Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

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Submersible Blend Pump Mixing Evaluation

M. R. Poirier

April 2019

SRNL-STI-2019-00176, Revision 0

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Printed in the United States of America

Prepared for
U.S. Department of Energy

Keywords: *Blending, SWPF, Mixer Pump, Tank 42*

Retention: *Permanent*

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EXECUTIVE SUMMARY

Savannah River Remediation (SRR) requested Savannah River National Laboratory (SRNL) to perform an engineering analysis to investigate the mixing behavior in feed blend tanks for the Salt Waste Processing Facility (SWPF). The baseline for mixing the feed blend tanks is a U_0D of 5.1 ft^2/s, a pump nozzle elevation of 165.86 inches above the sludge layer and 174 inches above the tank bottom, a liquid level 174.28 inches above the pump nozzle, and a blend time of 10.63 hours. The current Salt Batch Plan identifies Tanks 21, 26, 41, and 42 as the designated blend tanks. This supplemental study only addresses Type IIIA tanks (i.e., Tanks 26, 41, and 42). Using the Tank 41 current configuration as the baseline, the analysis considers the impact on blending if:

- the distance between the pump discharge nozzle and the liquid surface increases above the baseline,
- the distance between the pump discharge nozzle and the liquid surface decreases below the baseline,
- the distance between the pump discharge nozzle and the sludge layer at the bottom of the tank increases above the baseline, or
- the distance between the pump discharge nozzle and the sludge layer at the bottom of the tank decreases below the baseline, each while maintaining the minimum U_0D of 5.1 ft^2/s.
    - Per subsequent direction from SRR, the minimum distance between the pump discharge nozzle and the sludge will be 165.86 inches. Hence, distances less than 165.86 inches between the pump discharge nozzle and the sludge were not included in the analysis.
- In addition, SRR requested SRNL to evaluate the impact of the abandoned in place, failed slurry pumps in Tank 42 on liquid blending.

Two approaches were employed to assess the impact of changing the distance between the pump discharge nozzle and the liquid surface and the distance between the pump discharge nozzle and the sludge surface in Tank 41 in preparing salt solution for the SWPF. The approaches are matching the Froude number and examining existing jet blending correlations. The impact of an abandoned in place, failed slurry pump on liquid blending in Tank 42 was evaluated by performing a momentum balance on the flow in the tank to estimate the change in fluid velocity caused by the drag from the abandoned slurry pumps, and its impact on liquid blending.

The conclusions from this study follow.

- Increasing the liquid height in the blend tanks relative to the pump discharge nozzles could increase the blend time. The maximum increase is calculated to be 4 - 9% above the baseline.
- Increasing the pump discharge nozzle elevation relative to the sludge level (or tank bottom) in the blend tanks could increase the blend time. The maximum increase is calculated to be 15 - 33% above the baseline.
- Decreasing the distance between the pump discharge nozzle and the liquid surface to as little as 100 inches is unlikely to adversely impact the liquid blend time, but it could reduce it.
- The abandoned pumps in Tank 42 occupy a very small fraction of the tank, much of the fluid motion in the tank will not be impacted by these abandoned pumps, and the increase in blend time is predicted to be 2.1% above the baseline.

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LIST OF ABBREVIATIONS

C_i	Constants
C_D	Drag coefficient
D	Pump or jet nozzle diameter
D_p	Pump assembly diameter
F_D	Drag force
Fr	Froude number
g	Gravitational acceleration
H	Height of tank or fluid
L	Length travelled by jet from pump center to tank wall
L_p	Length of pump assembly
$\widehat{m}$	Jet momentum
Re	Reynolds number
SRNL	Savannah River National Laboratory
SRR	Savannah River Remediation
SWPF	Salt Waste Processing Facility
T	Tank diameter
TTR	Task Technical Request
U_i	Nozzle discharge velocities
U	Velocity
y	Horizontal distance from pump center to tank wall
ρ	Liquid density
θ	Blend Time
ν	Kinematic viscosity

1.0 Introduction

Savannah River National Laboratory (SRNL) personnel performed testing utilizing a 1/10.85 pilot-scale model of Tank 50 to determine the specifications for a mixing pump to blend miscible liquids to prepare feed for the Salt Waste Processing Facility (SWPF).[1] One design parameter for opposing, dual nozzle, blending pumps is U_0D, where U_0 is the discharge velocity for each pump nozzle, and D is the nozzle diameter. With a liquid waste volume of 1,225,000 gallons (~349 inches of slurry) and a pump elevation of 174 inches (distance between tank bottom and pump discharge nozzle), the prior testing and analysis specified a minimum U_0D of 5.1 ft^2/s to ensure the liquids were adequately blended and a maximum U_0D of 6.1 ft^2/s to prevent the jets from disturbing and suspending the solid particles settled at the bottom of the Type IIIA Waste Tank.

The pilot-scale testing was performed at a liquid level equivalent to 348.28 inches in a full-scale waste tank. The pump discharge nozzles were the equivalent of 174 inches above the tank bottom in a full-scale waste tank, and the testing contained the equivalent of 8.14 inches of sludge solids on the tank bottom. The equivalent distance between the pump discharge nozzle and the sludge layer is 165.86 inches. The calculated blend time for the feed blend tanks is 10.63 hours with a U_0D of 5.1 ft^2/s. The actual installation of the Blend Pump in Tank 41 may result in different liquid levels and discharge nozzle elevations than that modeled.

Savannah River Remediation (SRR) requested SRNL to perform supplemental engineering analysis to investigate the impact on mixing of the blend feed tanks for SWPF. Using the Tank 41 current configuration as the baseline, the analysis considers the impact on blending if:

- the distance between the pump discharge nozzle and the liquid surface increases above the baseline,
- the distance between the pump discharge nozzle and the liquid surface decreases below the baseline,
- the distance between the pump discharge nozzle and the sludge layer at the bottom of the tank increases above the baseline,
- or the distance between the pump discharge nozzle and the sludge layer at the bottom of the tank decreases below the baseline, each while maintaining the minimum U_0D of 5.1 ft^2/s (see Attachment 1).[2]

Per direction from SRR, the minimum distance between the pump discharge nozzle and the sludge will be 165.86 inches. Hence, distances less than 165.86 inches between the pump discharge nozzle and the sludge will not be included in the analysis.

The current Salt Batch Plan identifies Tanks 21, 26, 41, and 42 as the designated blend tanks.[3] Tanks 26, 41, and 42 are Type IIIA Tanks with cooling coils. While the details of the tanks, such as blend pump location, riser locations, and cooling coil area may differ slightly, the differences should not impact the required U_0D for blending these tanks. In addition, SRR asked SRNL to evaluate the impact of abandoned in place, failed slurry pumps in Tank 42 on liquid blending (see Attachment 2). The focus of this analysis is on the Type IIIA tanks (Tanks 26, 41, and 42).

2.0 Approach

2.1 Changing Distance between Pump Nozzle and Liquid Surface or Sludge Surface

Two approaches were employed to assess the impact of changing the distance between the pump nozzle and the liquid surface or the sludge surface in the blend tanks (Tanks 26, 41, and 42) for SWPF. The approaches are matching the Froude number and examining existing jet mixing correlations.

2.1.1 Equal Froude Number

In analyzing and modeling the effects of changes in distance between the pump discharge nozzle and the liquid surface on mixing processes, a Froude number is often used.[4] The Froude number is the ratio of inertial forces to gravitational forces, and is described by equation [1]

$$\mathrm{Fr} = \frac{\mathrm{U}^2}{\mathrm{g} \cdot \mathrm{H}} \qquad [1]$$

where U is the fluid velocity, g is the acceleration due to gravity, and H is the fluid height above the discharge nozzle.

To maintain equal liquid surface motion for two different levels, the Froude number is assumed to be constant. For constant Froude number and gravitational acceleration, the relationship between fluid height and nozzle discharge velocity is described by equation [2].

$$\mathrm{U}_1^2 \cdot \mathrm{H}_2 = \mathrm{U}_2^2 \cdot \mathrm{H}_1 \qquad [2]$$

In equation [2], U_1 and H_1 refer to the nozzle discharge velocity and liquid height for the baseline conditions, and U_2 and H_2 refer to the nozzle discharge velocity and liquid height for the modified conditions. Given that mixer pump discharge nozzle diameter is constant, multiplying equation [2] by D^2 and solving for U_2D yields equation [3].

$$\mathrm{U}_2\mathrm{D} = \mathrm{U}_1\mathrm{D}\sqrt{\frac{\mathrm{H}_2}{\mathrm{H}_1}} \qquad [3]$$

The baseline condition is U_1D of 5.1 ft^2/s, liquid level of 348.28 inches, and pump elevation of 174 inches; hence H_1 is 174.28. If the distance between pump discharge nozzle and the liquid surface is increased to 190 inches, the U_2D required for equal surface motion is calculated in equation [4].

$$\mathrm{U}_2\mathrm{D} = 5.1\,\frac{\mathrm{ft}^2}{\mathrm{s}}\sqrt{\frac{190\ \mathrm{in}}{174.28\ \mathrm{in}}} = 5.3\,\frac{\mathrm{ft}^2}{\mathrm{s}} \qquad [4]$$

Equation [4] shows that an ~4% increase in U_0D would be required to have equivalent mixing at the liquid surface. If the U_0D is maintained at 5.1 ft^2/s, the blend time will increase, slightly. Equation [5] is a general expression for blend time in a jet mixed tank

$$\theta = \mathrm{C}_1\,\frac{\mathrm{f(T,H)}}{\mathrm{U}_0\mathrm{D}} \qquad [5]$$

where C is a constant and T is the tank diameter.[5] Since blend time is inversely proportional to U_0D and U_0D is not being increased, increasing the height will increase the blend time approximately 4%.

2.1.2 Miscible Liquid Blend Time Correlations

Another approach to assess the impact of changing liquid height and pump elevation on liquid blending is to look at the impact of liquid height in blend time correlations. The correlations were developed for open tanks with no cooling coils. However, the testing performed by SRNL showed a similar influence of U_0D on blend time with and without coils, with a different constant to account for the cooling coils.[1] One correlation that includes the impact of liquid height on blend time is described by equation [6][6]

$$\theta = C_2 \frac{T^{1.5}H^{0.5}}{U_0 D} \quad [6]$$

where θ is blend time. Equation [6] shows that the blend time increases with the square root of the change in tank liquid elevation. Since the mixer pump is located in the middle region of the tank rather than the bottom of the tank, the height used in equation [6] is the distance between the pump nozzle and the liquid surface or the difference between the pump nozzle and the sludge layer on the bottom of the tank.

Increasing the distance between the pump discharge nozzle and the liquid surface from 174.28 inches to 190 inches, is a 9% increase. Since the blend time is proportional to the square root of the height (equation [6]), this increase would lead to an ~4% increase in blend time.

Increasing the distance between the pump discharge nozzle and the sludge layer from 165.86 inches to 220 inches, is a 33% increase. Since the blend time is proportional to the square root of the height, this increase would lead to an ~15% increase in blend time.

Fox and Gex (equation [7]) and Lane and Rice (equation [8]) developed correlations that show the same dependence of mixing time on height, but a different influence of U_0D as compared to equation [6].[7]

$$\theta = C_3 \frac{TH^{0.5}}{(U_0 D)^{2/3}} \quad [7]$$

$$\theta = C_4 \frac{TH^{0.5}}{(U_0 D)^{2/3}} \quad [8]$$

Using equations [7] and [8], increasing the distance between the pump discharge nozzle and the liquid surface from 174.28 to 190 inches would increase the blend time by ~4%, and increasing the distance between the pump discharge nozzle and the sludge surface from 165.86 inches to 220 inches, would increase the blend time by 15%, consistent with the results from equation [6], given U_0D does not change.

Grenville and Tilton developed a correlation to predict the blend time in a jet mixed tank. Their correlation is described by equation [9].[8]

$$\theta = C_5 \frac{TH}{(U_0 D)\, L} \quad [9]$$

In equation [9], L is the distance travelled by the jet prior to hitting the wall of the tank. The submersible blend pump discharge nozzle is located 29 feet from the center of the tank having a radius of 42.5 feet.[9,10] The horizontal distance between the blend pump center and the tank wall (y) is described by equation [10] and Figure 1.

$$29^2 + y^2 = 42.5^2 \quad [10]$$

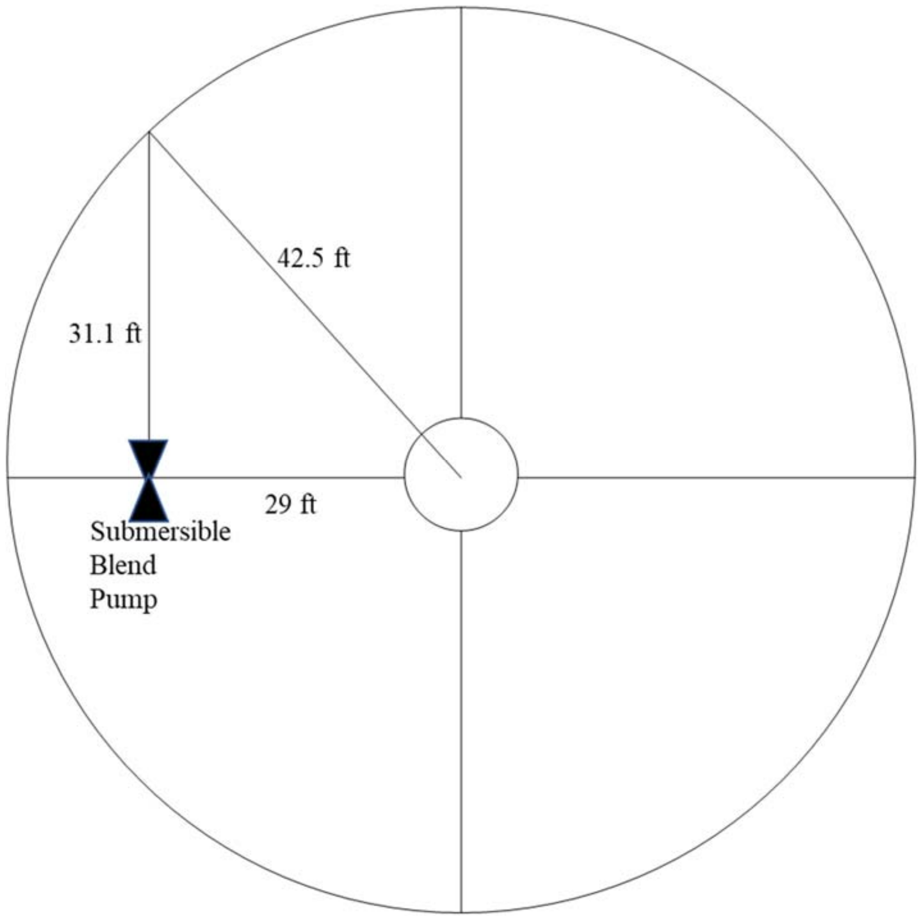

Figure 1. Layout of Submersible Blend Pump in Type IIIA Waste Tank

Solving equation [10] for y gives a distance of 31.1 feet. Because the pump discharge nozzles are angled 15˚ above the horizontal plane, the distance (L) travelled by the jet prior to hitting the wall of the tank is longer than 31.1 feet and is described by equation [11] and Figure 2.

$$\frac{31.1\ \text{ft}}{\text{L}} = \cos 15° \qquad [11]$$

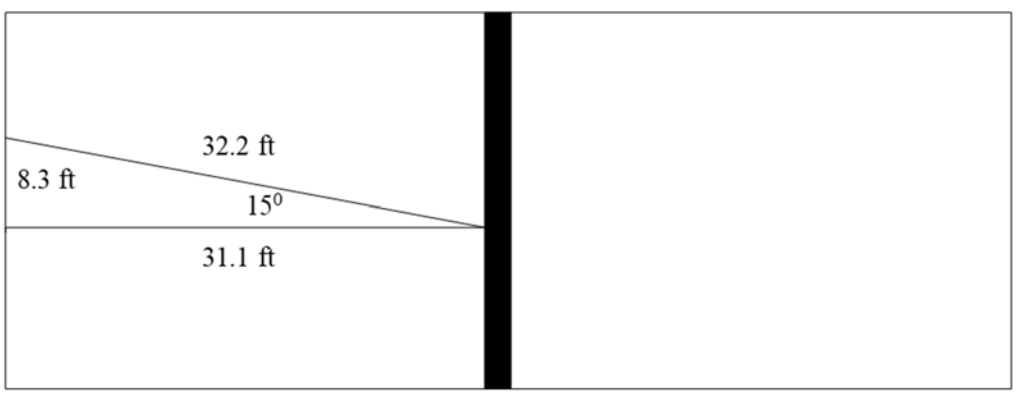

Figure 2. Side View of Pump Discharge Jet

Solving equation [11] for L, gives a value of 32.2 feet. The height above the nozzle at which the pump discharge jet impacts the wall is 8.3 feet, or 99.6 inches. The value of L will not change, but if this distance is greater than the distance between the pump discharge nozzle and the liquid surface, it would shorten the path length of the jet produced by the pump and increase the blend time. Since the minimum distance between the pump discharge nozzle and the liquid surface is 100 inches, the only impact of decreasing this distance from 165.86 inches to 100 inches would be to decrease the blend time. Because the discharge of the jet is not at the center of the pump assembly, the distance between the discharge at the jet nozzle to the tank wall will be slightly less than 32.2 feet, and the height above the nozzle at which the pump discharge jet impacts the wall will be slightly less than 99.6 inches.

For mixing at the liquid surface, increasing the height from 174.28 inches to 190 inches, increases the blend time by 9% compared with the baseline, according to equation [9].

For mixing at the sludge surface, increasing the distance between the pump discharge nozzle and the sludge surface from 165.86 inches to 220 inches, increases the blend time by 33% compared with the baseline, according to equation [9].

Applying the blend time correlations to assess the impact of increasing the distance between the pump discharge nozzle and the liquid surface shows the increase in blend time will range from 4% to 9%, compared with the baseline. Applying the blend time correlations to assess the impact of increasing the distance between the pump discharge nozzle and the sludge layer shows the increase in blend time will range from 15% to 33%, compared with the baseline.

2.2 Abandoned in Place Failed Slurry Pumps

Per the Task Technical Request (TTR), the submersible blend pump will be installed in riser B4 (see Attachment 2). The submersible blend pump has two discharge nozzles, with a nozzle diameter of 2.25 inches, and angled 15 degrees above the horizontal plane where each nozzle provides a U_oD of 5.1 ft^2/s. Per the TTR, there might be four abandoned and/or failed slurry pumps in Tank 42, two standard slurry pumps (Risers V1 and V2) and two quad pumps (Risers G and H).

The impact of the abandoned and/or failed slurry pumps in Tank 42 was assessed by performing a momentum balance over the contents of tank. The momentum of one of the jets discharging into the tank from the submersible blend pump is described by equation [12].[4]

$$\widehat{m} = \rho\, U_0^2 \frac{\pi D^2}{4} = \rho \frac{\pi}{4}\, U_0^2 D^2 = = \frac{\pi}{4} \frac{1.25\ \mathrm{g}}{\mathrm{cm}^3} \left(\frac{4738\ \mathrm{cm}^2}{\mathrm{s}}\right)^2 = 22{,}000{,}000\, \frac{\mathrm{g{\cdot}cm}}{\mathrm{s}^2} \qquad [12]$$

Multiplying the momentum flux by 2 to account for two nozzles produces the total momentum input into the tank, which is 44,000,000 g cm/s^2.

The presence of the abandoned slurry pumps will cause drag as the fluid moves around them, which will reduce the momentum of the fluid in the tank. The pumps will be treated as cylinders and equation [13] can be used to calculate the drag caused by the abandoned slurry pumps

$$F_d = \frac{C_D \rho U^2 D_p L_p}{2} \qquad [13]$$

where C_D is the drag coefficient, U is the velocity of the fluid at the abandoned slurry pump, D_p is the diameter of the abandoned slurry pump assembly (16 inches[11]), and L_p is the length of the pump assembly (348.28 inches).[4] A length of 348.28 inches (885 cm) was selected for conservatism, given the abandoned pumps do not extend to the tank bottom. Because the blend pump nozzles are angled upward, the impact of the abandoned slurry pumps below the elevation of the nozzles should not be significant, but it is included for conservatism. The velocity of the fluid approaching the abandoned slurry pump can be estimated using CFD modeling performed as part of the pilot-scale testing conducted to select design parameters for the submersible blend pump.[9] Reviewing the CFD calculated velocity distribution in the horizontal plane of the discharge jet for a case (Case 11a and Figure 10 in the document) with a V-shape pump discharge, a U_0D of 0.58 ft^2/s at pilot-scale (6.3 ft^2/s at full-scale), and no cooling coils, and considering the location of the abandoned pumps in Tank 42 (see Attachment 2), the maximum fluid velocity in the region of the abandoned pump in Riser G is approximately 0.2 ft/s (6.1 cm/s), and the maximum velocity in the regions of the abandoned pumps in Risers H, V1, and V2 is less than 0.13 ft/s. Since the equivalent U_0D in this case is larger than the planned U_0D in Tank 42, the actual velocity in Tank 42 should be less. Since the CFD case had no cooling coils, the velocity in the region of the abandoned pumps in Tank 42 (which has cooling coils) is likely less. Because the pump discharge nozzles are angled 15° upward, the velocity may be higher above the pump nozzle horizontal plane and lower below the pump nozzle horizontal plane. Because the abandoned pumps are not in the direct path of the discharge jets from the blend pump, this effect is likely small. Given the other conservatisms discussed above, the estimates for the velocity in the region of the abandoned pumps are believed to be reasonable for this calculation.

The drag coefficient is a function of Reynolds number which is defined by equation [14]

$$\mathrm{Re} = \frac{\mathrm{UD_p}}{\nu} = \frac{6.1\frac{\mathrm{cm}}{\mathrm{s}}40.6\mathrm{cm}}{0.024\frac{\mathrm{cm}^2}{\mathrm{s}}} = 10{,}319 \qquad [14]$$

where D_p = 40.6 cm, and ν (the kinematic viscosity of the salt solution) = 0.024 cm^2/s.[a] For a velocity of 0.2 ft/s, the Reynolds number is 10,319 as shown in equation [14]. For a fluid velocity of 0.13 ft/s, the Reynolds number is 6,707. According to reference 4, at a Reynolds number of 1,000 – 100,000 for a cylinder, the drag coefficient is approximately 1. For the pump in Riser G, the drag force is calculated with equation [15].

$$\mathrm{F_d} = 1\,\frac{1.25\mathrm{g}}{\mathrm{cm}^3}\left(\frac{6.1\mathrm{cm}}{\mathrm{s}}\right)^2\frac{40.6\mathrm{cm}\;885\mathrm{cm}}{2} = 836{,}000\,\frac{\mathrm{g\,cm}}{\mathrm{s}^2} \qquad [15]$$

The drag force for each pump in Risers H, V1, and V2 is calculated with equation [16]

$$\mathrm{F_d} = 1\,\frac{1.25\mathrm{g}}{\mathrm{cm}^3}\left(\frac{3.96\mathrm{cm}}{\mathrm{s}}\right)^2\frac{40.6\mathrm{cm}\;885\mathrm{cm}}{2} = 352{,}000\,\frac{\mathrm{g\,cm}}{\mathrm{s}^2} \qquad [16]$$

Adding the drag forces from each of the abandoned slurry pumps, the total drag force is 1,892,000 gcm/s^2 or 4.3% of the momentum produced by the submersible blend pump. The abandoned pumps reducing fluid momentum in the tank is equivalent to the input momentum being reduced by 4.3%. Since the momentum is proportional to the square of U_0D, reducing U_0D by the square root of 1.043 would produce the same effect as the drag from the abandoned pumps. The square root of 1.043 is 1.021. Since the blend time is inversely proportional to U_0D (see equations [5], [6], and [9]), the impact of the abandoned pumps will be to increase the blend time by a maximum of 2.1%. Equation [7] and [8] result in a smaller increase in blend time, given the 2/3 power on U_0D. The actual loss of momentum and increase in blend time is likely less, because the cooling coils will reduce fluid velocity near the abandoned pumps, and the fluid velocity in the

[a] A kinematic viscosity of 0.024 cm^2/s was selected for the calculation of the Reynolds number based upon a viscosity of 3 cp and a fluid density of 1.25 g/cm^3. The viscosity is typical of 5.6 – 6.0 M sodium salt solution, and the density is typical of a 5.6 M sodium salt solution. The drag coefficient is not sensitive to changes in Reynolds number between 1,000 – 100,000, so any uncertainty in the viscosity or density has little impact on C_D.

bottom section of the tank will be less than the fluid velocity in the plane of the pump discharge jets. While the fluid velocity in the vicinity of the abandoned pumps was estimated based on CFD calculations in the horizontal plane with angled discharge jets, the uncertainty from this difference is likely small and accounted for with the conservatism. This is an additive loss to that of level changes described previously.

2.3 Quality Assurance

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

The work scope requested by SRR is describing in a Task Technical Request.[2] SRNL approach to performing the analysis, along with the quality assurance requirements, are described in the Technical Task and Quality Assurance Plan.[12]

3.0 Discussion

This analysis employed two approaches to evaluate the impact of changing the distance between the pump discharge nozzle and the liquid surface or the distance between the pump discharge nozzle and the sludge surface in the blend tanks that prepare feed for the SWPF. The approaches were matching the Froude number and examining existing jet mixing correlations.

This analysis predicted an increased blend time from increasing the distance between the pump discharge nozzle and the liquid surface, with the increase ranging from 4 - 9%, and an increased blend time from changing the distance between the pump elevation and the sludge surface, with the increase ranging from 15 - 33%. The fact that two very different approaches produce similar results and that multiple jet blending correlations predict similar results should increase the confidence in these results and support the conclusion that the impact of changing the distance between the pump discharge nozzle and the liquid surface or the distance between the pump discharge nozzle and the sludge surface should be small.

Decreasing the distance between the pump discharge nozzle and the liquid surface should not increase the blend time unless the level is reduced to the point that the jet produced by the blend pumps reaches the liquid surface before it reaches the wall. Decreasing the distance between the pump discharge nozzle and the sludge surface is unlikely to increase the blend time in these tanks, but it could lead to additional sludge suspension. SRR plans to maintain the minimum distance between the pump discharge nozzle and the sludge at 165.86 inches.

The analysis showed that the abandoned, failed slurry pumps will lead to a decrease in fluid velocity in the blend tanks. However, the abandoned pumps occupy a very small fraction of the tank, much of the fluid motion in the tank will not be impacted by these abandoned pumps, and the increase in blend time is predicted to be 2.1%.

4.0 Conclusions

The conclusions from this study follow.

- Increasing the liquid height in the blend tanks relative to the pump discharge nozzles could increase the blend time. The maximum increase is calculated to be 4 - 9% above the baseline.
- Increasing the pump discharge nozzle elevation relative to the sludge level (or tank bottom) in the blend tanks could increase the blend time. The maximum increase is calculated to be 15 - 33% above the baseline.
- Decreasing the distance between the pump discharge nozzle and the liquid surface to as little as 100 inches is unlikely to adversely impact the liquid blend time, but it could reduce it.

- The abandoned pumps in Tank 42 occupy a very small fraction of the tank, much of the fluid motion in the tank will not be impacted by these abandoned pumps, and the increase in blend time is predicted to be 2.1% above the baseline.

5.0 References

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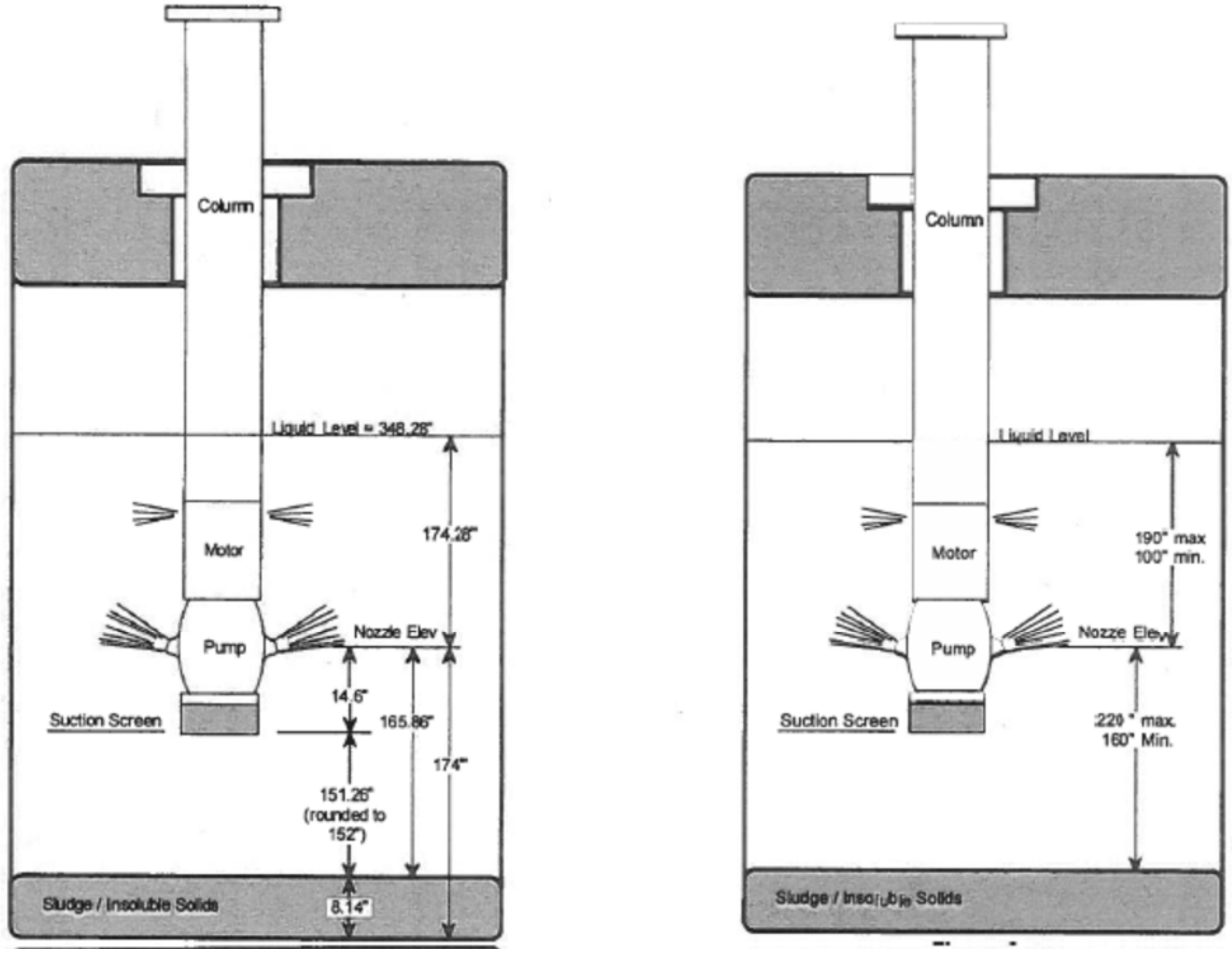
Attachment 1. Liquid Level and Pump Elevation in SWPF Blend Tanks



Attachment 2. Layout of Tank 42