assume no hindered settling behavior – i.e., particle-particle interactions – which is a reasonable assumption for dilute slurries of non-cohesive particles.

2.1 Plunging Jet

The author addressed this problem by treating the added salt solution as a "plunging liquid jet".[6,7] The following input parameters were used for the analysis.

- Downcomer pipe diameter = 3.068 inches
- Liquid flow rate = 75 gpm and 200 gpm
- Downcomer elevation = 388.125 inches
- Liquid level = 80 - 120 inches
- Liquid density = 1.26 g/mL[12]
- Liquid viscosity = 2.5 cP[12]

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

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

where Q is the flow rate and D is the downcomer internal diameter. For a flow rate of 75 gpm, the exit velocity is 3.3 ft/s. For a flow rate of 200 gpm, the exit velocity is 8.7 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]

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

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 = 24.0 feet). For a downcomer exit velocity of 3.3 ft/s, the velocity at the surface is 39.5 ft/s. For a downcomer exit velocity of 8.7 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 75 gpm, the jet diameter at the liquid surface is 0.88 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). With a flow rate of 75 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

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

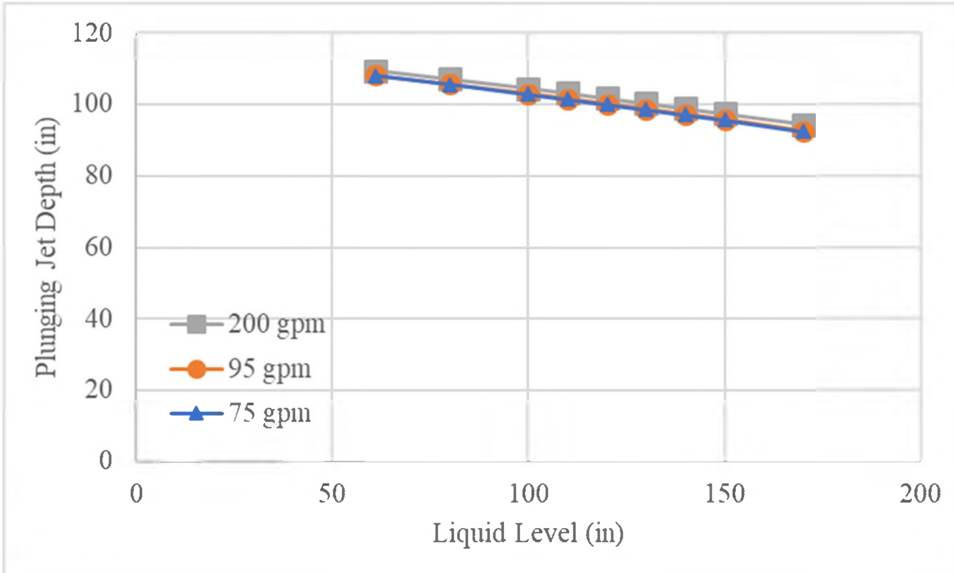
where Z is the depth below the liquid surface.

Table 1 and Figure 2 summarize the results of the analysis. Table 1 shows "plunging jet" properties at three liquid levels using the maximum flow rates, as well as another flow rate of 95 gpm. Figure 2 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 2 shows little effect of inlet flow rate 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

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

Figure 2. 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.

Based on Table 1 and Figure 2, a minimum liquid level of 120 inches is recommended in Tank 49H.

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" and to attempt to quantify the mass of solids disturbed, a computational fluid dynamics (CFD) simulation was performed using the M-Star® Lattice-Boltzmann software.

M-Star® Computational Fluid Dynamics (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 was classified as Class D software in X-SWCD-A-00011. However, its simulation results have been compared with data for other SRS applications such as impeller mixing of tanks and jet mixing of miscible liquids.[13] 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".

To model the "plunging jet" in Tank49H, the author used the software to create a cylindrical tank that is 388 inches high and 10 feet in diameter. The 10 ft diameter was selected to reduce the computational requirements and because 10 feet is much larger than the expected diameter of the plunging jet as it reaches and expands below the liquid surface (14 – 19 inches). The initial simulations contained no cooling coils. Later simulations modeled the cooling coils with vertical pipes 2.36 inches in diameter, spaced 3 feet apart. The coils also contained a 2.36-inch horizontal pipe connecting every other vertical pipe to simulate the bends at the bottom of the coils. A fluid with 1.26 g/mL density and 2.5 cP viscosity was placed in the tank at a level between 80 and 120 inches. Given that the density and viscosity of the added liquid and the existing liquid should be approximately the same, the density and viscosity of the added liquid should not have a significant effect on the simulations. Also, density and viscosity do not appear in the "plunging jet" correlation described in equation [4]. A mass of solid particles with density of 2.25 g/mL and size of either 10 micron or 100 micron was placed in the bottom of the tank. The 2.25 g/mL solid particle density was chosen for conservatism in suspending solid particles. Previous SRNL work investigating the impact of feed properties on settling and suspension of solid particles found the input force needed to suspend particles increases with increasing particle size and particle density, with particle density having a stronger effect.[13] A 2.25 g/mL particle would be easier to suspend than a 2.32 g/mL particle. The particle depth was either 1 inch or 0.5 inches. Most of the simulations were performed with a particle depth of 1 inch. A few were performed with a 0.5 inch particle depth to attempt to obtain better images. A 1 inch particle depth was initially selected to simplify the simulations. The impact of a particle depth of 1.1 inches or more could be determined by linearly increasing the mass of suspended solids to account for an increase in particle depth.

A liquid jet was input to the tank at an elevation ~20 inches above the liquid level. The fluid velocity and jet diameter at 20 inches above the liquid level were calculated using equations [1] – [3], based on an input flow rate at the downcomer of 95 gpm. The jet was added 20 inches above the liquid surface rather than at the top of the tank to save computer memory, to reduce the simulation time, and to prevent the calculation from becoming unstable due to the large increase in velocity between the downcomer and the liquid surface. Placing the jet above the liquid surface allowed for air entrainment, which would give the jet buoyancy and reduce its penetration depth. Table 2 summarizes the parameters used in the simulations.

Table 2. Input Parameters of M-Star Simulations of Plunging Jet

Parameter	Value
Inlet Flow Rate (gpm)	95
Liquid Height (in)	80, 100, 110, 120
Fluid Density (g/mL)	1.26
Fluid Viscosity (cP)	2.5
Solid Particle Size (micron)	10, 100
Particle density (g/mL)	2.25
Particle layer thickness (in)	0.5, 1

2.2.1 120 Inch Liquid Level with No Cooling Coils

Table 1 showed that at a liquid level of 120 inches, the depth of the "plunging jet" is approximately 100 inches. M-Star® simulations were performed at this liquid level to provide a comparison with previous work and correlations. Figure 3 shows a side view of the "plunging jet" with a liquid level of 120 inches. Two images of the side view are shown. The image on the left uses a y-velocity scale of -1 m/s to 1 m/s. This scale was selected to show the coherent jet that forms. The image on the right uses a velocity scale of -0.1 m/s to 0.1 m/s. This scale was chosen to show how deep the "plunging jet" penetrates into the liquid. The plot shows that the "plunging jet" does not reach the solid particles at the bottom of the tank, but it does disturb a small fraction of the particles. The fraction disturbed is small, not lifted much above the bottom, and results in a minimal number of particles being transported to the transfer pump. The figure shows some instances of fluid moving downward at the tank walls. This phenomenon may be due to the presence of the artificial walls rather than the fluid motion that would occur in a larger diameter vessel. In Tank 49H, these walls would not exist, and fluid motion would be away from the addition point. This observation must be considered when evaluating the data later, and it may have contributed to some of the particles being disturbed.

Equation [5] describes the width of the "plunging jet". A "plunging jet" with a 100-inch depth would have a width of ~19 inches. While the images in Figure 3 and following figures are consistent with equation [5], a downward velocity is observed away from the "plunging jet" and the center of the vessel. One cause of this phenomenon could be numerical transport. Numerical transport occurs because the lattice points are discrete rather than continuous and can lead to over estimating mass and momentum transport. M-Star® recommends having at least 5 points across the diameter of a jet nozzle, which was done in these simulations. A finer lattice spacing should be investigated for future simulations of "plunging jets" to try to reduce numerical transport.

Figure 4 shows a bottom view of the tank after 60 seconds (the scale in the grid is in meters). The figure shows the direction and distance from the simulated tank walls to the Tank 49H center, the Tank 49H wall, and the transfer pump. These structures are not located within 5 feet of the downcomer, so they should not affect the "plunging jet" and were not included in the simulation. The figure also shows a small fraction of the particles being disturbed. From the grid, the size of the disturbed area is approximately 0.6 meters by 0.4 meters (1.97 ft by 1.31 ft). This result is consistent with Table 1 and Figure 2. However, if there are insoluble solid particles suspended in the 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 will be met. The analysis of the insoluble solids concentration in Tank 21H for SWPF Batch 2 qualification showed the insoluble solids concentration to be 39.3 mg/L.[14]

Figure 3. Side View of Plunging Jet with 120-inch Liquid Level

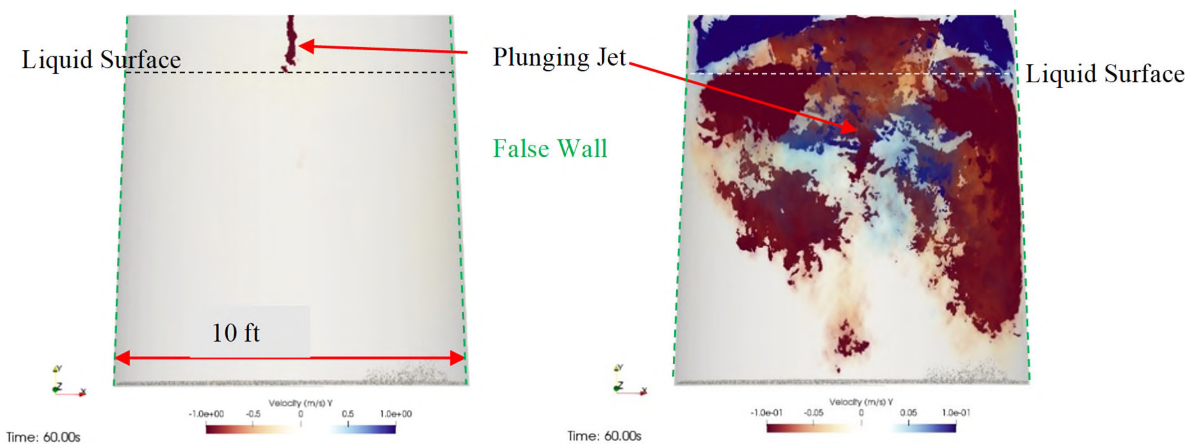
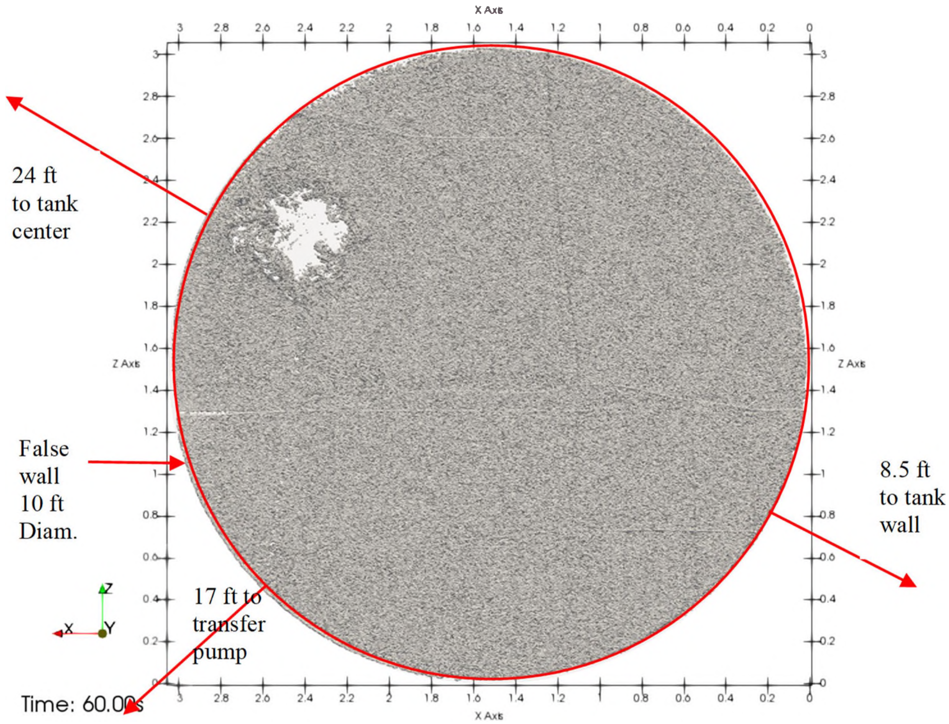


Figure 4. Bottom View of Plunging Jet with 120-inch Liquid Level



Reviewing Figure 4, the area of the disturbed particles is approximately 0.4 m by 0.6 m (1.31 ft by 1.97 ft). Using a diameter of 0.6 m (1.97 ft) for conservatism and a height of 1.1 inches (based on the inputs provided by SRR), the volume of solid particles disturbed is described by equation [6]

$$V = \pi D^2 H/4 = (3.14)\ (60\ cm)^2\ (2.79\ cm)/4 = 7{,}900\ cm^3 = 7.9\ L \qquad [6]$$

where V is the volume, D is the diameter of the disturbed region, and H is the height of the disturbed region.

Assuming a particle density of 2.6 g/mL (the 2.6 g/mL density was chosen for conservatism and based on the inputs provided by SRR) and a particle concentration of 30 vol %, the mass of particles suspended is described by equation [7]

$$M = x\ \rho\ V = (0.3\ mL/mL)\ (2.60\ g/mL)\ (7{,}900\ mL) = 6{,}200\ g = 6.2\ kg \qquad [7]$$

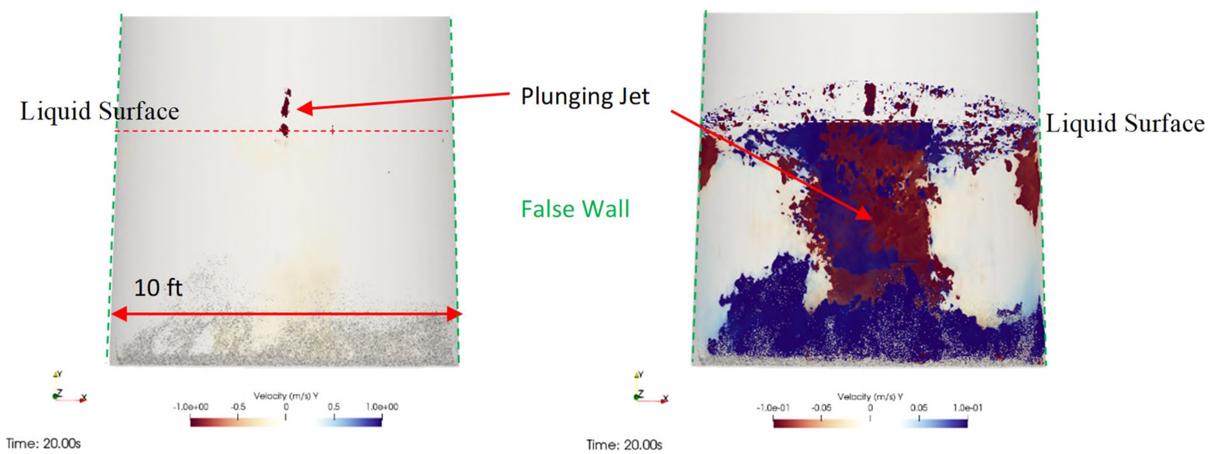
where M is the mass of solid particles disturbed, x is the volume fraction of solid particles, and ρ is the solid particle density.

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

2.2.2 80 Inch Liquid Level

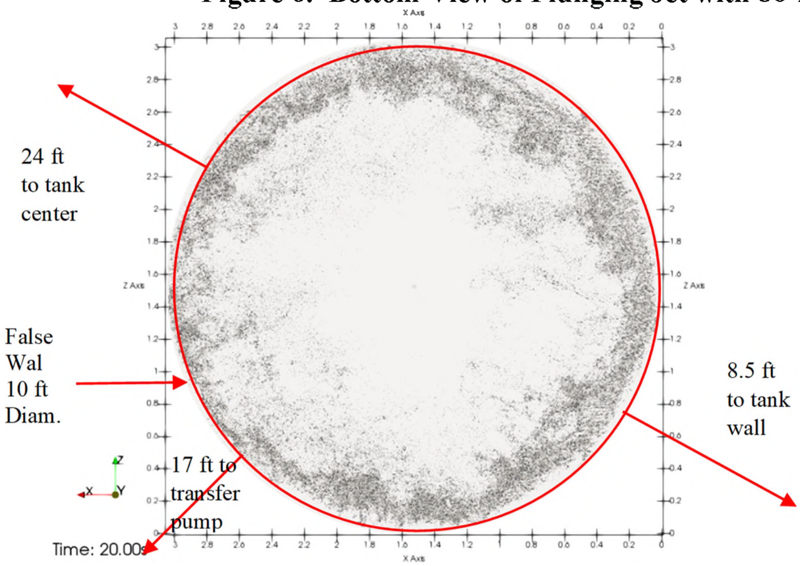
Using equations [1] – [4] with an inlet flow rate of 95 gpm and a liquid level of 80 inches, the calculated depth of the plunging jet is 106 inches, which is significantly larger than the liquid level. At this liquid level, the "plunging jet" is expected to disturb the solid particles on the tank bottom. M-Star® simulations were performed at this liquid level to verify that the solid particles are disturbed. Figure 5 and Figure 6 show a side view and bottom view of the "plunging jet" with a liquid level of 80 inches. Two images of the side view are shown. The image on the left uses a y-velocity scale of -1 m/s to 1 m/s. The image on the right uses a velocity scale of -0.1 m/s to 0.1 m/s. It shows that the jet influence reaches to the bottom of the tank. The figure shows some instances of fluid moving downward at the tank walls. This phenomenon may be due to the presence of the walls rather than the fluid motion that would occur in a larger diameter vessel. This observation must be considered when evaluating the data later. The plots show significant disturbance of the solid particles on the bottom of the tank after 20 seconds. The bottom view shown in Figure 6 shows that a large fraction of the solid particles on the tank bottom are disturbed by the "plunging jet". While not all particles are disturbed, the fraction of particles disturbed may have been limited by the 10 ft (3.05 m) diameter of the vessel simulated. Subsequent discussion will assume that all particles in the 10 ft (3.05 m) diameter under the riser were disturbed. This result is consistent with Table 1 and Figure 2.

Figure 5. Side View of Plunging Jet with 80-inch Liquid Level



Using equations [6] and [7], and assuming that all particles were disturbed, the volume of disturbed solid particles is 204 Liters and the mass is 159 kg.

Figure 6. Bottom View of Plunging Jet with 80-inch Liquid Level



2.2.3 100 Inch Liquid Level

After confirming the model predictions agree with the expected behavior at 80- and 120-inches liquid levels, additional simulations were performed at 100 inches liquid level.

Table 1 showed that at a liquid level of 100 inches, the depth of the "plunging jet" is approximately 103 inches. Figure 7 shows a side view of the "plunging jet" with a liquid level of 100 inches. The image on the left shows the vertical velocity with a scale of -1 m/s to 1 m/s, and the image on the right shows a vertical velocity scale of -0.1 to 0.1 m/s. The image shows that the "plunging jet" does disturb the solid particles on the tank bottom. Figure 8 shows a bottom view of the solid particles. The scale for the grid is in meters. The image also shows evidence of disturbance of the particles on the tank bottom from the "plunging jet". Most of the solid particles on the tank bottom are disturbed, so subsequent calculations will assume all particles in the 10 ft (3.05 m) diameter under the riser are disturbed.

Using equations [6] and [7], and assuming that all particles were disturbed, the volume of disturbed solid particles is 204 Liters and the mass is 159 kg.

Figure 7. Side View of Plunging Jet with 100-inch Liquid Level

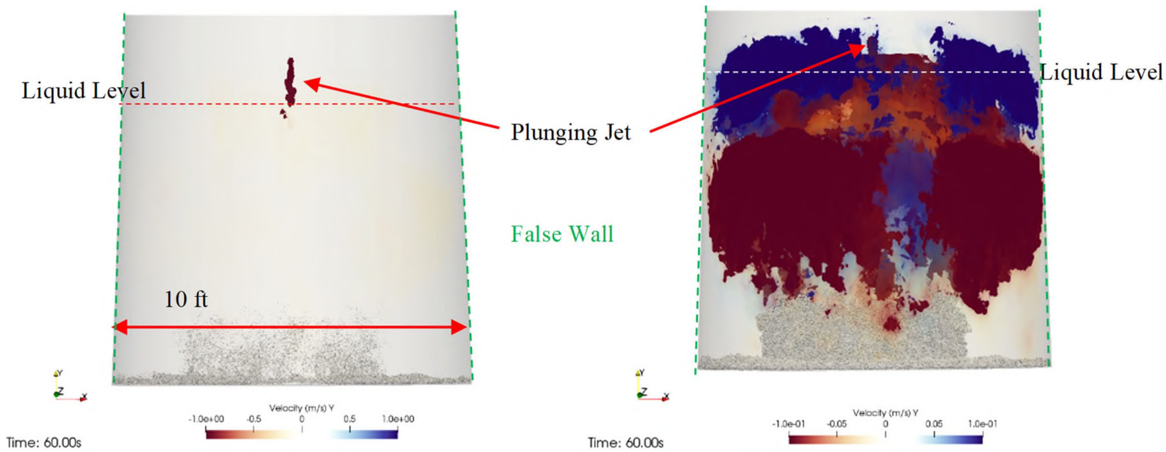
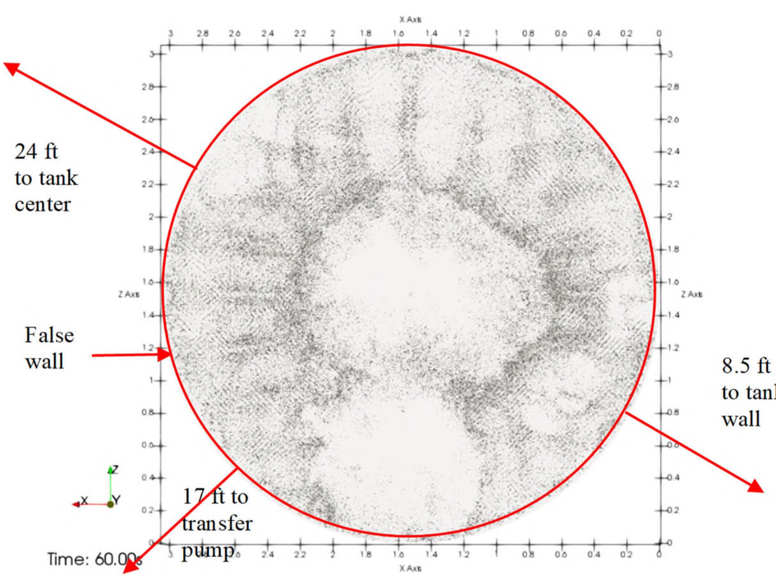


Figure 8. Bottom View of Plunging Jet with 100-inch Liquid Level



2.2.4 120 Inch Liquid Level with Cooling Coils

An additional simulation was performed with a liquid level of 120 inches and cooling coils. Figure 9 shows a side view of the tank from this simulation. The image on the left has a velocity scale of -1 to 1 m/s, and the image on the right has a velocity scale of -0.1 to 0.1 m/s. The images show that the "plunging jet" does not reach the bottom of the tank, and no solids are observed lifting off the tank bottom. This result is different from the result in Figure 3 and suggests that the cooling coils may have some impact on the penetration depth of the "plunging jet". Figure 10 shows a bottom view of the tank. Some disturbance of the solid particles is observed. Given that the distance between the vertical pipes is 3 feet (0.915 m), the disturbed area is approximately 2 ft by 2 ft (0.61 m by 0.61 m).

Figure 9. Side View of Plunging Jet with 120-inch Liquid Level and Cooling Coils

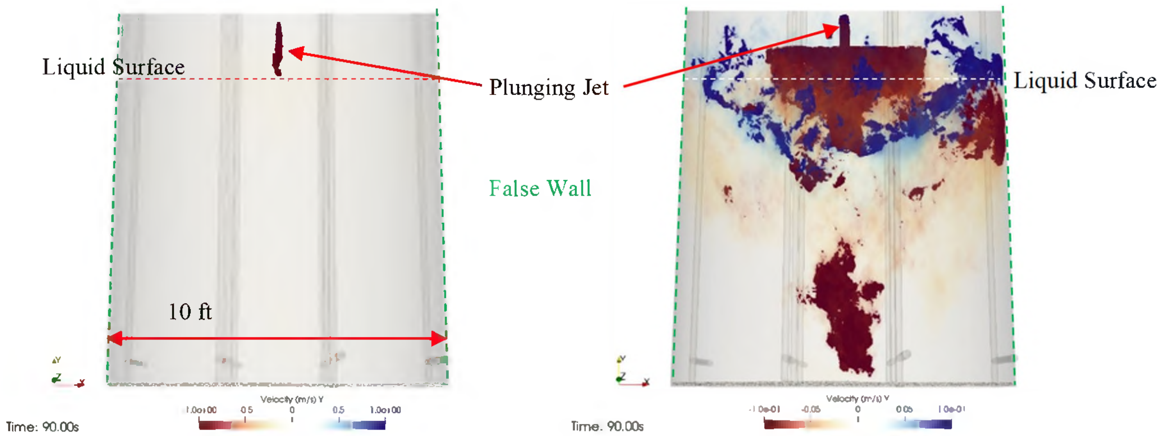
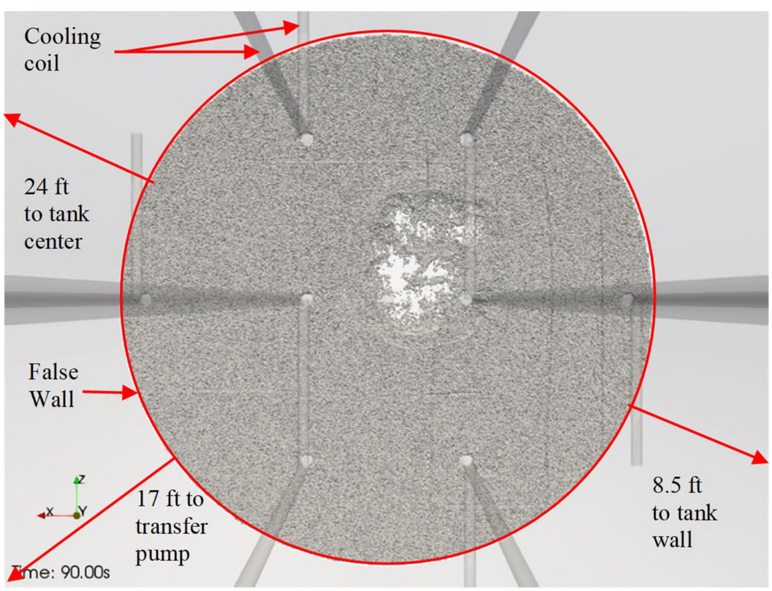


Figure 10. Bottom View of Plunging Jet with 120-inch Liquid Level and Cooling Coils



Using equations [6] and [7], and assuming that all particles within the zone were disturbed, the volume of disturbed solid particles is 8.1 Liters and the mass is 6.4 kg. This mass of disturbed solids is larger than the mass of disturbed solids without cooling coils, but the difference is likely within the uncertainty of the estimate.

2.2.5 100 Inch Liquid Level with Cooling Coils

An additional simulation was performed with a liquid level of 100 inches and cooling coils. Figure 11 and Figure 12 show a side view and bottom view of the tank from this simulation. The image on the left in Figure 11 has a velocity scale of -1 to 1 m/s, and the image on the right has a velocity scale of -0.1 to 0.1 m/s. The images show that the "plunging jet" does reach the bottom of the tank, and solids disturbance is observed. Four large disturbed areas are observed in Figure 12. Given that the distance between the vertical pipes is 3 feet, the area in the center of the tank is ~ 3 feet (0.915 m) in diameter, the area in the upper right is ~ 2 feet (0.61 m) in diameter, the area on the right is ~ 2 feet (0.61 m) in diameter, and the area on the left is ~ 2 feet (0.61 m) in diameter.

Figure 11. Side View of Plunging Jet with 100-inch Liquid Level and Cooling Coils

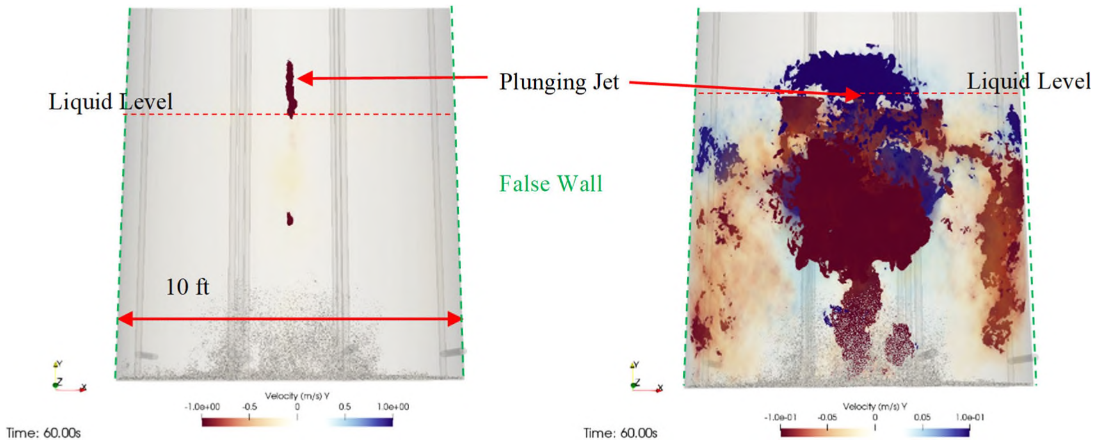
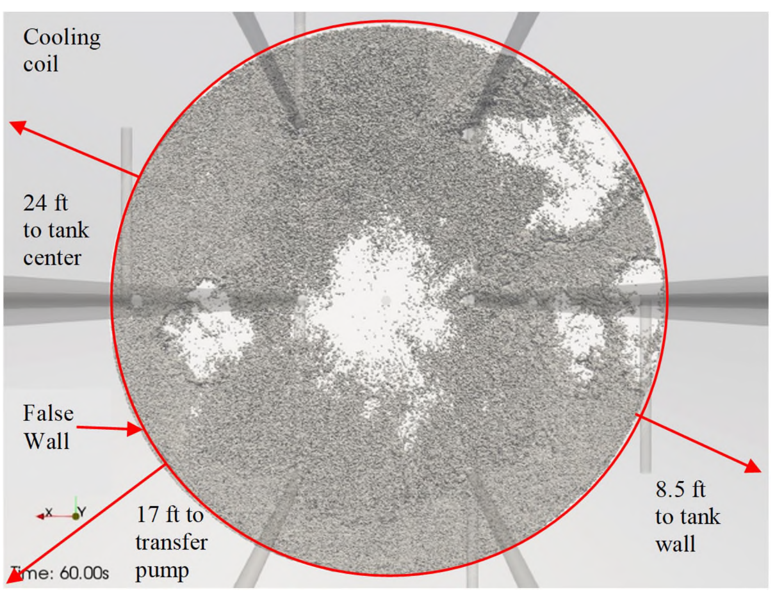


Figure 12. Bottom View of Plunging Jet with 100-inch Liquid Level and Cooling Coils



Using equations [6] and [7], and assuming that all particles within the zones were disturbed, the volume of disturbed solid particles is 46.6 Liters and the mass is 33.5 kg.

2.2.6 110 Inch Liquid Level with Cooling Coils

An additional simulation was performed with a liquid level of 110 inches and cooling coils. Figure 13 shows a side view of the tank from this simulation. The image on the left has a velocity scale of -1 to 1 m/s, and the image on the right has a velocity scale of -0.1 to 0.1 m/s. The images show that the "plunging jet" does reach the bottom of the tank, and solids disturbance is observed. Using the grid in Figure 14, the disturbed area in the center is approximately 1.5 meters (4.92 ft) in diameter, and the disturbed area to the left is approximately 0.2 m by 0.8 m (0.66 ft by 2.62 ft).

Figure 13. Side View of Plunging Jet with 110-inch Liquid Level and Cooling Coils

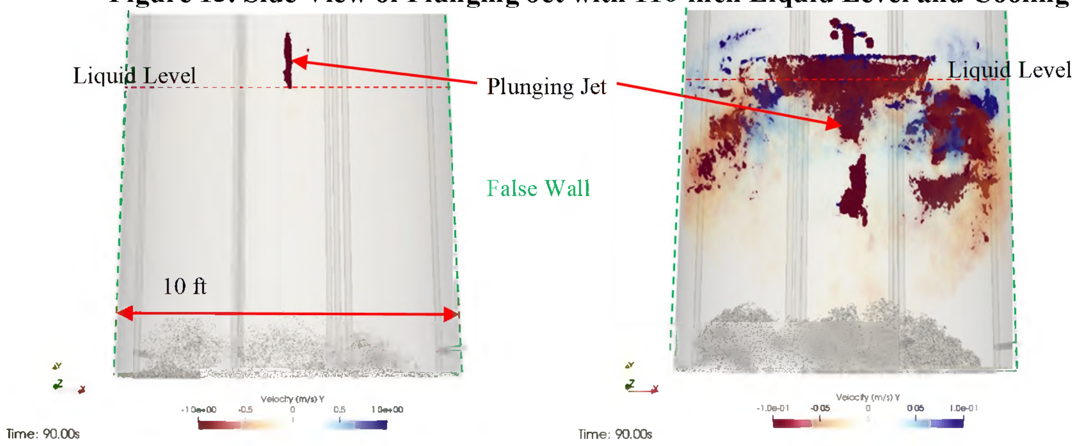
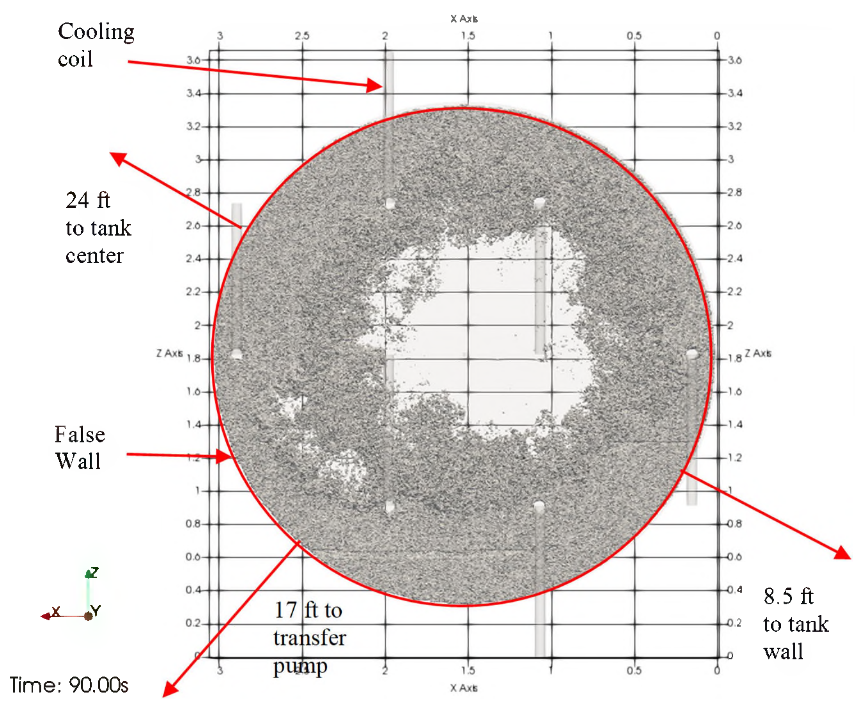


Figure 14. Bottom View of Plunging Jet with 110-inch Liquid Level and Cooling Coils



Using equations [6] and [7], and assuming that all particles within the zones were disturbed, the volume of disturbed solid particles is 49 Liters and the mass is 38 kg. This mass of disturbed solids is larger than at a 100 inch level, but the differences are likely within the uncertainty of the estimate.

2.2.7 100 Inch Liquid Level with Cooling Coils and 15 foot Diameter

An additional simulation was performed with a liquid level of 100 inches, cooling coils, and a 15 ft diameter tank. Figure 15 shows a side view of the tank from this simulation. The image on the left has a velocity scale of -1 to 1 m/s, and the image on the right has a velocity scale of -0.1 to 0.1 m/s. Figure 16 shows a bottom view of the tank. The images show that the "plunging jet" reaches the bottom of the tank, and that the "plunging jet" disturbs solids throughout the 15 ft (4.57 m) diameter. This result differs from the simulation with the 10 ft (3.05 m) diameter tank and suggests that a larger diameter region should be considered for future simulations.

Figure 15. Side View of Plunging Jet with 100-inch Liquid Level and Cooling Coils and 15 Ft Diameter Tank

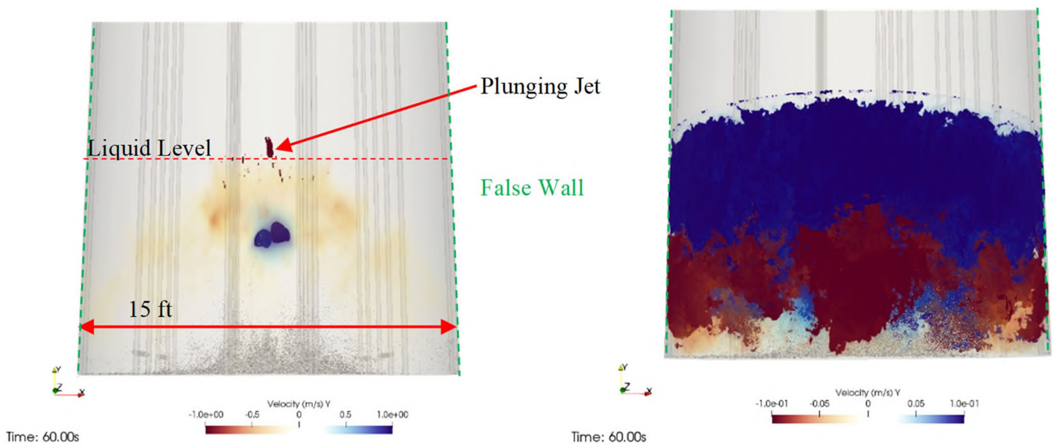
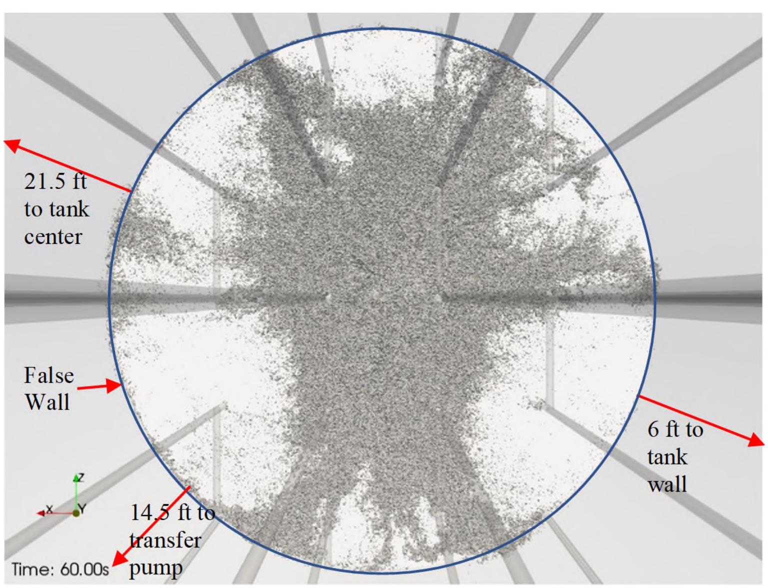


Figure 16. Bottom View of Plunging Jet with 100-inch Liquid Level and Cooling Coils and 15 Ft Diameter



2.2.8 80 Inch Liquid Level with 100 Micron Particles

Because of the disturbance of particles for the 80 inch liquid level, simulations were performed with 100 micron particles. Figure 17 shows a side view of the "plunging jet" with a liquid level of 80 inches. The plot shows the vertical velocity with a scale of -0.1 m/s – 0.9 m/s. The plot shows that the "plunging jet" disturbs the solid particles on the tank bottom. Figure 18 shows a view of the solid particles from under the tank. The figure also shows evidence of scouring of the particles on the tank bottom from the "plunging jet". Most of the solid particles on the tank bottom are disturbed, so subsequent calculations will assume all particles in the 10 ft (3.05 m) diameter under the riser are disturbed. The investigation of 100 micron particles did not show a significant reduction in the mass of disturbed solids. Previous work by SRNL investigating the impact of properties on settling and suspension of solid particles showed that the force needed to suspend particles is a weak function of particle size and a stronger function of particle density.[14]

Using equations [6] and [7], and assuming that all particles were disturbed, the volume of disturbed solid particles is 204 Liters and the mass is 159 kg.

Figure 17. Side View of Plunging Jet with 80-inch Liquid Level and 100 Micron Particles

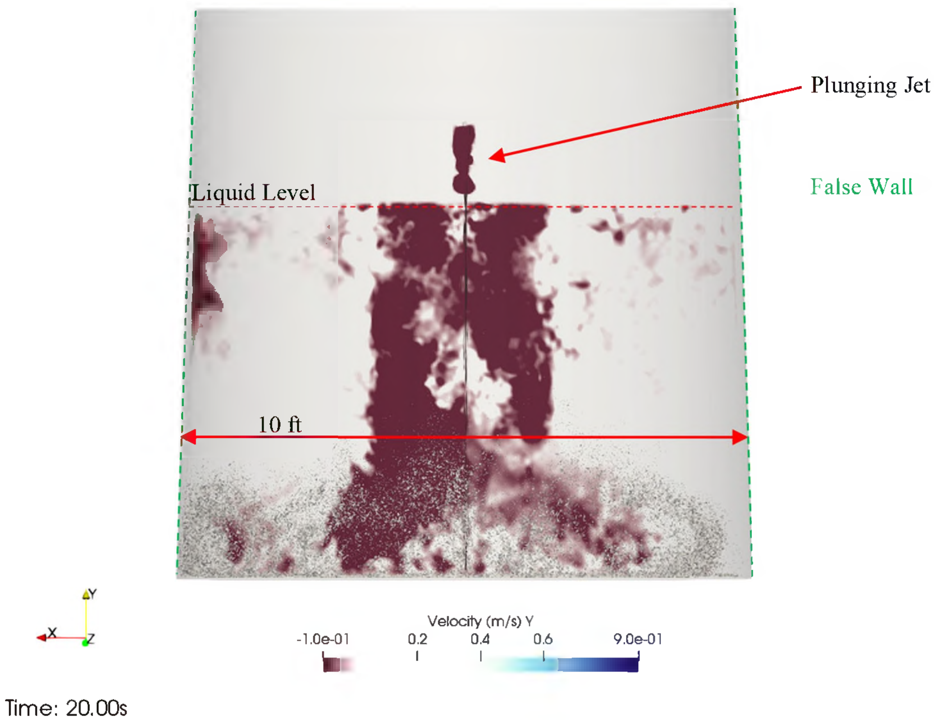
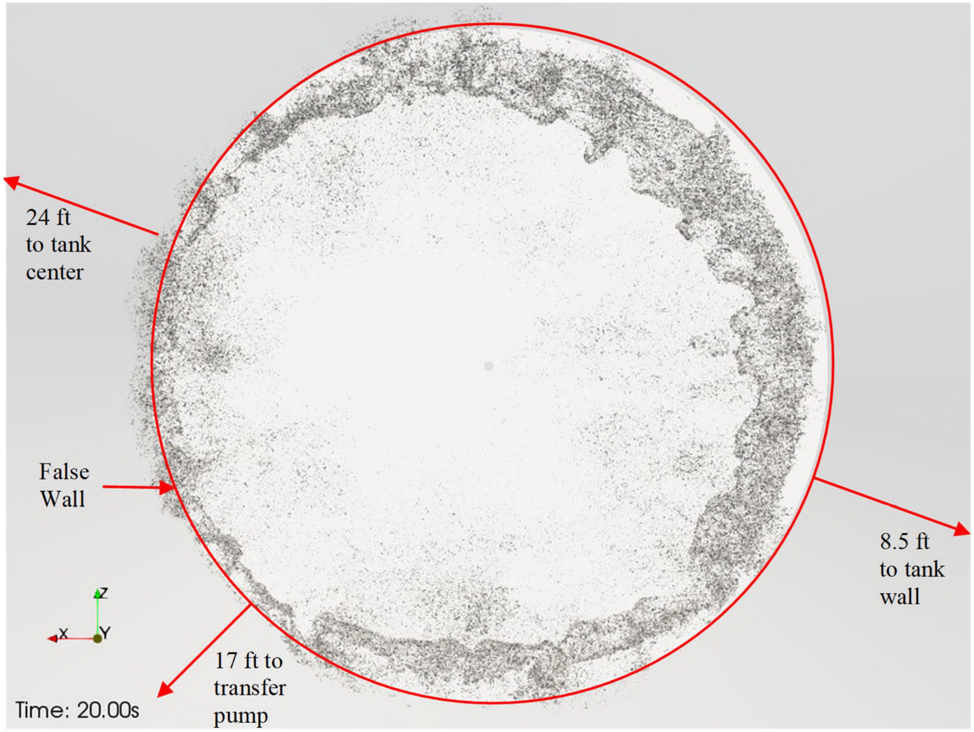


Figure 18. Bottom View of Plunging Jet with 80-inch Liquid Level and 100 Micron Particles



2.3 Suction Flow into Transfer Pump

From the figures in Section 2.2, one can estimate the mass of solid particles suspended by the "plunging jet". Four approaches were employed 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 bulk concentration in the entire volume of liquid transferred to the SWPF, (2) calculating the concentration of disturbed solids in the volume above the tank bottom containing the disturbed solids and including a dilution factor to account for mixing with other liquid in the tank as the material is transported to the transfer pump, (3) using the results from approach 2, and accounting for the time required for the disturbed solids to reach the transfer pump, and (4) accounting for particle settling between transfers.

The first approach for calculating the solid particle concentration in the liquid transferred to the SWPF is to take the mass of solid particles suspended and divide it by the liquid volume transferred to SWPF in a 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. 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, which is below the SWPF WAC. 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 particle in the transfer to Tank 49H, the concentration of these particles must be considered in determining whether the SWPF WAC will be met. The concentration of insoluble solids in the Tank 21H SWPF Batch 2 qualification was 39.3 mg/L, which is much less than the 1200 mg/L SWPF WAC limit.[15]

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. 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 1.8 g/L, which is above the SWPF WAC limit. This calculation is repeated for the other operating conditions described in Section 2.2. The results from this approach 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 limit. However, if there are insoluble solid particles suspended in the supernate prior to the transfer or insoluble particle in the transfer, the concentration of these particles must be considered in determining whether the SWPF WAC will be met. In addition, when the region diameter is increased from 10 feet to 15 feet, the mass of solid particles disturbed increases, and the bulk concentration in the transfer to SWPF exceeds the WAC. This result is unexpected and cannot be explained. Plausible explanations include the presence of the walls in the simulation and numerical transport, which were discussed earlier.

Examining Table 3, the presence of cooling coils significantly reduced the mass of disturbed solids with a liquid level of 100 inches. Likely reasons for this phenomenon are the drag caused by the coils and the coils dissipating the waves or ripples formed at the liquid surface. The magnitude of this effect is surprising given the diameter of the "plunging jet" and the distance between the coils.

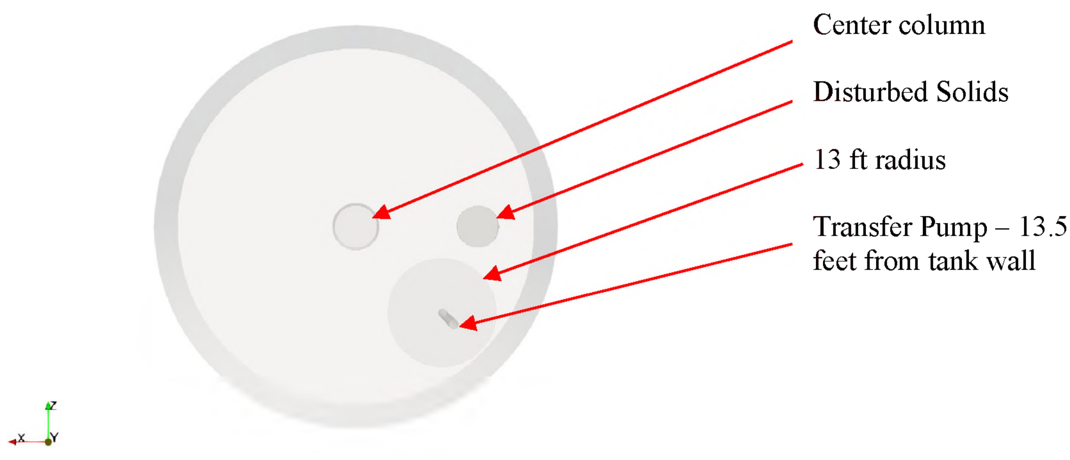
Table 3. Concentration of Disturbed Solids in Transfer to SWPF

Liquid Level	Region Diameter (ft)	Coils	Particle Size (μm)	Fraction Disturbed	Volume Disturbed (L)	Mass Disturbed (kg)	Bulk Concentration in Transfer to SWPF(g/L)
120 in	10	N	10	0.04	7.9	6.2	0.071
100 in	10	N	10	1.00	204	159	1.8
80 in	10	N	10	1.00	204	159	1.8
80 in	10	N	100	1.00	204	159	1.8
120 in	10	Y	10	0.04	8.1	6.4	0.073
110 in	10	Y	10	0.24	49	38	0.43
100 in	10	Y	10	0.23	46.6	33.5	0.38
100 in	15	Y	10	1.00	459	358	4.1

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 and 16 inches high. The 16 inches is selected to equal the height of the transfer pump suction. The volume of this cylinder is 2965 Liters. Using this liquid volume, the concentration of solid particles in the 10 ft diameter cylinder above the solid particles suspended is 6,200 g/2965 L = 2.09 g/L.

The transfer pump is 13.5 ft from tank wall (see Figure 19), and it will draw fluid from all directions. The flow of fluid into the transfer pump can be modeled as a converging channel flow. The radius of the converging channel flow to the transfer pump suction is assumed to be 13 ft, which is less than the distance to the wall. This 13 ft radius does not reach the disturbed solids under riser B4, so this calculation is conservative. The circumference of the converging channel is $2 \pi r = 2 \pi (13 \text{ ft}) = 81.7$ ft. Using a maximum diameter of 10 ft for the disturbed solids zone, the dilution from mixing added fluid containing disturbed solids with other tank material in the transfer pump is 8.17:1.

Figure 19. Location of Disturbed Solids and Transfer Pump in Tank 49H



Using the dilution factor of 8.17:1, described above, the concentration at the transfer pump suction with a liquid level of 120 inches and no cooling coils would be 0.26 g/L, which is below the SWPF WAC. This calculation is repeated for the other operating conditions described in Section 2.2. The results from this approach are described in Table 4. At all liquid levels below 120 inches, the calculated concentration is above the SWPF WAC limit.

Table 4. Concentration of Disturbed Solids Entering the Transfer Pump Suction Based on Dilution with Tank 49H Contents

Liquid Level	Region Diameter (ft)	Coils	Particle Size (µm)	Fraction Disturbed	Volume Mass Disturbed (kg)	Concentration of Disturbed Solids (g/L)	Concentration at Transfer Pump Suction (g/L)
120 in	10	N	10	0.04	6.2	2.09	0.26
100 in	10	N	10	1.00	159	53.6	6.56
80 in	10	N	10	1.00	159	53.6	6.56
80 in	10	N	100	1.00	159	53.6	6.56
120 in	10	Y	10	0.04	6.4	2.16	0.26
110 in	10	Y	10	0.24	38	12.8	1.57
100 in	10	Y	10	0.23	33.5	11.3	1.38
100 in	15	Y	10	1.00	358	121	14.8

The pump suction will draw material from above 16 inches, so this calculation is likely conservative.

2.4 Disturbed Particle Transport to Transfer Pump

This section discusses the transport of disturbed particles to the transfer pump, and the probability of the particles being transferred to the SWPF. Two particle sizes are considered: 10 micron diameter and 100 micron diameter. A particle density of 2.25 g/mL is chosen for conservatism. 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 [8] – [11].

The particle settling velocity is calculated by the following equations[16]

$$v_s = g(s-1)d_p^2/18\nu \quad \text{for } Re_p < 1.4 \quad [8]$$

$$v_s = 0.13[g(s-1)]^{0.72} d_p^{1.18} \nu^{-0.45} \quad \text{for } 1.4 < Re_p < 500 \quad [9]$$

$$v_s = 1.74[g(s-1)\, d_p]^{0.5} \quad \text{for } Re_p > 500 \quad [10]$$

$$Re_p = d_p v_s/\nu \quad [11]$$

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 ($\nu = \mu/\rho$).

Using equation [8] with a particle size of 10 micron, the particle settling rate is 7.07 x 10^{-5} ft/s, and with a particle size of 100 micron, the particle settling rate is 7.07 x 10^{-3} ft/s.

The time for a fluid particle to be transported from the region under the "plunging jet" to the transfer pump is equal to the distance traveled by the particle divided by the particle velocity. The fluid particle velocity is equal to the transfer pump flow rate divided by the cross-sectional area (A) that the fluid particles pass through. A flow rate of 159 gallons per minute (0.35 ft^3/s) was selected for conservatism, and a channel height of 16 inches was selected to equal the elevation of the transfer pump suction. Fluid will likely be drawn to the transfer pump from above 16 inches, so the actual fluid velocity is likely less than calculated. The transport time can be described by equation [12]

$$t = \frac{r}{V} = \frac{r\,A}{Q} = \frac{(r\,ft)\,(A\,ft^2)}{0.35\,ft^3/s} \quad [12]$$

Because the cross-sectional area is varying, this equation is solved by taking a differential and integrating it. The differential is described by equation [13]

$$dt = \frac{(r\,ft)}{0.35\,ft^3/sec}\,dA = \frac{(r\,ft)}{0.35\,ft^3/sec}\,2\pi H\,dr = \frac{(r\,ft)}{0.35\,ft^3/sec}\,2\pi\left(\frac{16}{12}ft\right)dr\,ft = 24r\,dr \quad [13]$$

The transport time is determined by integrating equation [13] as described in equation [14]

$$\int_0^t dt = \int_1^{22} 24\,r\,dr = \left[\frac{24}{2}r^2\right]_1^{22} \;(12)(22^2 - 1^2) = 5{,}800\text{ sec} = 97\,min \quad [14]$$

Based on the particle settling rates calculated with equations [8] – [11], a 10 micron particle would settle 0.41 ft (4.9 inches) in 97 minutes. Given the height to which these particles were suspended, 10 micron particles are likely to reach the suction pump suction and be transported to SWPF if they are disturbed by the plunging jet. Based on equations [8] – [11], 100 micron particles that are disturbed would settle 41 feet in 97 minutes, and are unlikely to reach the transfer pump and be transported to the SWPF.

In addition, the duration of a transfer is 23,200 gallons/159 gallons per minute, which equals 146 minutes. Since 97 minutes are required for a fluid particle to be transferred from the region above the disturbed solids to the transfer pump, solid particles will only reach the transfer pump during 34% of the transfer. The concentrations of insoluble solids calculated in Table 4 can be multiplied by 0.34 to account for this effect. These results are described in Table 5. The calculations show with cooling coils present, the concentration of insoluble solid particles in the transfer to SWPF may be below the SWPF WAC limit with liquid levels of 100 – 120 inches. However, the calculation performed with a 15 ft diameter region and 100 inch liquid level suggests that the concentration could be above the limit. If SRR desires to reduce the liquid level to 100 inches or lower, additional analyses should be performed.

Table 5. Concentration of Disturbed Solids Entering the Transfer Pump Suction Accounting for Transfer Time

Liquid Level	Region Diameter (ft)	Coils	Particle Size (μm)	Fraction Disturbed	Volume Mass Disturbed (kg)	Concentration at Transfer Pump Suction Accounting for Transfer Time (g/L)
120 in	10	N	10	0.04	6.2	0.088
100 in	10	N	10	1.00	159	2.23
80 in	10	N	10	1.00	159	2.23
80 in	10	N	100	1.00	159	2.23
120 in	10	Y	10	0.04	6.4	0.088
110 in	10	Y	10	0.24	38	0.53
100 in	10	Y	10	0.23	33.5	0.47
100 in	15	Y	10	1.00	358	5.03

2.5 Particle Settling During and Between Transfers

SRR will make a transfer to SWPF every 21.6 hours (1296 minutes). If the transfer time is 146 minutes as described above, the time between transfers is 1150 minutes. This calculation assumes the transfer 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.

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, 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. Given a 10 micron particle with a particle density of 2.25 g/mL, a liquid density of 1.26 g/mL, and a liquid viscosity of 2.5 cP, equation [8] calculates a settling velocity of 7.07×10^{-5} ft/s.

Over 1150 minutes, the 10 micron particle will settle 4.88 ft, and is unlikely to be transported to the transfer pump during subsequent transfers. This calculation was repeated for other particle sizes, and the results are shown in Table 6. The results show that significant particle settling will occur between transfers. Following the first transfer from Tank 49H to the SWPF, the chance of the disturbed solids from the "plunging jet" being transferred to the SWPF is significantly reduced. However, quantifying the reduction depends on the particle size of the disturbed solids in Tank 49H.

Table 6. Particle Settling as a Function of Particle Size

Particle Size (micron)	Settling Rate (ft/s)	Settling in 1150 minutes (ft)
1	7.07×10^{-7}	0.049
2	2.83×10^{-6}	0.20
4	1.13×10^{-5}	0.78
6	2.55×10^{-5}	1.76
8	4.53×10^{-5}	3.13
10	7.07×10^{-5}	4.88

Previous work by SRNL collected data on the particle size of simulated sludge and actual sludge.[17] Figure 20 shows the results. The median particle size for the actual SRS sludge samples ranged between 2.6 micron and 15.1 micron. The figure shows very few particles larger than 100 micron.

Figure 20. Particle Size of Simulated SRS Sludge and Actual SRS Sludge

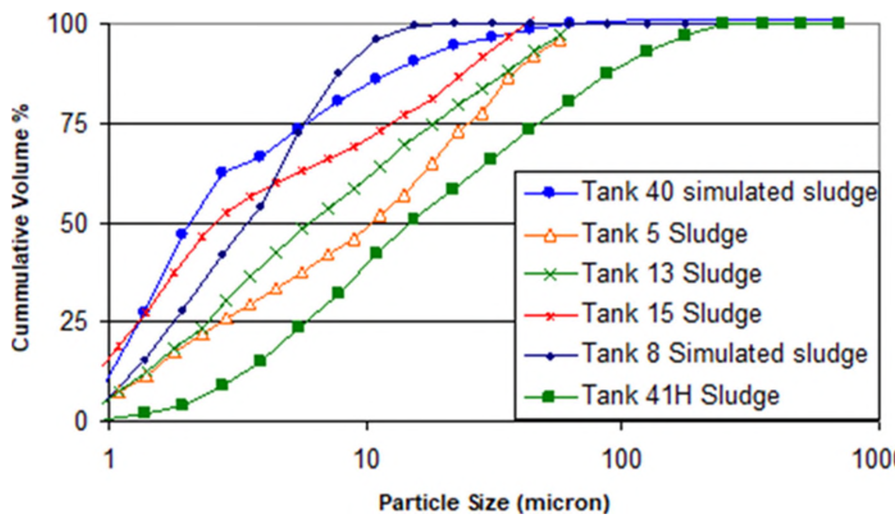
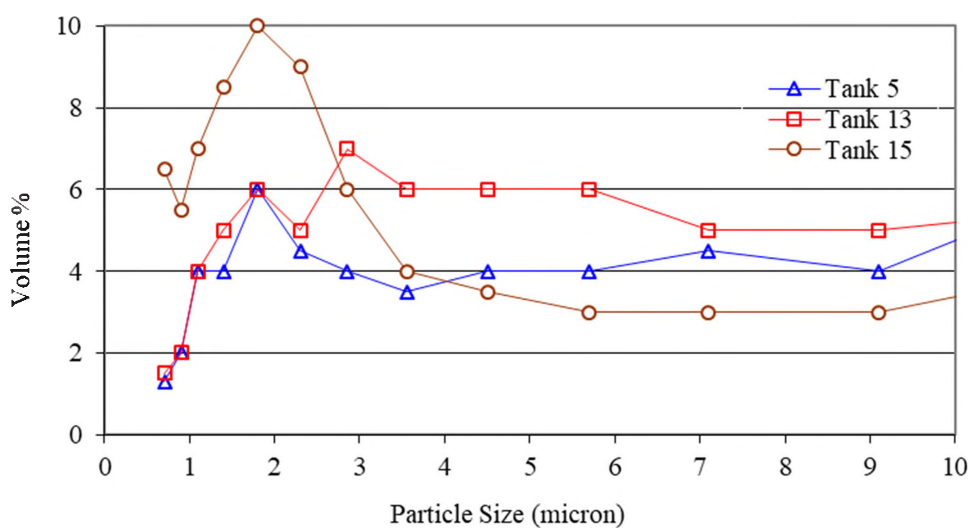


Figure 21 shows the fraction of particles less than 10 micron measured in samples of Tank 5, Tank 13, and Tank 15 sludge. The data show that ~12% of the Tank 15 sample particles were less than 1 micron.

Figure 21. Fraction of Particles Less than 10 Micron in SRS Sludge Samples



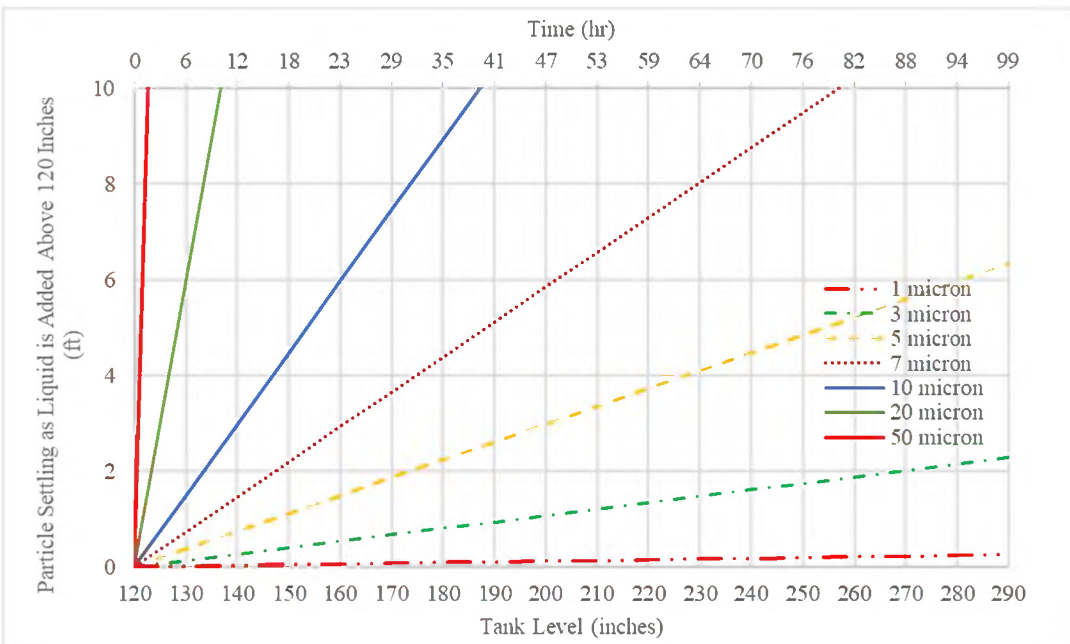
If liquid is added to Tank 49H with a liquid level less than 120 inches, particle disturbance will occur. Once the liquid level reaches 120 inches, the "plunging jet" will have minimal impact on the solid particles at the tank bottom. As the liquid level increases, the depth of the "plunging jet" will decrease, and its region of impact will be farther from the tank bottom. Once the disturbed solids are outside of the region of impact of the "plunging jet", they will settle. At a flow rate of 100 gpm into Tank 49H, the liquid level will increase from 120 inches to 290 inches (~1,000,000 gallons) in a minimum of 4 days.[c] The 4 day time assumes a

[c] The 100 gpm flow rate and 4 days of settling applies to Tank 21H to Tank 49H transfers. The flow rate may be larger for transfers from Tank 41H and Tank 42H.

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 22 shows the estimated 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 3 micron and larger will settle at least 2 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. Particles less than 3 micron may not settle to the tank bottom. This particle settling may prevent exceeding the SWPF WAC limits for insoluble solids but is dependent on the particle size of the particles at the bottom of Tank 49H.

Figure 22. Particle Settling as Liquid is Added to Tank 49H



2.6 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 and the dilution that will occur with other liquid in Tank 49H, it may be possible to meet the SWPF WAC 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 less than 10 micron in diameter, any disturbed particles are likely to be transported to the transfer pump, and then transferred to SWPF. If the particles are greater than 100 micron in diameter, any disturbed particles are likely to settle before being transported to the transfer pump.

However, calculations of the dilution that will occur with the liquid above the solid particles as they are disturbed and the blending that will occur as they are transported to the transfer pump (see Sections 2.3 and 2.4) suggest that their concentration may be below the SWPF WAC. SRNL and SRR should review the details of the planned transfers to determine whether these calculations can be used to justify a lower liquid level in Tank 49H.

Significant particle settling could occur during the transfer of liquid into Tank 49H and between transfers from Tank 49H to SWPF (see Section 2.5). This settling will reduce the concentration of solid particles that are transferred to SWPF and may allow a lower liquid level in Tank 49H at the start of transfer. This settling is a function of the size of the solid particles.

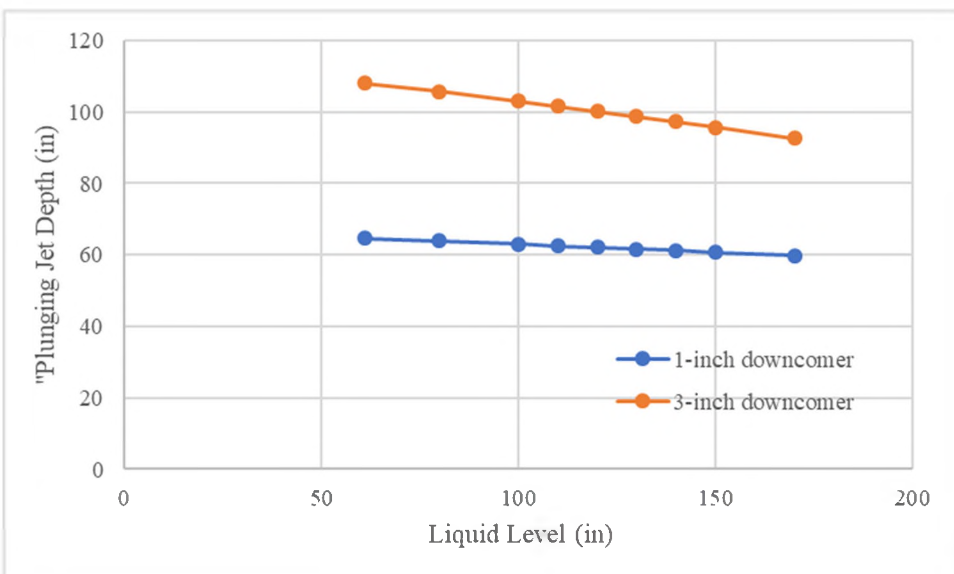
Other approaches that SRR should consider if they wish to maintain a lower level in Tank 49H are to lower the elevation at which the liquid enters the tank, adding a device to disperse the added liquid into droplets that will not penetrate deeply below the liquid surface, or adding a nozzle to the downcomer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

Future transfers into Tank 49H will use different risers with liquid exiting the downcomers at a lower elevation. The lower elevation will reduce the velocity at the liquid surface and the penetration depth of the "plunging jet". This analysis should be repeated for those conditions. A TTR has been drafted for this work.

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.

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 23 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 with the smaller diameter, keeping the inlet flow rate constant at 95 gpm.

Figure 23. "Plunging Jet" Depth as a Function of Downcomer Diameter



The M-Star® CFD simulations performed provide an estimate of the mass of solid particles disturbed and can aid in determining whether the SWPF WAC is exceeded at liquid levels of less than 120 inches. There is uncertainty in these simulations. Some of this uncertainty results from numerical transport and the spacing between lattice points. In the simulations described above, the the lattice spacing was set to have 5 lattice points across the "plunging jet" diameter at the liquid surface. A larger lattice spacing was used away from the jet and at the vessel walls. This larger spacing may have led to increased numerical transport and the downward fluid velocities observed near the vessel walls.

Following discussions with M-Star®, an additional simulation was performed with a 3 ft diameter vessel, 7 lattice points across the jet diameter, and a constant lattice spacing. Figure 24 shows the results. The shape of the "plunging jet" is consistent with Equations [1] – [5] and the technical literature.[6,7,8] While the finer lattice spacing increases the time to perform these simulations, the results show better agreement with the technical literature. Future work investigating the disturbance of solid particles from the addition of liquid to a tank should use a finer, constant lattice spacing to model "plunging jets". Because of the longer simulation time that will be needed, a smaller, more focused set of operating parameters should be selected for those simulations.

Figure 24. M-Star Simulation of "Plunging Jet" with Constant Lattice Spacing

3.0 Conclusions

The analysis showed that with a solid particle size of 10 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 the particle size is 100 micron or larger, the liquid level in the tank can be reduced to as low as 80 inches. At this level, the larger particles will be disturbed, but they will settle to the tank bottom before reaching the transfer pump. Since a large fraction of the solid particles in Tank 49 are expected to be less than 10 microns based on previous analyses of SRS sludge particle size which measured median particle sizes of 2.6, 6.1, 10.8, and 15.1 microns, the 120-inch liquid level is recommended at this time.

Calculations of the dilution that will occur with the liquid above the solid particles as they are disturbed and blending that will occur as they are transported to the transfer pump suggest that their concentration may be below the SWPF WAC with liquid levels between 100 – 120 inches. SRNL and SRR should review the details of the planned transfers to determine whether these calculations can be used to justify a lower liquid level in Tank 49H. Depending on the solid particle size, significant particle settling could occur between transfers. Following the first transfer to SWPF for each batch, the concentration of insoluble solids in the transfer will likely decrease.

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

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 (~1,000,000 gallons), significant particle settling could occur, which may prevent exceeding the SWPF WAC limits for insoluble solids, but the settling is dependent on the size of the particles at the bottom of Tank 49H.

If Savannah River Remediation 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.

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

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