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Retention:
Permanent

TANK 32 EVAPORATOR FEED PUMP TRANSFER ANALYSIS

D.A. Tamburello
R.A. Dimenna
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JANUARY 2009

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

Prepared for the U.S. Department of Energy Under
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DISCLAIMER

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

A_{scour}	Area of scour
C	Empirical parameter for the Weber number
CFD	Computational fluid dynamics
d_{imp}	Impinging diameter
d_o	Orifice diameter
d_p	Particle diameter
g	Acceleration due to gravity
h	Tank liquid level (above the sludge layer)
H	Plunge height
L_c	Jet break-up length; $L_c = C \cdot d_o \cdot We^{\frac{1}{2}}$
Q_o	Volumetric flow rate
SRNL	Savannah River National Laboratory
t_{turbid}	Thickness of the turbid region
UDS	Undissolved solids
V_{min}	Minimum particle scour velocity; $V_{\min} = \left(\frac{d_p}{h}\right)^{-0.1} \cdot \sqrt{2.5 \cdot g \cdot d_p \cdot \left(\frac{\rho_p}{\rho_f} - 1\right)}$
V_{imp}	Impinging velocity; $V_{imp} = \sqrt{V_o^2 + 2 \cdot g \cdot H}$
V_o	Orifice velocity
V_{total}	Total velocity magnitude; $V_{total} = \sqrt{V_x^2 + V_y^2 + V_z^2}$
V_x	x-component of velocity
V_y	y-component of velocity
V_z	z-component of velocity
Vol_{scour}	Volume of scour
Vol_{tank}	Volume of the supernate in the tank (above the cohesive sludge layer)
We	Weber number; $We = \frac{\rho_f \cdot V_o^2 \cdot d_o}{\sigma}$
ρ_f	Fluid density
ρ_p	Particle density
σ	Fluid surface tension

1.0 EXECUTIVE SUMMARY

The transfer of liquid salt solution from Tank 32 to an evaporator is to be accomplished by activating the evaporator feed pump, with the supernate surface at a minimum height of approximately 74.4 inches above the sludge layer, while simultaneously turning on the downcomer with a flow rate of 110 gpm. Previously, activation of the evaporator feed pump was an isolated event without any other components running at the same time. An analysis of the dissolved solution transfer has been performed using computational fluid dynamics (CFD) methods to determine the amount of entrained sludge solids pumped out of the tank toward the evaporator with the downcomer turned on.

The analysis results shows that, for the minimum tank liquid level of 105 inches above the tank bottom (which corresponds to a liquid depth of 74.4 inches above the sludge layer), the evaporator feed pump will contain less than 0.1 wt% sludge solids in the discharge stream, which is an order of magnitude less than the 1.0 wt% undissolved solids (UDS) loading criteria to feed the evaporator. Lower liquid levels with respect to the sludge layer will result in higher amounts of sludge entrainment due to the increased plunging jet velocity from the downcomer disturbing the sludge layer.

2.0 INTRODUCTION

Tank 32 is a feed tank to transfer supernate to another tank or to an evaporator. The discharge stream must contain less than a maximum weight percent of sludge solids at any time during the transfer. An analysis of the tank during the liquid transfer to the evaporator has been performed using computational fluid dynamics (CFD) methods to estimate the amount of sludge drawn from Tank 32 through the evaporator feed pump when the downcomer is activated during the transfer process.

Figure 2.1 provides a sketch (not to scale) of the tank when filled to its maximum allowable height (above the downcomer exit). The tank consists of a supernate solution with a settled sludge layer at the bottom of the tank that is approximately 30.6 inches deep. The sludge layer contains 20 vol.% UDS less than 1 μm [1, 2] in diameter. The supernate level can range from a maximum height of 372 inches above the tank bottom to a minimum height of 105 inches, which is required to maintain the proper pressure head for the feed pump. The feed pump suction height is 89 inches above the bottom of the tank and has a draw flow rate of 3 to 40 gpm. The downcomer is located 344.6 inches above the tank bottom and has a flow rate of approximately 110 gpm.

Under normal conditions, the downcomer would first add liquid to Tank 32. Then, after any sludge particulate that had been stirred up by the downcomer had been allowed to resettle to

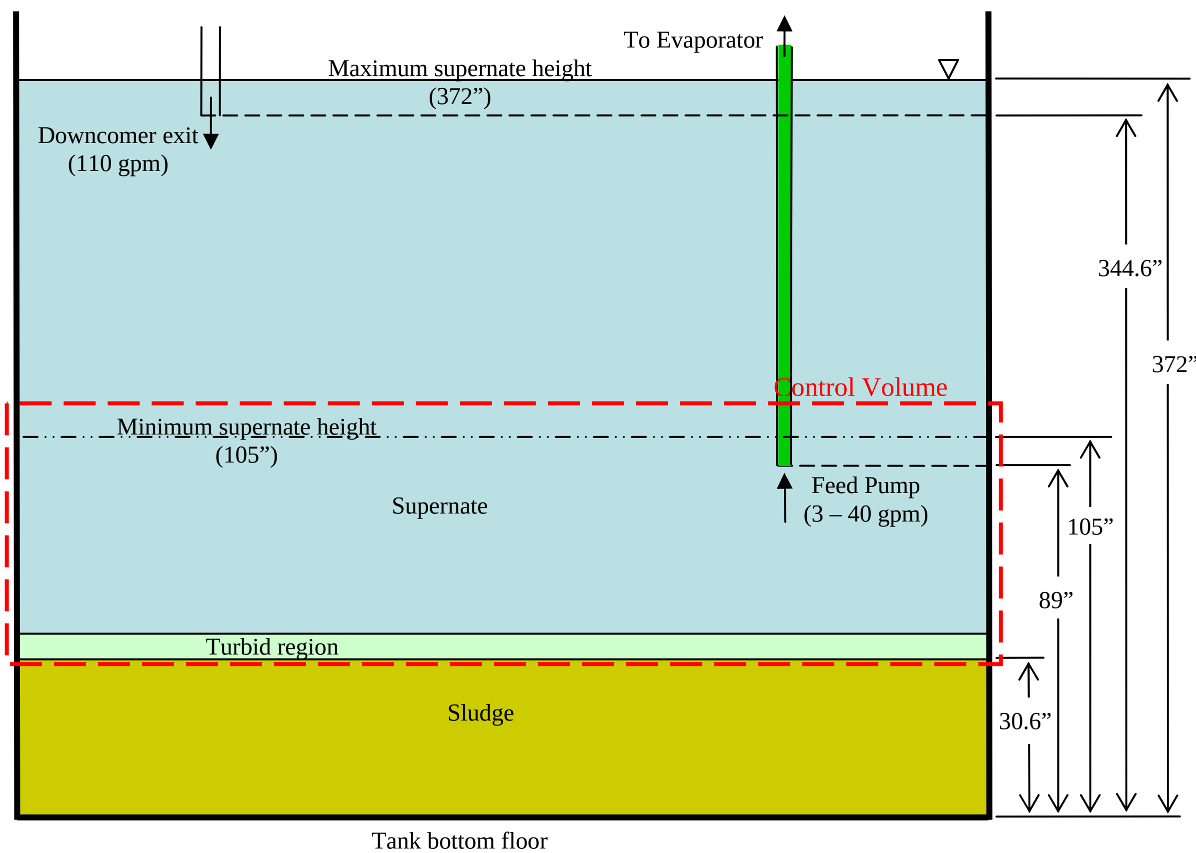

Figure 2.1. Two-dimensional sketch of the Tank 32 basic geometry. Not to scale.

the bottom of the tank, the feed pump would be activated to transfer supernate to the evaporator. A limit of 1.0 wt.% sludge undissolved solids (UDS) is imposed on fluid drawn out of Tank 32 through the feed pump eductor for transfers to the evaporator [3]. As a time-saving (and cost-saving) measure, it has been proposed that both the downcomer and the feed pump could be activated simultaneously without violating the sludge limit of 1.0 wt%.

The following analysis will determine the weight-percentage of sludge UDS drawn into the feed pump when both the feed pump and the downcomer are operating (at steady state) at 40 and 110 gpm, respectively. In the following analysis, the supernate height is 105 and 120 inches above the tank bottom. Besides the absolute minimum allowable supernate level just mentioned, the minimum supernate height ever recorded during a transfer is 120 inches [3] above the tank bottom.

3.0 METHODOLOGY

The downcomer and feed pump are located asymmetrically within Tank 32, which makes a three-dimensional model appropriate for this calculation. The governing equations solved for each analysis included a mass balance, the three-dimensional momentum equations, and two turbulence equations. The standard, two-equation, k-ε model was used to estimate the fluid turbulence. Figure 2.1 provides a sketch (not to scale) of the tank that was modeled using the FLUENT™ CFD code, while Table 3.1 lists the modeling conditions that were used.

A three-dimensional view of the CFD model is provided in Figure 3.1. The modeling domains for the supernate levels of 105 (case 1) and 120 (case 2) inches are made of approximately 850,000 and 1,000,000 grid elements, respectively. In each domain, the grid points are densely distributed near the downcomer and the feed pump to better capture the flow field in these areas.

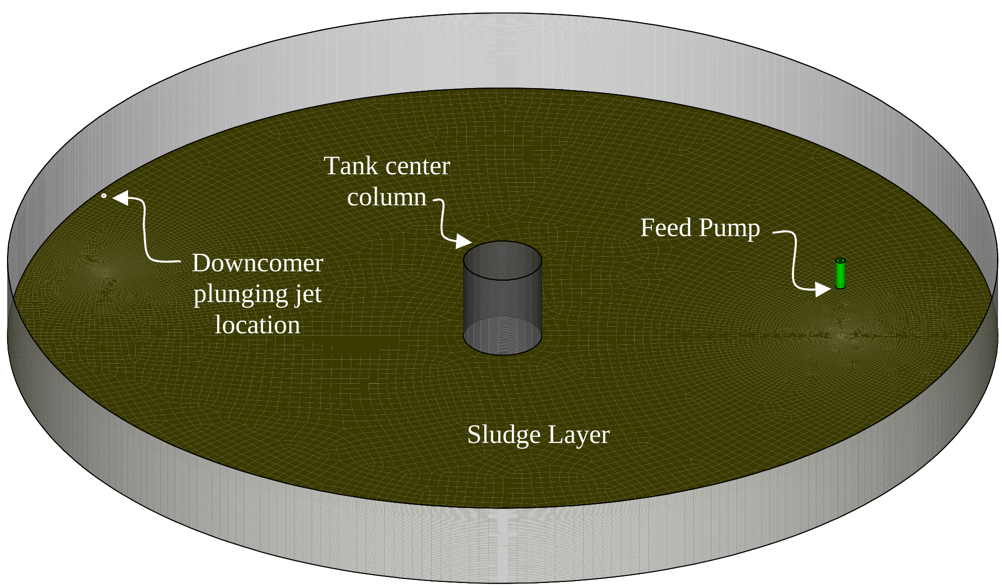

Figure 3.1. Three-dimensional model of the liquid domain.

Table 3.1. Modeling conditions used for the calculations.

Parameter	Absolute Min. Level Case 1 -- 105 in	Recorded Min. Level Case 2 -- 120 in
Supernate liquid level above the sludge layer (h)	74.4 in (1.89 m)	89.4 in (2.27 m)
Sludge layer at tank bottom	30.6 in tank level	30.6 in tank level
Downcomer jet flow rate (Q_o)	110 gpm	110 gpm
Downcomer exit diameter (d_o) [4]	3 in SCH 10S Pipe (3.26 in ID)	3 in SCH 10S Pipe (3.26 in ID)
Downcomer exit velocity (V_o)	4.23 ft/s (1.29 m/s)	4.23 ft/s (1.29 m/s)
Downcomer plunge jet height to the liquid surface (H) [5]	239.6 in (6.10 m)	224.6 in (5.70 m)
Downcomer jet break-up length (L_c)	309 in – 374 in (7.85 m – 9.50 m)	309 in – 374 in (7.85 m – 9.50 m)
Downcomer plunge jet diameter (d_{imp}) at the air-liquid interface	1.12 in (28.3 mm)	1.13 in (28.8 mm)
Downcomer plunge jet velocity (V_{imp}) at the air-liquid interface	36.1 ft/s (11.0 m/s)	35.0 ft/s (10.7 m/s)
Feed pump suction rate (Q_o)	40 gpm	40 gpm
Feed pump diameter (d_o) [3]	3.0 in (76.2 mm)	3.0 in (76.2 mm)
Feed pump velocity (V_o)	-1.82 ft/s (0.553 m/s)	-1.82 ft/s (0.553 m/s)

Note: Flow rates are set to the highest values for the feed pump, which has a range of 3 – 40 gpm [6].

The following conditions, in coordination with Table 3.1, were used to analyze Tank 32:

- Only the liquid within Tank 32 is modeled. Particle motions are inferred based on the velocity field and the interactions (entrainment, settling, etc.) that would occur because of those velocities.
- Flow rates for the feed pump are set to the highest value of 40 gpm out of its operating range of 3 to 40 gpm [6].
- The downcomer flow is treated as a plunging jet, as described in the literature [4].
- Tank 32 contains primarily cohesive, densely-packed sludge, with a turbid layer approximately 6 inches deep of loosely-packed solids above the sludge layer [3].
- Based on sampling test results for Tank 40 sludge Batch 3 [2], the typical range of particulate diameters is between 0.1 and 25 μm, with approximately 20 vol.% of the sludge distribution consisting of particles less than 1 μm in diameter.

The following assumptions were made to create this model:

- Internal tank structures (piping, etc.) are not included for simplification [7].
- The surface waves and instabilities at the supernate surface were neglected, with a pressure outlet boundary condition of atmospheric pressure at the free surface.

- The liquid volume in Tank 32 is assumed to stay relatively constant during the transfer process because the downcomer, which adds liquid at 110 gpm, will increase the fluid height by a maximum of 0.031 inches per minute.
- The fluid properties over the entire region of the tank are the same, with the supernate treated as water at 20°C in the calculation. Previous calculations [8] have shown very little sensitivity to fluid temperature in the resulting flow patterns. Therefore, any reasonable temperature is acceptable for the isothermal calculation.
- The sludge layer is modeled as a solid, level surface with a free slip condition.
- Loosely-packed sludge solids in the turbid region are assumed to contain approximately 99 wt% supernate and 1 wt% UDS.
- Sample results from the sludge in Tank 40 [2] provide the best representation of the sludge in Tank 32 as no sample data is available at this time.
- The turbid region is treated as part of the tank liquid space; it is modeled as water without any sludge particles.
- Solids in the sludge layer are homogeneously distributed and are picked up into the flow when the local velocity at the sludge layer surface (at the solid boundary) exceeds the minimum scour velocity required to transport sludge solids.
- The liquid in Tank 32 is homogeneously mixed based on previous results [1] and the resulting flow patterns.

The working fluid for the following analysis is water because of its similar properties to those of supernate [8]. Previous work [1] has shown negligible differences in the calculated flow fields between supernate and water.

If the fluid velocity is too low to break the bonds between cohesively packed sludge solids, then the sludge will appear as a solid surface to the fluid. Conversely, loosely-packed solids along the sludge surface may follow the fluid in a pure slip fashion. The sludge in Tank 32 is primarily composed of cohesive, densely-packed solids, with a loosely-packed turbid layer (approximately 6 inches deep) along the top of the sludge layer [3]. According to laboratory testing [9], the turbidity probes used in the tank farm can reach their maximum values with as little as 0.4 wt% sludge particles and is unable to measure higher values within the supernate. Thus, the turbid layer could have a wide range of values.

Because the turbid region is not well defined, it cannot be accurately modeled. Instead, several limiting assumptions (as listed above) were employed in the current analysis. A free slip boundary is used at the sludge surface to maximize the velocity at the bottom of the tank. The liquid flow over the sludge region will entrain all UDS that would be suspended by the calculated velocity. For example, a velocity sufficient to entrain 1 μm particles will entrain the entire population of particles that are smaller than or equal to 1 μm within the affected volume. Particles larger than 1 μm are assumed to continue to settle. Given the inactivity of Tank 32, the sludge content of the turbid region is estimated to be 1 wt% particulate with a representative size of 1 μm in diameter.

In the present study, the sludge solids are not removed from the sludge layer (scoured) unless the liquid velocity at the sludge surface is greater than the minimum velocity (V_{min}) necessary to entrain particles from the top of the sludge layer. According to the literature [8, 10], the minimum scouring velocity for cohesive sludge solids is 0.7 m/s (2.27 ft/s). When the solids are loosely-packed, as in the 6-inch turbid layer, the scouring velocity depends upon several factors as described in the following empirical correlation published by Graf [11] using data from the literature.

$$V_{\min} = \left(\frac{d_p}{h}\right)^{-0.1} \cdot \sqrt{2.5 \cdot g \cdot d_p \cdot \left(\frac{\rho_p}{\rho_f} - 1\right)}, \tag{3.1}$$

where d_p is the particle diameter, h is the tank liquid level (above the sludge layer), g is the acceleration due to gravity, ρ_p is the density of the sludge particulate, and ρ_f is the density of the fluid. Typical values of the density ratio (ρ_p / ρ_f) for water and supernate are 2.5 and 1.67, respectively. Minimum scouring velocities for sludge particles ranging between 0.1 and 25.0 μm in diameter is provided in Table 3.2 because these are the typical particle sizes in the sludge and turbid regions in the tanks at SRS, including Tank 32 [1, 2].

Table 3.2. Minimum velocities (V_{min}) of supernate required to entrain loosely-packed solid particles from a solid surface.

Particle size	Case 1 -- 105 in	Case 2 -- 120 in
0.1 μm	0.0252 ft/s (0.00768 m/s)	0.0250 ft/s (0.007632 m/s)
0.5 μm	0.0480 ft/s (0.0146 m/s)	0.0477 ft/s (0.0145 m/s)
1.0 μm	**0.0633 ft/s (0.0193 m/s)**	**0.0629 ft/s (0.0192 m/s)**
5.0 μm	0.121 ft/s (0.0367 m/s)	0.120 ft/s (0.0365 m/s)
10.0 μm	0.159 ft/s (0.0485 m/s)	0.158 ft/s (0.0482 m/s)
15.0 μm	0.187 ft/s (0.0570 m/s)	0.186 ft/s (0.0567 m/s)
20.0 μm	0.210 ft/s (0.0640 m/s)	0.209 ft/s (0.0636 m/s)
25.0 μm	0.230 ft/s (0.0700 m/s)	0.228 ft/s (0.0695 m/s)
Cohesive sludge [8, 10]	2.27 ft/s (0.692 m/s)	2.27 ft/s (0.692 m/s)

According to the literature [1, 2], submicron particles such as 0.1 μm solids do not settle readily since Brownian motion becomes significant for particles with diameters less than 0.5 μm. SRNL test results [2] show that approximately 20 vol.% of sludge for Tank 40 Batch 3 consists of particles less than 1 μm in diameter. Sample results from Tank 40 have been identified as the best source of data available, as no specific sludge data exists for Tank 32 at this time. Thus, the present study assumes a representative particle size of 1 μm in diameter as a conservative estimate of the sludge layer solids.

The downcomer discharges vertically downward into the air as a free jet before impacting the liquid surface as a plunging jet. A liquid free jet will leave the jet exit as a column but will eventually lose coherence and break apart downstream below the nozzle exit. Sallam *et al.* [12] published the following correlation for this distance, known as the break-up length (L_c), for a water jet in air.

$$L_c = C \cdot d_o \cdot We^{\frac{1}{2}}, \tag{3.2}$$

where d_o is the jet exit diameter, We is the jet Weber number, and C is an empirical parameter having a magnitude on the order of unity. For liquid jets with a Weber of 670 – 13,700 (We = 1780 for the downcomer in both cases), C is equal to 2.1 with a standard deviation of 0.2 [12]. From Equation (3.2), the break-up length ranges from 309 to 374 inches for both cases. Thus, the downcomer—which has jet plunge heights of 239.6 inches (case 1) and 224.6 inches (case 2)—should remain a column until impacting the liquid surface.

The plunging jet velocity is derived from conservation of energy via the free fall equation.

$$V_{imp} = \sqrt{V_o^2 + 2 \cdot g \cdot H}\ , \tag{3.3}$$

where V_o is the velocity at the jet exit. The time-averaged plunging jet diameter (d_{imp}) can then be found using the conservation of mass.

$$d_{imp} = \sqrt{\frac{4}{\pi} \cdot \frac{Q_o}{V_{imp}}}\ , \tag{3.4}$$

where Q_o is the volumetric flow rate leaving the jet exit.

In the present work, the weight percentage of sludge solids will be predicted from the ratio of the volume of sludge (Vol_{scour}) to the volume of supernate (Vol_{tank}) for a conservative evaluation of the sludge carryover during the operation of the feed pump and the downcomer. The volume of sludge is calculated as the area at the bottom of the tank with a total velocity higher than the minimum scour velocity times the depth of loosely-packed sludge solids. This procedure is shown in greater detail in the authors' previous work [5].

4.0 CALCULATIONS AND RESULTS

The following results examine models where the supernate height corresponds to the absolute minimum (case 1, 105 inches from the tank bottom) and the recorded minimum (case 2, 120 inches from the tank bottom) levels.

Figure 4.1 shows a sketch (not to scale) of the flow patterns created by the downcomer's plunging jet and the suction from the feed pump. Depending upon the supernate level, liquid from the downcomer falls between 224.6 inches (5.70 m) and 239.6 inches (6.10 m) before impacting the supernate with a velocity of 35.0 ft/s (10.7 m/s) to 36.1 ft/s (11.0 m/s), respectively. At this range of impact velocities, the downcomer flow maintains much of its strength as it plunges through the supernate to the sludge layer 74.4 inches (1.89 m) to 89.4 inches (2.27 m) below. At the sludge layer, the fluid scours UDS (from the sludge layer where the fluid velocity is greater than V_{min}) as it flows outward in all directions until it reaches the tank walls. The fluid then flows up the wall and along the supernate surface until it is entrained back downward toward the bottom of the tank. In this manner, large recirculation regions are formed that essentially mix the tank, spreading any scoured particulate throughout the tank.

The steady-state flow pattern near the feed pump corresponding to the red dashed box within Figure 4.1 is shown in Figure 4.2. Here the color of the velocity vector corresponds to the

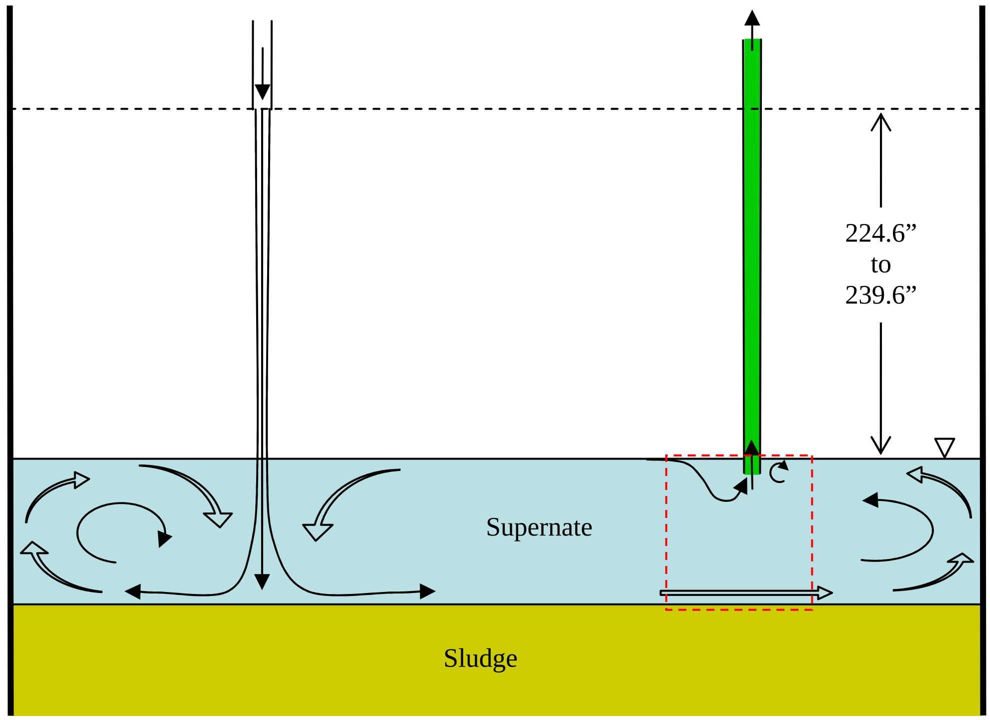

Figure 4.1. Two-dimensional sketch of the flow patters produced by the downcomer plunging jet and the feed pump. Not to scale.

total velocity magnitude (V_{total}). Note that the color scale is skewed low to accentuate the low velocity magnitudes in this region and that arrows have been included throughout Figure 4.2 to show its similarity to Figure 4.1. While still showing some influence from the feed pump, the velocity vectors more than twelve pipe diameters downstream of the orifice are no longer drawn toward the feed pump but instead continue in a horizontal direction. In addition, all of the fluid traveling into the feed pump can be traced back to the supernate surface, as is also shown in Figure 4.3. The flow tracers in Figure 4.3 provide additional evidence that the fluid leaving the tank is drawn from the upper half of the supernate above the sludge layer, particularly from the supernate surface on the downcomer side. These results are typical for both cases 1 and 2.

There are two main points that can be made from Figures 4.1 through 4.3. First, the recirculation regions mix the tank fairly well so that any solids that are scoured from the sludge layer will be spread throughout the tank. Second, the fluid entering the feed pump originates from the supernate surface because of the recirculation regions rather than the sludge layer directly.

Figures 4.4a and b present the total velocity contours at the sludge layer for cases 1 and 2, respectively. The highest velocities at the sludge layer are found below the downcomer, with values of 1.9 ft/s (0.58 m/s) and 1.57 ft/s (0.48 m/s), respectively. Neither of these values reaches the minimum scour velocity of 2.27 ft/s (0.7 m/s) necessary to scour cohesive, densely-packed particles. However, as shown in Table 3.2, both of these values are more than enough to disturb and entrain the loosely-packed unsettled solids in the turbid region above the sludge layer.

From laboratory turbidity measurements [3, 9] and past experience [5], this layer is estimated to be approximately 6 inches deep and have a solids weight-percentage on the order of 1%. Using the minimum scour velocities from Table 3.2 with the velocities contours in Figure 4.4, an area of scour (A_{scour}) can be found. The area of scour represents the area along the sludge surface with the minimum scour velocity (V_{min}) necessary to entrain particles of a given size. The volume of scour (Vol_{scour}) is then calculated by multiplying A_{scour} by the thickness of the turbid region (t_{turbid}). For a well-mixed tank, the volume fraction of sludge entrained from the turbid region can be estimated by dividing the Vol_{scour} by the tank volume and multiplying the result by the assumed weight fraction of UDS within the turbid region. Using the characteristic particle size of 1 μm and the assumed 1 wt% of particulate within the turbid region, the evaporator feed transfer from Tank 32 will contain approximately 0.061 vol%, or 0.102 wt%, sludge particles for case 1 and approximately 0.047 vol%, or 0.079 wt%, sludge particles for case 2. Tables 4.1 and 4.2 provide additional values based on several characteristic particle diameters within the turbid region.

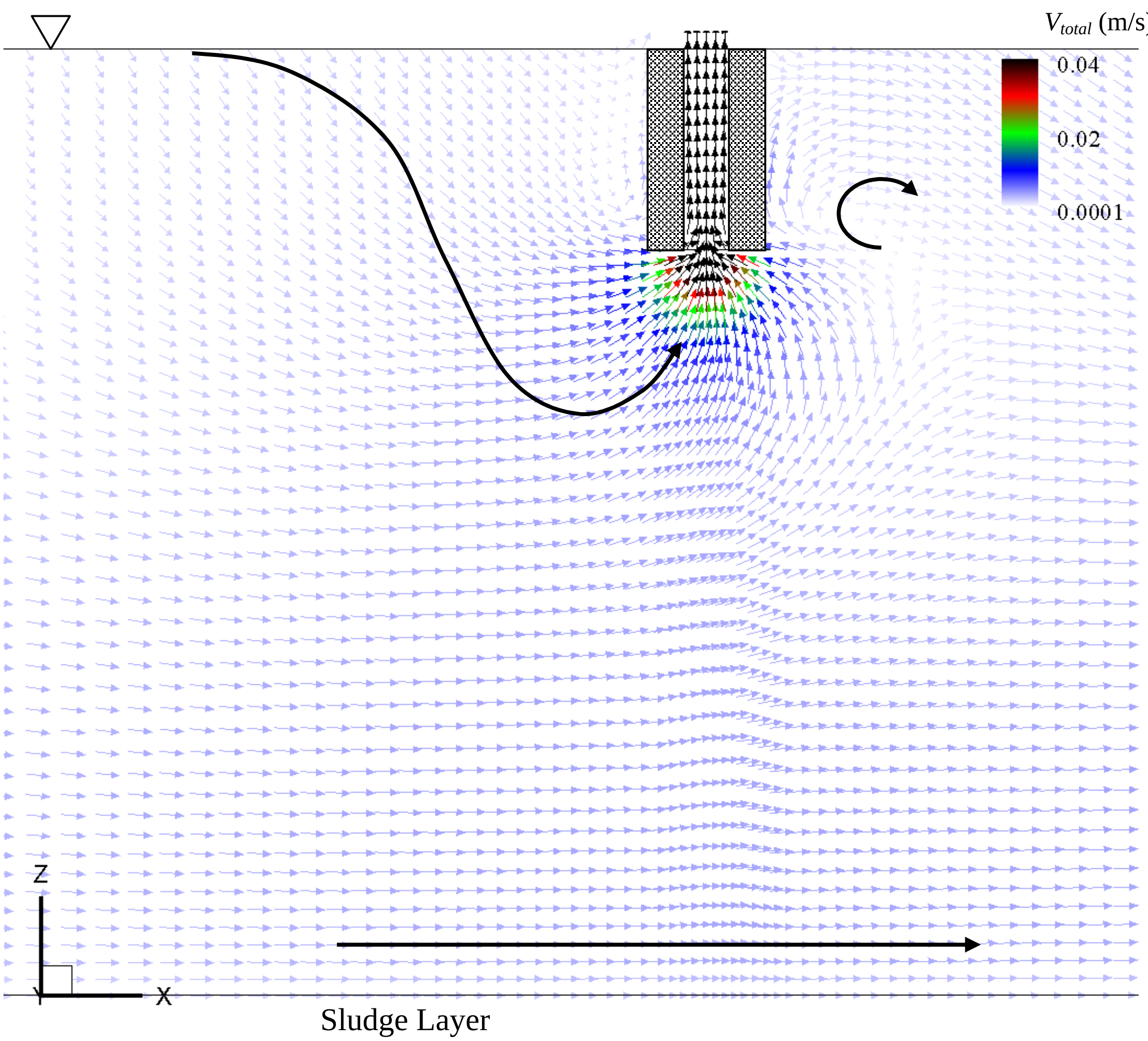

Figure 4.2. Velocity vector field showing the flow patterns at the feed pump suction corresponding to the red dashed box in Figure 4.1. Case 1 – supernate level at 105 in.

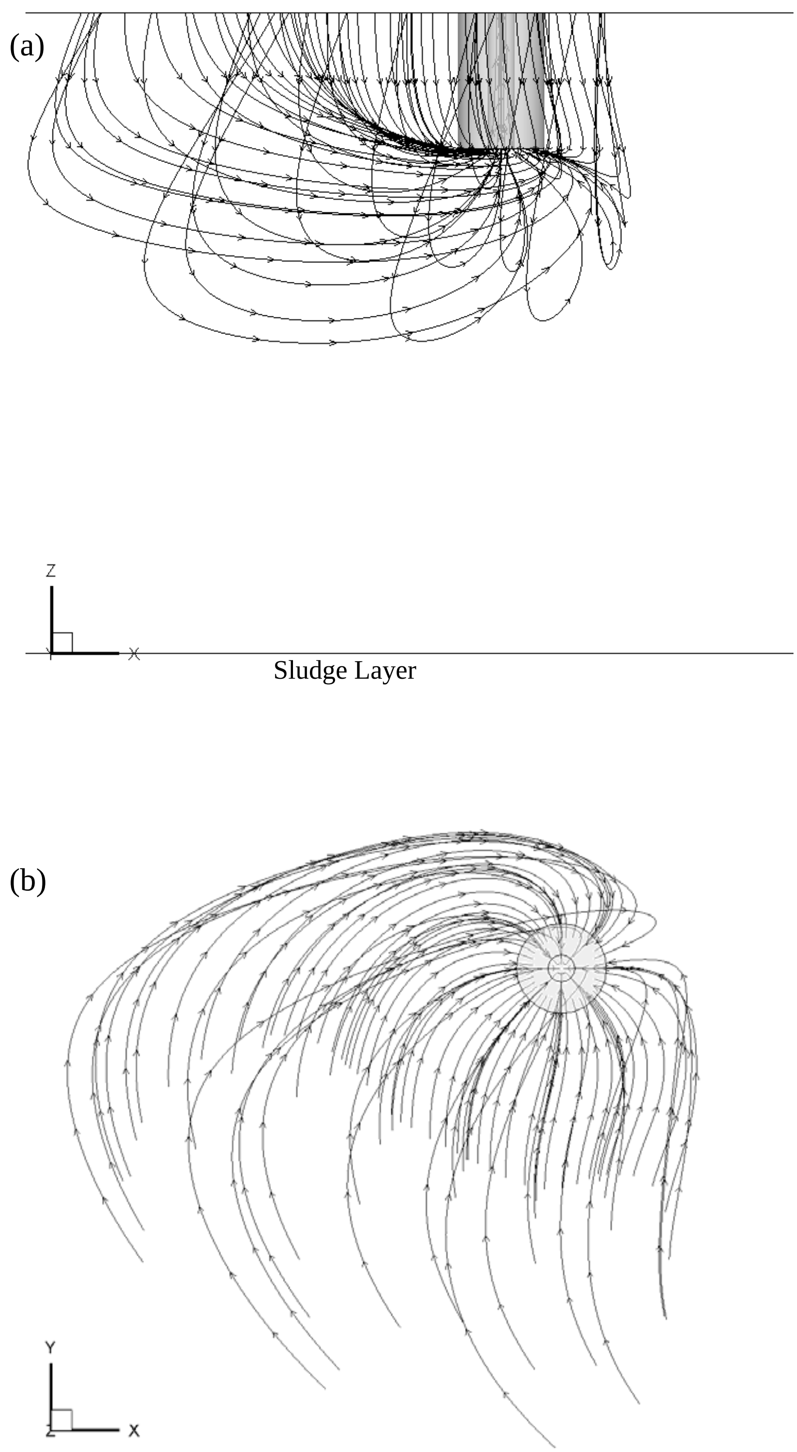

Figure 4.3. Flow tracers for the fluid flow leaving Tank 32 through the feed pump suction. Side (a) and top (b) views. Case 1 – supernate level at 105 in.

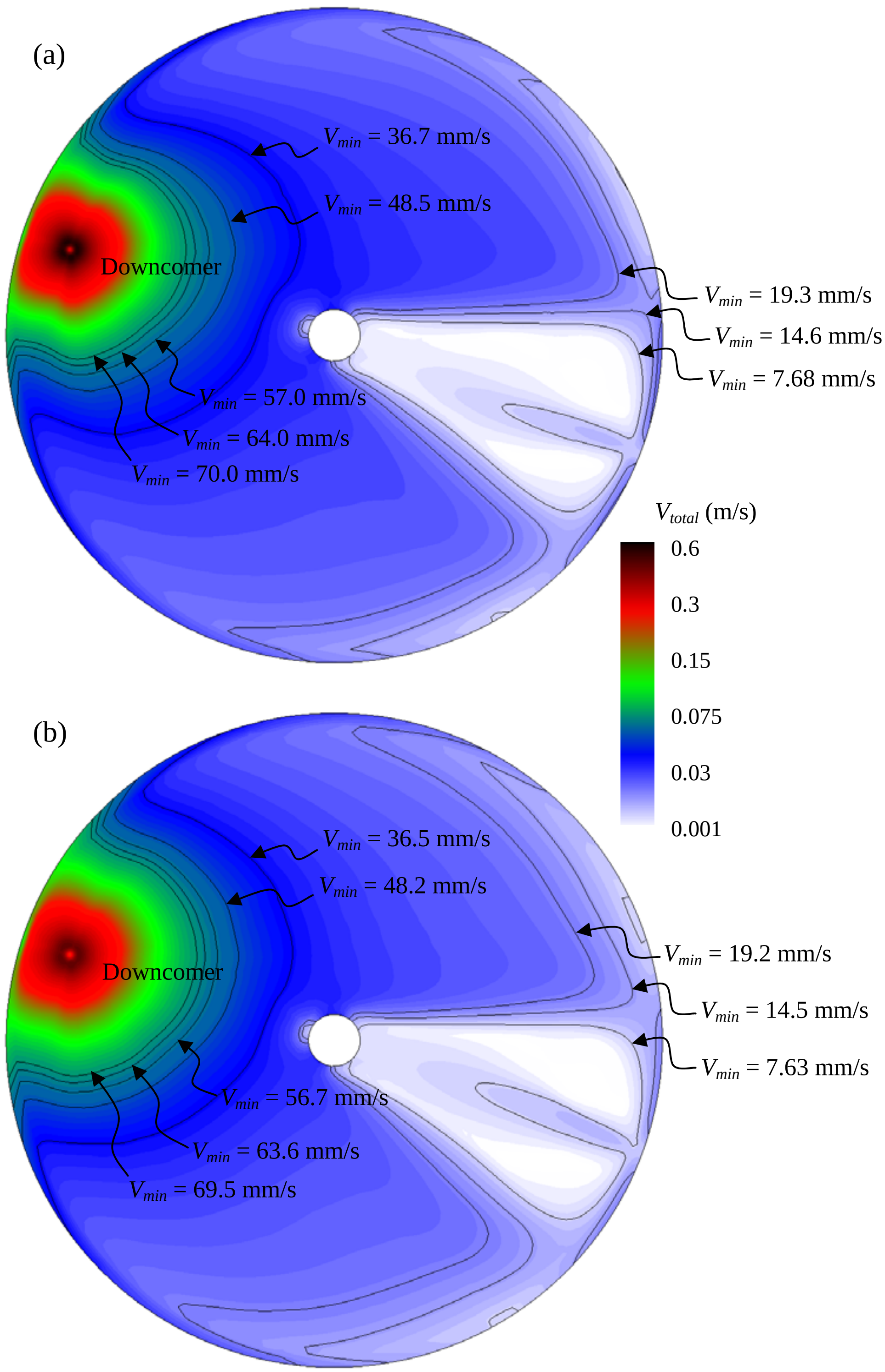

Figure 4.4. Total velocity contours at the sludge layer for Case 1 – supernate level at 105 in (a) and Case 2 – supernate level at 120 in (b).

Table 4.1. Volume- and weight-percentage of UDS drawn out of the tank by the feed pump based on 1.0 wt% particulate within the turbid region for Case 1 – supernate level at 105 in.

Characteristic Particle Size	V_{min}	A_{scour}	Vol_{scour}	Vol% sludge	Wt% sludge
0.1 μm	0.302 in/s (7.68 mm/s)	5,070 ft^2 (471 m^2)	2,540 ft^3 (71.8 m^3)	0.0726%	0.121%
0.5 μm	0.576 in/s (14.6 mm/s)	4,670 ft^2 (434 m^2)	2,330 ft^3 (66.1 m^3)	0.0668%	0.112%
1.0 μm	0.760 in/s (19.3 mm/s)	4,260 ft^2 (396 m^2)	2,130 ft^3 (60.3 m^3)	0.0609%	0.102%
5.0 μm	1.45 in/s (36.7 mm/s)	1,210 ft^2 (113 m^2)	605 ft^3 (17.1 m^3)	0.0173%	0.0289%
10.0 μm	1.91 in/s (48.5 mm/s)	770 ft^2 (71.5 m^2)	385 ft^3 (10.9 m^3)	0.0110%	0.0184%

Table 4.2. Volume- and weight-percentage of UDS drawn out of the tank by the feed pump based on 1.0 wt% particulate within the turbid region for Case 2 – supernate level at 120 in.

Characteristic Particle Size	V_{min}	A_{scour}	Vol_{scour}	Vol% sludge	Wt% sludge
0.1 μm	0.300 in/s (7.63 mm/s)	5,070 ft^2 (471 m^2)	2,540 ft^3 (71.8 m^3)	0.0604%	0.101%
0.5 μm	0.572 in/s (14.5 mm/s)	4,490 ft^2 (417 m^2)	2,240 ft^3 (63.5 m^3)	0.0534%	0.0892%
1.0 μm	0.755 in/s (19.2 mm/s)	3,950 ft^2 (367 m^2)	1,970 ft^3 (55.9 m^3)	0.0470%	0.0785%
5.0 μm	1.44 in/s (36.5 mm/s)	1,280 ft^2 (119 m^2)	638 ft^3 (18.1 m^3)	0.0152%	0.0254%
10.0 μm	1.90 in/s (48.2 mm/s)	850 ft^2 (79.0 m^2)	425 ft^3 (12.0 m^3)	0.0101%	0.0169%

5.0 CONCLUSIONS

The preceding analysis of Tank 32 was based on the following conditions, in coordination with Table 3.1:

- Only the liquid within Tank 32 is modeled. Particle motions are inferred based on the velocity field and the interactions (entrainment, settling, etc.) that would occur because of those velocities.
- Flow rates for the feed pump are set to the highest value of 40 gpm out of its operating range of 3 to 40 gpm [6].
- The downcomer flow is treated as a plunging jet, as described in the literature [4].
- Tank 32 contains primarily cohesive, densely-packed sludge, with a turbid layer approximately 6 inches deep of loosely-packed solids above the sludge layer [3].
- Based on sampling test results for Tank 40 sludge Batch 3 [2], the typical range of particulate diameters is between 0.1 and 25 μm, with approximately 20 vol.% of the sludge distribution consisting of particles less than 1 μm in diameter.

The preceding analysis was also based on the following assumptions:

- Internal tank structures (piping, etc.) are not included for simplification [7].
- The surface waves and instabilities at the supernate surface were neglected, with a pressure outlet boundary condition of atmospheric pressure at the free surface.
- The liquid volume in Tank 32 is assumed to stay relatively constant during the transfer process because the downcomer, which adds liquid at 110 gpm, will increase the fluid height by a maximum of 0.031 inches per minute.
- The fluid properties over the entire region of the tank are the same, with the supernate treated as water at 20^{o}C in the calculation. Previous calculations [8] have shown very little sensitivity to fluid temperature in the resulting flow patterns. Therefore, any reasonable temperature is acceptable for the isothermal calculation.
- The sludge layer is modeled as a solid, level surface with a free slip condition.
- Loosely-packed sludge solids in the turbid region are assumed to contain approximately 99 wt% supernate and 1 wt% particulate.
- Sample results from the sludge in Tank 40 [2] provide the best representation of the sludge in Tank 32 as no sample data is available at this time.
- The turbid region is treated as part of the tank liquid space; it is modeled as water without any sludge particles.
- Solids in the sludge layer are homogeneously distributed and are picked up into the flow when the local velocity at the sludge layer surface (at the solid boundary) exceeds the minimum scour velocity required to transport sludge solids.
- The liquid in Tank 32 is homogeneously mixed based on previous results [1] and the resulting flow patterns.

From these conditions and assumptions, the feed pump will draw less than 0.1 wt% sludge solids out of Tank 32 into the eductor during the supernate transfer to an evaporator with the downcomer releasing 110 gpm as long as the tank liquid level remains higher than 105 inches above the tank bottom and higher than 74.5 inches above the sludge layer. This is an order of magnitude less than the transfer requirement of 1.0 wt% UDS. Comparing the tank liquid levels at 105 inches and 120 inches above the tank bottom (74.5 inches and 89.5 inches above the sludge layer, respectively), higher tank liquid levels result in lower amounts of sludge entrainment due to the decreased plunging jet velocities as well as the increased dissipation depth.

6.0 REFERENCES

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APPENDIX A. ADDITIONAL TURBIDITY CALCULATIONS

Because very little is known about the turbid region, additional calculations were performed for both cases discussed in this work. In these calculations, the wt% particulate within the turbid region was varied between 0.1 and 10.0 wt%. The results of these calculations are found in Tables A.1 – A.8.

Table A.1. Volume- and weight-percentage of UDS drawn out of the tank by the feed pump based on 0.1 wt% particulate within the turbid region for Case 1 – supernate level at 105 in.

Characteristic Particle Size	V_{min}	A_{scour}	Vol_{scour}	Vol% sludge	Wt% sludge
0.1 μm	0.302 in/s (7.68 mm/s)	5,070 ft^2 (471 m^2)	2,540 ft^3 (71.8 m^3)	0.0073%	0.0121%
0.5 μm	0.576 in/s (14.6 mm/s)	4,670 ft^2 (434 m^2)	2,330 ft^3 (66.1 m^3)	0.0067%	0.0112%
1.0 μm	0.760 in/s (19.3 mm/s)	4,260 ft^2 (396 m^2)	2,130 ft^3 (60.3 m^3)	0.0061%	0.0102%
5.0 μm	1.45 in/s (36.7 mm/s)	1,210 ft^2 (113 m^2)	605 ft^3 (17.1 m^3)	0.0017%	0.0029%
10.0 μm	1.91 in/s (48.5 mm/s)	770 ft^2 (71.5 m^2)	385 ft^3 (10.9 m^3)	0.0011%	0.0018%

Table A.2. Volume- and weight-percentage of UDS drawn out of the tank by the feed pump based on 0.5 wt% particulate within the turbid region for Case 1 – supernate level at 105 in.

Characteristic Particle Size	V_{min}	A_{scour}	Vol_{scour}	Vol% sludge	Wt% sludge
0.1 μm	0.302 in/s (7.68 mm/s)	5,070 ft^2 (471 m^2)	2,540 ft^3 (71.8 m^3)	0.0363%	0.0606%
0.5 μm	0.576 in/s (14.6 mm/s)	4,670 ft^2 (434 m^2)	2,330 ft^3 (66.1 m^3)	0.0334%	0.0558%
1.0 μm	0.760 in/s (19.3 mm/s)	4,260 ft^2 (396 m^2)	2,130 ft^3 (60.3 m^3)	0.0305%	0.0509%
5.0 μm	1.45 in/s (36.7 mm/s)	1,210 ft^2 (113 m^2)	605 ft^3 (17.1 m^3)	0.0087%	0.0145%
10.0 μm	1.91 in/s (48.5 mm/s)	770 ft^2 (71.5 m^2)	385 ft^3 (10.9 m^3)	0.0055%	0.0092%

Table A.3. Volume- and weight-percentage of UDS drawn out of the tank by the feed pump based on 5.0 wt% particulate within the turbid region for Case 1 – supernate level at 105 in.

Characteristic Particle Size	V_{min}	A_{scour}	Vol_{scour}	Vol% sludge	Wt% sludge
0.1 µm	0.302 in/s (7.68 mm/s)	5,070 ft^2 (471 m^2)	2,540 ft^3 (71.8 m^3)	0.363%	0.606%
0.5 µm	0.576 in/s (14.6 mm/s)	4,670 ft^2 (434 m^2)	2,330 ft^3 (66.1 m^3)	0.334%	0.558%
1.0 µm	0.760 in/s (19.3 mm/s)	4,260 ft^2 (396 m^2)	2,130 ft^3 (60.3 m^3)	0.305%	0.509%
5.0 µm	1.45 in/s (36.7 mm/s)	1,210 ft^2 (113 m^2)	605 ft^3 (17.1 m^3)	0.0866%	0.145%
10.0 µm	1.91 in/s (48.5 mm/s)	770 ft^2 (71.5 m^2)	385 ft^3 (10.9 m^3)	0.0550%	0.0919%

Table A.4. Volume- and weight-percentage of UDS drawn out of the tank by the feed pump based on 10.0 wt% particulate within the turbid region for Case 1 – supernate level at 105 in.

Characteristic Particle Size	V_{min}	A_{scour}	Vol_{scour}	Vol% sludge	Wt% sludge
0.1 µm	0.302 in/s (7.68 mm/s)	5,070 ft^2 (471 m^2)	2,540 ft^3 (71.8 m^3)	0.726%	1.21%
0.5 µm	0.576 in/s (14.6 mm/s)	4,670 ft^2 (434 m^2)	2,330 ft^3 (66.1 m^3)	0.668%	1.12%
1.0 µm	0.760 in/s (19.3 mm/s)	4,260 ft^2 (396 m^2)	2,130 ft^3 (60.3 m^3)	0.610%	1.02%
5.0 µm	1.45 in/s (36.7 mm/s)	1,210 ft^2 (113 m^2)	605 ft^3 (17.1 m^3)	0.173%	0.289%
10.0 µm	1.91 in/s (48.5 mm/s)	770 ft^2 (71.5 m^2)	385 ft^3 (10.9 m^3)	0.110%	0.184%

Table A.5. Volume- and weight-percentage of UDS drawn out of the tank by the feed pump based on 0.1 wt% particulate within the turbid region for Case 2 – supernate level at 120 in.

Characteristic Particle Size	V_{min}	A_{scour}	Vol_{scour}	Vol% sludge	Wt% sludge
0.1 μm	0.300 in/s (7.63 mm/s)	5,070 ft^2 (471 m^2)	2,540 ft^3 (71.8 m^3)	0.0060%	0.0101%
0.5 μm	0.572 in/s (14.5 mm/s)	4,490 ft^2 (417 m^2)	2,240 ft^3 (63.5 m^3)	0.0053%	0.0089%
1.0 μm	0.755 in/s (19.2 mm/s)	3,950 ft^2 (367 m^2)	1,970 ft^3 (55.9 m^3)	0.0047%	0.0078%
5.0 μm	1.44 in/s (36.5 mm/s)	1,280 ft^2 (119 m^2)	638 ft^3 (18.1 m^3)	0.0015%	0.0025%
10.0 μm	1.90 in/s (48.2 mm/s)	850 ft^2 (79.0 m^2)	425 ft^3 (12.0 m^3)	0.0010%	0.0017%

Table A.6. Volume- and weight-percentage of UDS drawn out of the tank by the feed pump based on 0.5 wt% particulate within the turbid region for Case 2 – supernate level at 120 in.

Characteristic Particle Size	V_{min}	A_{scour}	Vol_{scour}	Vol% sludge	Wt% sludge
0.1 μm	0.300 in/s (7.63 mm/s)	5,070 ft^2 (471 m^2)	2,540 ft^3 (71.8 m^3)	0.0302%	0.0504%
0.5 μm	0.572 in/s (14.5 mm/s)	4,490 ft^2 (417 m^2)	2,240 ft^3 (63.5 m^3)	0.0267%	0.0446%
1.0 μm	0.755 in/s (19.2 mm/s)	3,950 ft^2 (367 m^2)	1,970 ft^3 (55.9 m^3)	0.0235%	0.0392%
5.0 μm	1.44 in/s (36.5 mm/s)	1,280 ft^2 (119 m^2)	638 ft^3 (18.1 m^3)	0.0076%	0.0127%
10.0 μm	1.90 in/s (48.2 mm/s)	850 ft^2 (79.0 m^2)	425 ft^3 (12.0 m^3)	0.0051%	0.0085%

Table A.7. Volume- and weight-percentage of UDS drawn out of the tank by the feed pump based on 5.0 wt% particulate within the turbid region for Case 2 – supernate level at 120 in.

Characteristic Particle Size	V_{min}	A_{scour}	Vol_{scour}	Vol% sludge	Wt% sludge
0.1 μm	0.300 in/s (7.63 mm/s)	5,070 ft^2 (471 m^2)	2,540 ft^3 (71.8 m^3)	0.302%	0.504%
0.5 μm	0.572 in/s (14.5 mm/s)	4,490 ft^2 (417 m^2)	2,240 ft^3 (63.5 m^3)	0.267%	0.446%
1.0 μm	0.755 in/s (19.2 mm/s)	3,950 ft^2 (367 m^2)	1,970 ft^3 (55.9 m^3)	0.235%	0.393%
5.0 μm	1.44 in/s (36.5 mm/s)	1,280 ft^2 (119 m^2)	638 ft^3 (18.1 m^3)	0.0759%	0.127%
10.0 μm	1.90 in/s (48.2 mm/s)	850 ft^2 (79.0 m^2)	425 ft^3 (12.0 m^3)	0.0506%	0.0845%

Table A.8. Volume- and weight-percentage of UDS drawn out of the tank by the feed pump based on 10.0 wt% particulate within the turbid region for Case 2 – supernate level at 120 in.

Characteristic Particle Size	V_{min}	A_{scour}	Vol_{scour}	Vol% sludge	Wt% sludge
0.1 μm	0.300 in/s (7.63 mm/s)	5,070 ft^2 (471 m^2)	2,540 ft^3 (71.8 m^3)	0.604%	1.01%
0.5 μm	0.572 in/s (14.5 mm/s)	4,490 ft^2 (417 m^2)	2,240 ft^3 (63.5 m^3)	0.534%	0.892%
1.0 μm	0.755 in/s (19.2 mm/s)	3,950 ft^2 (367 m^2)	1,970 ft^3 (55.9 m^3)	0.470%	0.785%
5.0 μm	1.44 in/s (36.5 mm/s)	1,280 ft^2 (119 m^2)	638 ft^3 (18.1 m^3)	0.152%	0.254%
10.0 μm	1.90 in/s (48.2 mm/s)	850 ft^2 (79.0 m^2)	425 ft^3 (12.0 m^3)	0.101%	0.169%