Key Words:
Mixing, Tank 50H, Isopar L®

Retention:
Permanent

ASSESSMENT OF THE ABILITY OF STANDARD SLURRY PUMPS TO MIX MISCIBLE AND IMMISCIBLE LIQUIDS IN TANK 50H

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June 15, 2011

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

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LIST OF ACRONYMS

ARP	Actinide Removal Process
CFD	Computational Fluid Dynamics
DSS-HT	Decontaminated Salt Solution Hold Tank
DWPF	Defense Waste Processing Facility
ETP	Effluent Treatment Project
ISDP	Integrated Salt Disposition Project
LWO	Liquid Waste Operations
MCU	Modular Caustic Side Solvent Extraction Unit
rpm	Revolutions per minute
SDIP	Salt Disposition Integration Project
SPF	Saltstone Production Facility
SRNL	Savannah River National Laboratory
SRR	Savannah River Remediation
SRS	Savannah River Site
U_0	Pump Nozzle Discharge Average Velocity
X	Downstream Distance from Nozzle

NOMENCLATURE

A_1	Constant in Equation [10]
C	Constant in Blend Time Correlation, Equation [3]
d_p	Droplet Diameter
D	Pump Nozzle Inside Diameter
D_{max}	Maximum Droplet Size
g	Acceleration Due to Gravity
r	Height above centerline of pump discharge nozzle
s	Ratio of Droplet Density to Fluid Density
t	Mixing Time To Reach 95% of Equilibrium Value
T	Tank Inside Diameter
U_0	Nozzle Discharge Velocity
v	Maximum Fluid Velocity in Radial Wall Jet Flow
v_s	Droplet Rise Velocity
x	Distance From Pump Discharge Nozzle
μ	Fluid Viscosity
ν	Fluid Kinematic Viscosity
ρ	Density
ε	Mean Kinetic Energy Dissipation
σ	Interfacial Surface Tension

1.0 SUMMARY

Tank 50H is the feed tank for the Saltstone Production Facility (SPF). At present, Tank 50H contains two standard slurry pumps and two Quad Volute slurry pumps. Current requirements and mixing operation is to run three pumps for one hour prior to initiating a feed transfer to SPF. Savannah River Site (SRS) Liquid Waste would like to move one or both of the Quad Volute pumps from Tank 50H to Tank 51H to replace pumps in Tank 51H that are failing. In addition, one of the standard pumps in Tank 50H exhibits high seal leakage and vibration. SRS Liquid Waste requested Savannah River National (SRNL) to conduct a study to evaluate the feasibility of mixing the contents of Tank 50H with one to three standard slurry pumps.

To determine the pump requirements to blend miscible and immiscible liquids in Tank 50H, the author reviewed the pilot-scale blending work performed for the Salt Disposition Integration Project (SDIP) and the technical literature, and applied the results to Tank 50H to determine the number, size, and operating parameters needed to blend the tank contents.

The conclusions from this analysis follow.

- A single rotating standard slurry pump (with a 13.6 ft^2/s U_0D) will be able to blend miscible liquids (i.e., salt solution) in Tank 50H within 4.4 hours.
- Two rotating standard slurry pumps will be able to blend miscible liquids in Tank 50H within 3.1 hours.
- Three rotating standard slurry pumps will be able to blend miscible liquids in Tank 50H within 2.5 hours.
- A single rotating standard slurry pump (with a 13.6 ft^2/s U_0D) will disperse Isopar L® droplets that are less than or equal to 15 micron in diameter. If the droplets are less than 15 micron, they will be dispersed within 4.4 hours. Isopar L® provides a lower bound on the maximum size of droplets that will be dispersed by the slurry pumps in Tank 50H.
- Two rotating standard slurry pumps will disperse Isopar L® droplets less than 15 micron within 3.1 hours, and three rotating standard slurry pumps will disperse Isopar L® droplets less than 15 micron within 2.5 hours.
- If the Isopar L® droplets are drawn through the pump, they will be further reduced in size, with a maximum drop size less than 15 micron.

2.0 INTRODUCTION

Tank 50H is the feed tank for the Saltstone Production Facility. In the first quarter of the 2011 calendar year, Tank 50H accepted transfers of approximately 15 kgal from the Effluent Treatment Project (ETP), approximately 15 kgal from Tank 710—the H-Canyon General Purpose Evaporator, approximately 73 kgal from the H-Canyon Super Kukla campaign, approximately 285 kgal from the Actinide Removal Process / Modular Caustic Side Solvent Extraction Unit (ARP/MCU) Decontaminated Salt Solution Hold Tank (DSS-HT), and approximately 21 kgal from other sources. The DSS from ARP/MCU could contain as much as 10 mg/L of Isopar L®.[1,2,3] The Isopar L® size is expected to be less than 20 microns.[4,5] The entrained solids concentration is expected to be minimal and the particle size is on the order of 5 micron.[6]

At present, Tank 50H contains two standard slurry pumps and two Quad Volute slurry pumps. Current requirements and mixing operation is to run three pumps for one hour prior to initiating a feed transfer to SPF.[7] Tank 51H contains four Quad Volute slurry pumps located in risers B1, B4, G, and H. During recent sludge batch washing, the pump in riser G experienced operational problems. In addition, the pump in riser B4 has experienced excessive bearing water leakage. Since Tank 51H is a sludge tank and Tank 50H is a salt tank, Tank 51H needs higher horsepower pumps than Tank 50H. SRS Liquid Waste would like to move one or both of the Quad Volute pumps from Tank 50H to Tank 51H to replace pumps in Tank 51H that are failing. In addition, one of the standard pumps in Tank 50H exhibits high seal leakage and vibration. This pump may become unusable in the near future.

SRS Liquid Waste requested Savannah River National (SRNL) to conduct various literature studies to evaluate the feasibility of mixing the contents of Tank 50H with one to three standard slurry pumps.[8]

The objective provided by SRS Liquid Waste Operations (LWO) is to determine the required number, type, and operating parameters of the pump(s) needed to mix the contents of Tank 50H prior to transferring them to Saltstone for the various scenarios listed below:

1. Determine whether a single standard slurry pump is sufficient to mix the supernate in Tank 50H to a homogenous consistency. This work was based on previous SRNL studies and reports, the technical literature, and mixing calculations.

2. Determine the adequacy of one to three standard pumps being able to achieve a homogenous mixture of supernate and Isopar L®. The bounding case will be the receipt of decontaminated salt solution from MCU to a tank at a maximum liquid level of 363 inches. MCU decontaminated salt solution transfer volume is ~5500 gallons with volumes as high as 6,100 reported. [If Tank 50H contains 363 inches of liquid (1,274,000 gallons) with no Isopar L®, and the MCU DSS transfers 6,100 gallons of DSS with 10 mg/L of Isopar L®, the bulk Isopar L® concentration will be 0.05 mg/L. If Tank 50H contains 285,000 gallons of DSS and 1,274,000 gallons of liquid, the bulk Isopar L® concentration would be 2.2 mg/L.]

3. Assess whether one to three standard slurry pumps can establish a homogenous mixture of supernate, Isopar L®, and solids at the transfer pump suction.

   If one pump is not adequate, assess whether operation of a single standard pump can move the settled solids outside the transfer pump's zone of influence, i.e., show the solids won't reach the jet during simultaneous MCU addition and transfer to Saltstone.

4. If necessary, evaluate the feasibility of blending supernate, Isopar L®, and solid particles with quad-volute pumps.

In this document, SRNL will address scenarios 1 and 2. Scenario 3 will be addressed in a future document, and scenario 4 will be addressed if needed.

3.0 APPROACH

To determine the pump requirements to blend miscible liquids in Tank 50H, the author reviewed the pilot-scale blending work performed for the Salt Disposition Integration Project (SDIP)[9] and applied the results to Tank 50H to determine the number, size, and operating parameters needed to blend the tank contents.

To determine the pump requirements to blend the Isopar L® with the salt solution in Tank 50H, the author reviewed the technical literature for data and models to determine the mixing requirements for the Isopar L® to be mixed and dispersed throughout the tank.

4.0 RESULTS

4.1 BLENDING MISCIBLE LIQUIDS

Table 1 show specific dimensional and performance aspects of the various mixer pumps contained in Tank 50H.

Table 1. Dimensional and Performance aspects of Mixer Pumps in Tank 50H[10,11]

Mixer	Nozzle		At Maximum RPM		
	Number	D (in)	U_0 (ft/s)	U_0D (ft^2/s)	Power (HP)
Standard Slurry Pump	2	1.5	109	13.6	70
Quad Volute Slurry Pump	2	3.62	72	21.7	118

Previous SRS Tank Farm experience preparing the first macrobatch for the Integrated Salt Disposition Process (ISDP) showed that a tank containing 1,161,000 gallons of salt solution could be blended with a single Quad Volute pump.[12,13] SRS LWO added 444,000 gallons of Tank 23H salt solution to 721,000 gallons of salt solution in Tank 49H. They mixed these solutions with a single quad-volute slurry pump. The analysis of the ISDP qualification sample showed the liquid to be well mixed. The tank had a volume of 1,161,000 gallons and the pump had a U_0D (nozzle velocity multiplied by nozzle diameter) of 21.7 ft^2/s. The tank was mixed for 7.25 hours. Batch qualification sample analysis showed the supernate to be homogeneous.[12] Tank 41H and Tank 50H are type IIIA tanks with a center column and cooling coils. While the coil layouts are not exactly the same, they are similar and are expected to have similar impacts on tank mixing.

As a follow on to this work and to help Savannah River Remediation (SRR) determine the necessary pump for blending miscible liquids (i.e., salt solution) in the Salt Disposition Integration Project (SDIP) Blend and Feed tanks, SRNL conducted pilot-scale liquid blending tests[9] in a nominal 1/10th scale type IIIA waste tank.[a] The pilot-scale testing showed that a type IIIA waste tank (e.g., Tank 50H) could be blended with a single standard non-rotating pump with two opposing nozzles provided that the nozzles had a U_0D greater than 8.8 ft^2/s. Since a standard slurry pump has a nozzle diameter of 1.5 inches and a maximum flow rate of 600 gpm

[a] Actual scale was 1/10.85 by linear dimension

per nozzle (maximum discharge velocity of 109 ft/s and maximum U_0D of 13.6 ft^2/s), a single standard slurry pump will be able to blend miscible liquids (i.e., salt solution) in Tank 50H.[13]

In the pilot-scale tests[9], the mixer pump did not rotate. However, a rotating mixer pump will improve the mixing and reduce the blend time for miscible liquids.[14] The standard slurry pumps in Tank 50H rotate between 1/5 – 1/3 rpm. The mixer pump in the SDIP design and in the pilot-scale testing was placed at the mid-tank elevation rather than at the bottom of the tank. A mixer pump placed near the tank bottom, like the pumps in Tank 50H, may not mix the material in Tank 50H as quickly as a pump placed at mid-tank elevation, resulting in an increase in mixing times. As the pump nozzles sweep past the tank wall, the jets discharging from the pump will impinge on the wall, behaving like a radial wall jet (see Figure 1), where some of the liquid will move from the bottom of the tank to the top of the tank producing the required vertical mixing.

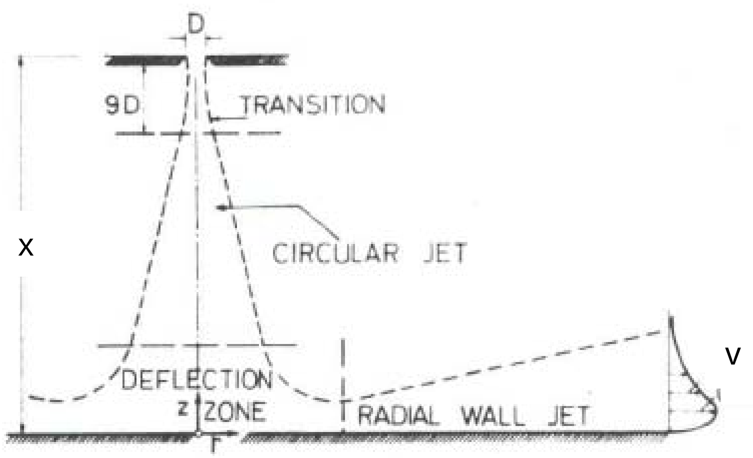


Figure 1. Radial Wall Jet Model[15]

Equation [1] describes the maximum velocity of a radial wall jet in the velocity profile generated by the interaction of the jet and wall

$$v = 0.9\frac{x^{0.1}U_oD}{r^{1.1}} \qquad [1]$$

where v is the maximum fluid velocity in the radial wall jet, x is the distance from the jet origin (i.e., pump discharge nozzle) to the tank wall, U_0 is the nozzle discharge velocity, D is the nozzle diameter, and r is the radial distance (i.e., height above pump nozzle).[15] Figure 2 shows a tank top drawing of Tank 50H.[16] The standard slurry pump in Tank 50H riser E1 is located ~ 18.5 feet from the tank wall (i.e., x = 18.5 feet). Other potential riser locations for standard pumps in Tank 50H (B3, B2, and B4) are approximately 18.5 feet from the tank wall. In addition, the velocity of a radial wall jet is a weak function of x. A 10% change in x would cause a 1% change in velocity. The nozzle discharge velocity is 109 ft/s, and the nozzle diameter is 1.5 inches (U_0D = 13.6 ft^2/s). The pump nozzle centerline discharge is 24 inches above the tank bottom. Since the tank volume is approximately 3510 gallons per inch, r is 9.9 feet for 500,000 gallons, 21.7 ft for 1,000,000 gallons, and 28.25 ft for 1,274,000 gallons. At these tank volumes, equation [1] predicts fluid velocities of 1.3 ft/s, 0.55 ft/s, and 0.41 ft/s at the liquid interface. Table 2 shows the distance from the wall and the calculated maximum fluid velocity of a radial wall jet at 9.9, 21.7, and 28.25 feet above the pump nozzle (500,000, 1,000,000, and 1,274,000 gallons). These velocities show the pumps will generate vertical flow of the tank contents as they impinge on the tank wall and the radial position of the pump has little effect on the velocity. Additionally, as the level of the tank decreases, the increasing velocity at the liquid interface results in a more vigorous surface motion throughout the tank.

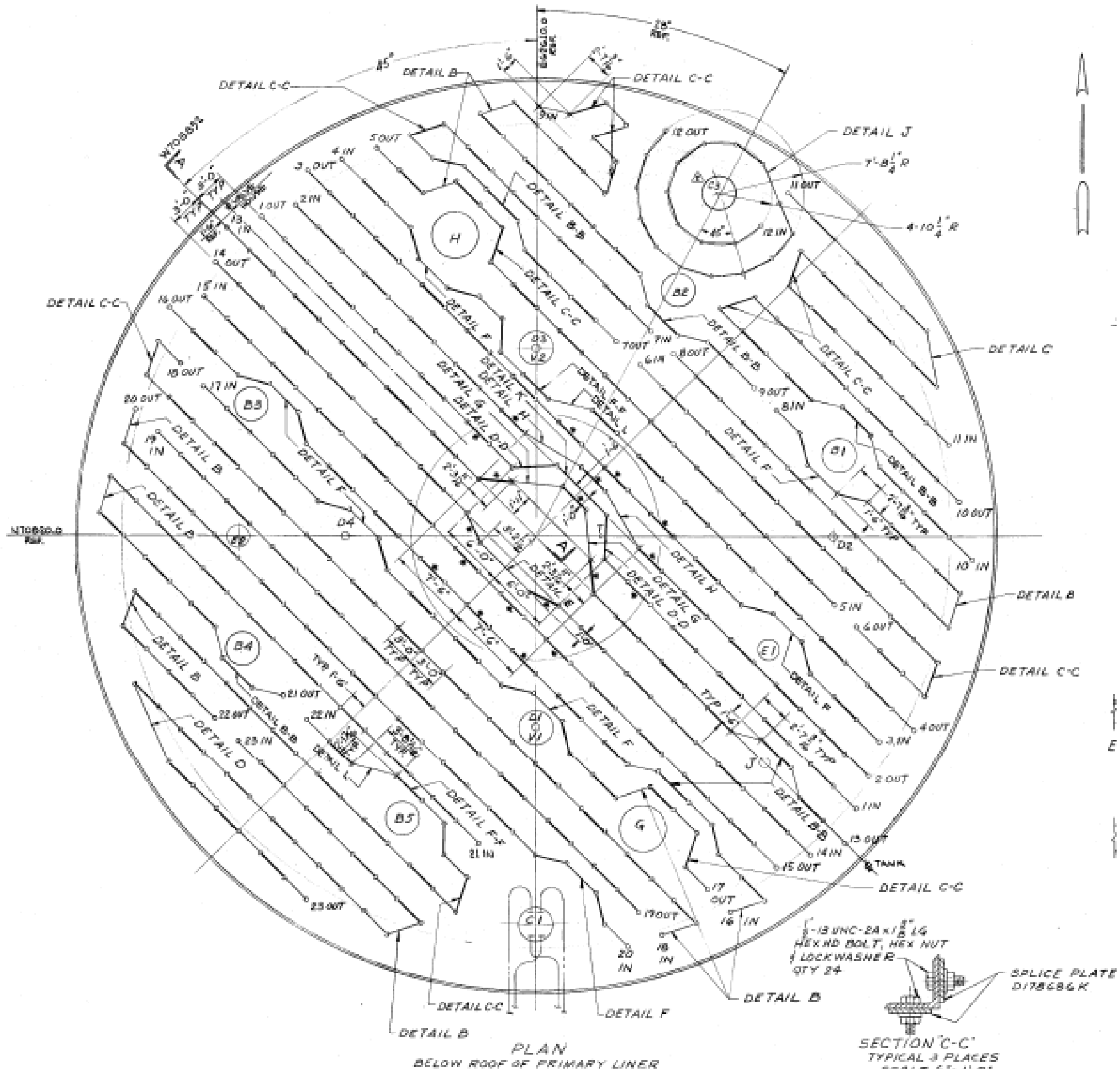
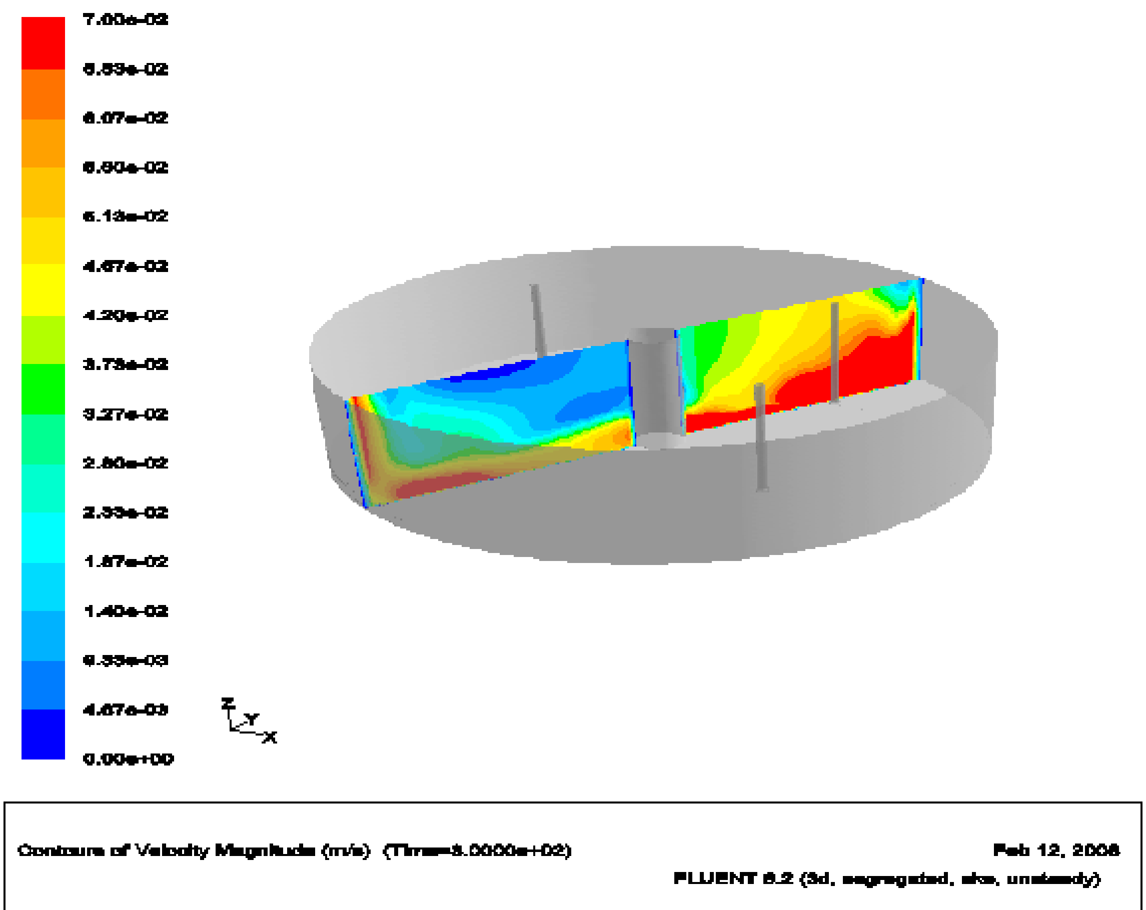


Figure 2. Tank 50H Tank Top

The Scientific Engineering Computation group of SRNL performed Computational Fluid Dynamics (CFD) Modeling of jet mixing in Tank 50H with a single standard slurry pump located in riser B2 to determine the impact of different pump configurations on solids suspension and mixing in Tank 50H. The model included the center column, the pump columns, and the pump housing, but it did not include the cooling coils. The pump rotated at 1/5 rpm. The tank volume for the calculations was 1,000,000 gallons. The model calculated fluid velocities in the plane of the telescoping transfer pump at 300 and 500 seconds after the start of the calculation.[17] The model showed (see Figure 3) that at 300 seconds, there was a strong vertical flow on the wall farthest away from the pump (as much as 0.23 ft/s). Therefore, strong vertical flow patterns would be expected everywhere in the tank as the pump rotates and the jets impact the wall.

Table 2. Distance from Tank 50H Riser to Tank Wall

Riser	Distance to Wall (ft)	Maximum Velocity at Specified Tank Volumes Liquid/Air Interface		
		500,000 gal	1,000,000 gal	1,274,000 gal
		v (ft/s)	v (ft/s)	v (ft/s)
E1	18.5 ft	1.32	0.55	0.41
B2	16 ft	1.30	0.55	0.41
B3	13.5 ft	1.28	0.54	0.40
B4	13 ft	1.27	0.54	0.40



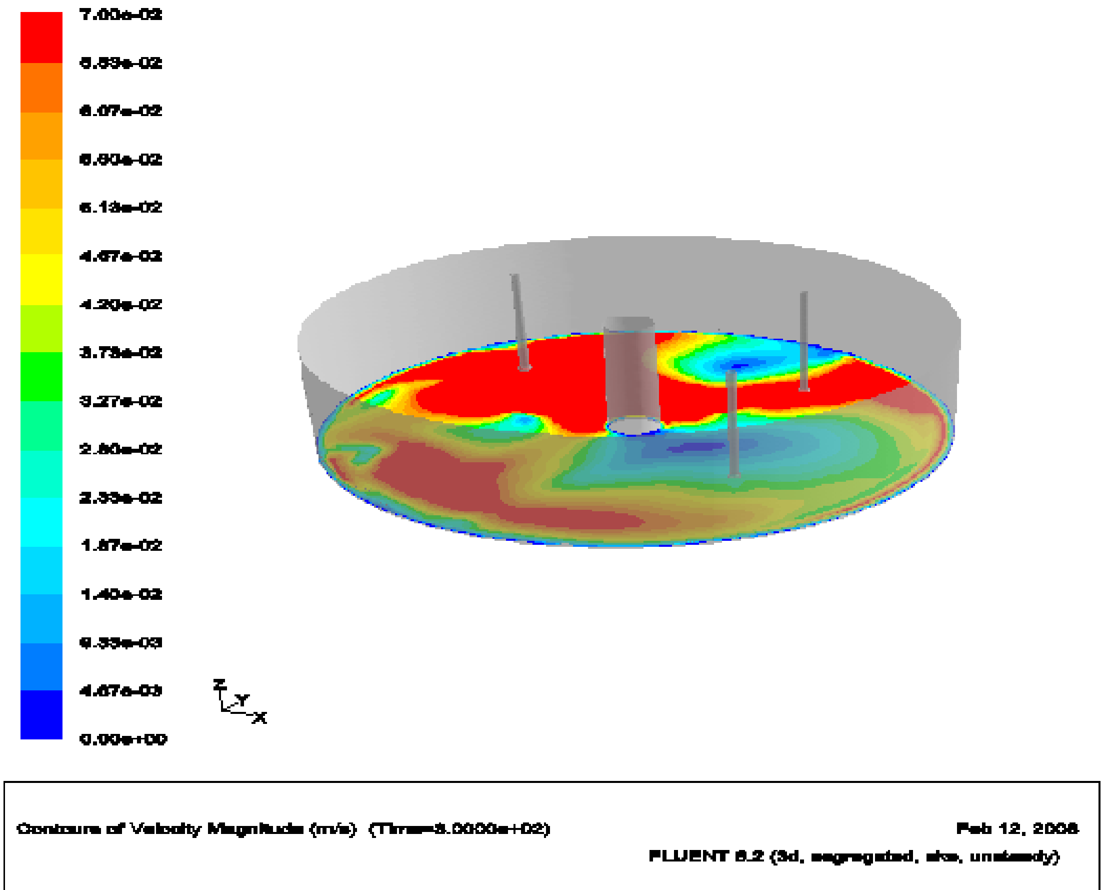


Figure 3. CFD Calculated Fluid Velocities in Plane of Tank 50H Telescoping Transfer Pump (From Figure 22 in Reference 17)

The pilot-scale testing developed an equation to calculate the mixing time of miscible liquids in a tank with cooling coils. The blending time is described by equation [2]

$$t = 7.4\frac{T^2}{U_o D} = 7.4\frac{(85\text{ft})^2}{109\frac{\text{ft}}{\text{sec}}\cdot 0.125\text{ft}\cdot\frac{3600\,\text{sec}}{\text{hr}}} = 1.1\ \text{hours} \qquad [2]$$

where t is the mixing time to reach 95% of equilibrium and T is the tank inside diameter.[9] For a tank diameter of 85 ft and a U_0D of 13.6ft^2/s, the calculated mixing time is 1.1 hours. The mixing time is increased 4X to account for uncertainty, producing a final mixing time of 4.4 hours.[9]

Therefore, a single rotating standard slurry pump (with a 13.6 ft^2/s U_0D) will be able to blend miscible liquids (i.e., salt solution) in Tank 50H within 4.4 hours.

If three standard slurry pumps are used to blend the salt solution, the mixing time is decreased as shown by equation [3]

$$t_n = 7.4\frac{T^2}{U_o D n^{1/2}} = 7.4\frac{(85\,ft)^2}{109\frac{ft}{\sec}\cdot 0.125\,ft\cdot\frac{3600\sec}{hr}(3)^{1/2}} = 0.63\ \ hours \qquad [3]$$

where n is the number of pumps.[18,19] Multiplying by 4 to account for uncertainty produces a blend time of 2.5 hours. Using two pumps, the calculated blend time is 0.77 hours. Multiplying by 4 to account for uncertainty produces a blend time of 3.1 hours.

4.2 BLENDING ISOPAR L®

Binnie and Phillips investigated the deviation in the velocity of a sphere from the velocity of water in horizontal pipe flow.[20] They found that if the terminal (settling) velocity of the particles was less than 1% of the mean water velocity, then the spherical particles would have the same mean velocity as the water, i.e., no slip between fluid and solid.

The particle settling velocity or droplet rise velocity is calculated by the following equations[21]

$$v_s = g(1-s)\frac{d_p^2}{18\nu} \qquad \text{for } Re_p < 1.4 \text{ (Stokes Equation)} \qquad [4]$$

$$v_s = 0.13[g(1-s)]^{0.72}\frac{d_p^{1.18}}{\nu^{0.45}} \qquad \text{for } 1.4 < Re_p < 500 \qquad [5]$$

$$v_s = 1.74[g(1-s)d_p]^{0.5} \qquad \text{for } Re_p > 500 \qquad [6]$$

$$Re_p = \frac{d_p v_s}{\nu} \qquad [7]$$

where v_s is the droplet rise velocity, g is the acceleration due to gravity, s is the ratio of droplet and fluid densities (s = droplet density/fluid density), d_p is the droplet diameter, μ is fluid viscosity, ρ is fluid density, and ν is the fluid kinematic viscosity ($\nu = \mu/\rho$).

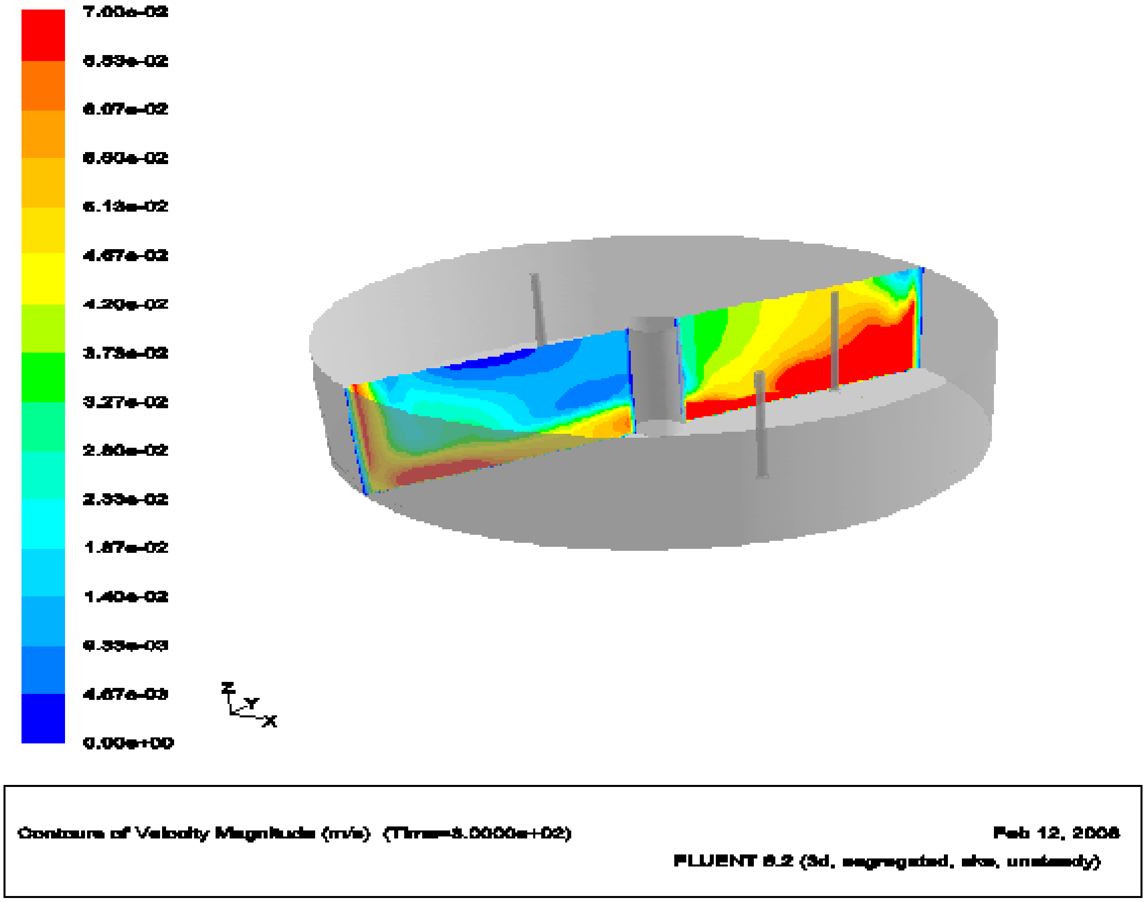
To perform the calculation, one assumes a particle Reynolds number, calculates the rise velocity with the appropriate equation, and calculates a new particle Reynolds number with the calculated rise velocity. If the Reynolds number is in the correct range for the equation used, the calculated rise velocity is correct. If the Reynolds number is not in the correct range for the equation used, a different equation is used to calculate the rise velocity. These steps are repeated as necessary.

For a 20 micron Isopar L® droplet (density = 0.77 g/mL), supernate density of 1.26 g/mL, and viscosity of 3 centipoise, the rising terminal velocity of the Isopar L® droplet is approximately

1.2×10^{-4} ft/s using Stokes Law (Re ≈ 0.0003 for the droplet). Therefore, the supernate fluid velocity must be greater than 1.2×10^{-2} ft/s for the Isopar L® droplets to follow the liquid in Tank 50H.

The author calculated the rise velocity of a solvent droplet (density = 0.852 g/cm^3, viscosity = 3 cp.) with equations [4] – [7], also. The calculated rise velocity of a 22.6 micron droplet is 1.2×10^{-4} ft/s using Stokes Law. Therefore, the supernate fluid velocity must be greater than 1.2×10^{-2} ft/s for the solvent droplets to follow the liquid in Tank 50H, and Isopar L® provides an upper bound on the maximum size of a droplet from MCU that will follow the liquid in Tank 50H.

The CFD modeling described above calculated fluid velocities in the plane of the telescoping transfer pump at 300 and 500 seconds after the start of the calculation. Figure 4 shows calculated fluid velocities in the plane of the telescoping transfer pump. The modeling showed a minimum fluid velocity of 0.012 ft/s in the plane of the telescoping transfer pump (in Figures 22 and 23 of reference 17).[17] Since the fluid velocities are greater than or equal to 0.012 ft/s, droplets smaller than 20 micron will follow the liquid and be dispersed throughout the tank (with no cooling coils). The CFD calculations placed the slurry pump in riser B2. For this application, the pump could be placed in risers E1, B2, B3, or B4. If only one standard pump is used to mix Tank 50H, similar minimum fluid velocities are expected if the pump is placed in riser E1, B3, or B4 rather than in riser B2, due to the slight differences in the radial positioning of the various pumps.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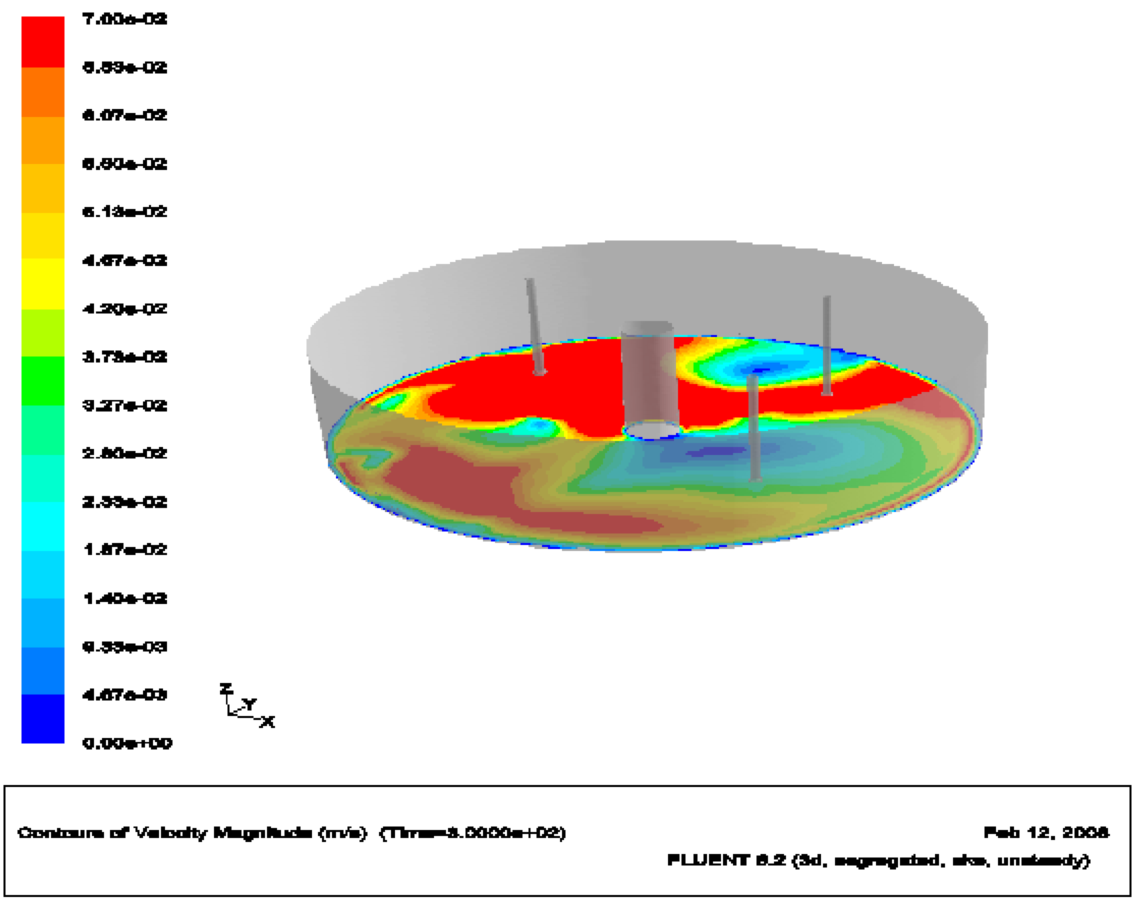
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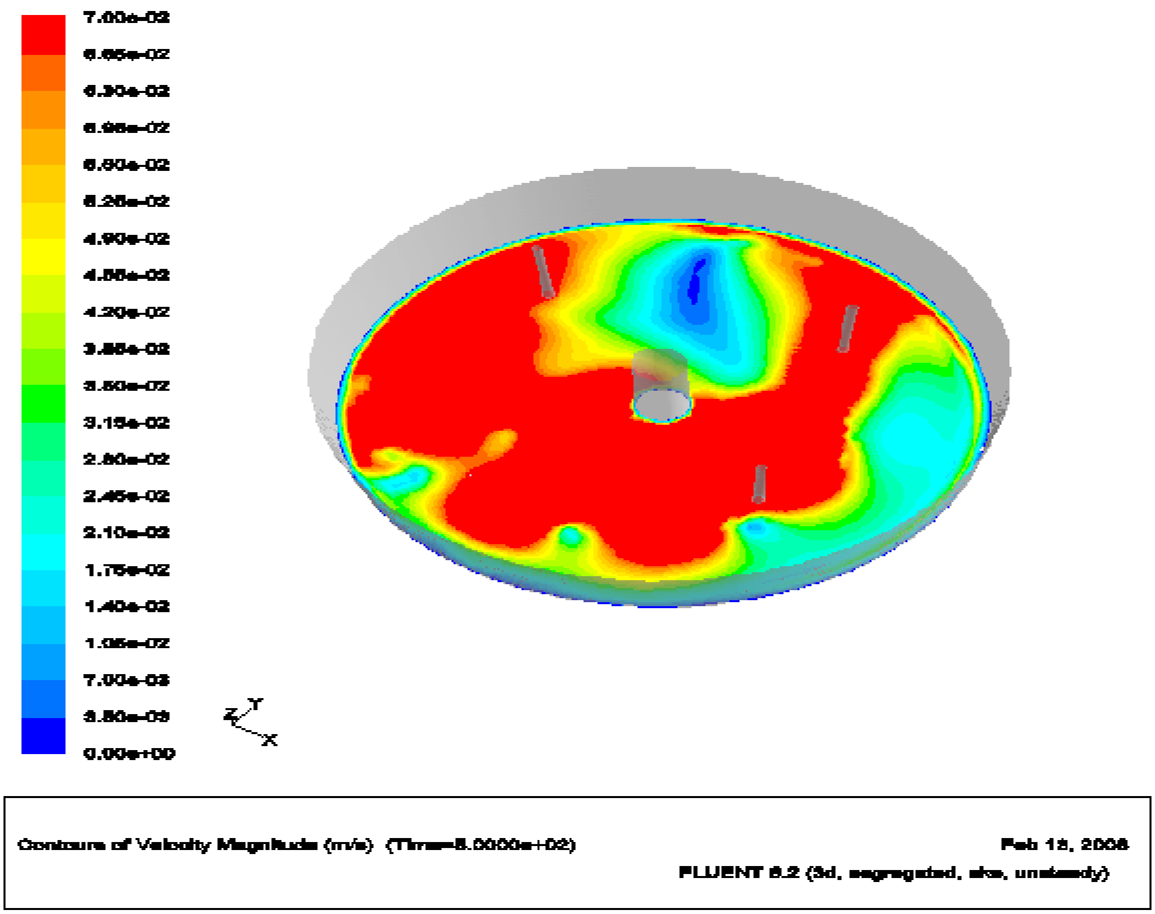

Figure 4. CFD Calculated Fluid Velocities in the Plane of the Telescoping Transfer Pump (From Figures 22 and 23 in Reference 17)

Since Tank 50H contains cooling coils, the fluid velocities must be corrected for the impact of cooling coils. SRNL conducted pilot-scale testing to evaluate the impact of the cooling coils on liquid-liquid blending in Tank 50H with a single non-rotating pump.[9] The testing showed the cooling coils increased the blending time in the pilot-scale test by approximately 90%. Blending times in jet mixed tanks are modeled by expressions like equation [8]

$$t = C\frac{T^2}{U_o D} \qquad [8]$$

where t is the blend time, C is a constant, T is the tank diameter, U_0 is the jet nozzle velocity, and D is the pump nozzle diameter.[9,22]

If the blending time is increased by a factor of 1.90, then the “effective U_0D” is decreased by a factor of 1.90 (or the constant C is increased by a factor of 1.90). Assuming that the cooling coils have a similar impact on the jet velocity throughout the tank, the local velocity calculated with CFD can be reduced by a factor of 1.90 to account for the impact of the cooling coils. The resulting minimum velocity in Tank 50H is 0.0063 ft/s. According to Stokes law, the size of an Isopar L® droplet that rises at 0.000063 ft/s (1% of the minimum fluid velocity) is 15 micron. Therefore, droplets 15 micron and smaller will follow the liquid throughout Tank 50H (with cooling coils) when a single standard slurry pump is operating at full speed. The consequences of a 15 micron droplet not following the flow field is that it may rise or slip occurs between the fluid and droplet until the droplet is engaged with a fluid velocity of greater than 0.012 ft/s.

Therefore, a single standard slurry pump will disperse Isopar L® droplets that are less than or equal to 15 micron in diameter. Droplets that are not dispersed in the salt solution will rise to the tank top and given insufficient fluid velocity to draw the droplet back into the tank will evaporate.[23] SRNL investigated the volatility of Isopar L® and found it to be significantly less than the volatility of water or benzene.[24] At 35 °C, the volatility of Isopar L® is 9.35×10^{-7} moles/cm^2s. Since Isopar L® has a molecular weight of 163 g/mole.[25] If Tank 50H was covered with a layer of Isopar L® or solvent and no accumulation of Isopar L® occurs in the vapor space, the Isopar L® would evaporate at a rate of 990 gallons per hour. When the contents in Tank 50H are not actively mixed, the droplets will rise (Stokes law) and potentially reach the surface, at which point they will evaporate. Droplets that coalesce and become much larger than 15 micron will still follow fluid flow patterns as that described for the 15 micron particles, but the velocities necessary to keep the droplets moving with the fluid will be larger.

A 1993 study of SRS pumps determined the minimum tank liquid levels to prevent vortexing and "rooster tailing".[26] The effort determined that vortexing would occur when the liquid level was less than 16 inches above the pump suction for standard slurry pumps. Typical standard slurry pumps are installed with the pump suction 7 – 10 inches above the tank bottom. Given a standard slurry pump suction of 10 inches above the tank bottom, the liquid level needs to be at least 26 inches (91,000 gallons) to prevent vortexing (i.e., entraining of air into the pump suction).

The 1993 study[26] found "rooster tailing" to occur when the pump submergence was 15 inches. Given a standard slurry pump suction of 10 inches above the tank bottom, the liquid level needs to be at least 25 inches (88,000 gallons) to prevent "rooster tailing".

When the tank liquid level drops below 91,000 gallons, vortexing will begin. The vortexing will draw floating Isopar L® into the pump suction. The shear produced by the pump impeller will cause the Isopar L® droplets to break into smaller droplets and has the potential to generate aerosols (due to the interactions with the air and solvents) as was observed in testing with a pilot-scale Defense Waste Processing Facility (DWPF) Strip Effluent Feed Tank.[27] SRS Liquid Waste reduces pump speed or stops the pumps as the liquid level drops in waste tanks to prevent vortexing and "rooster tailing". Therefore, the entrainment of floating layers of Isopar L® by vortexing or "rooster tailing" is unlikely to occur in Tank 50H.

Vortexing without air entrainment can occur, resulting in the entrainment of floating Isopar L® into the pump suction. This level at which this process occurs is not known and will occur at a level higher than that specified above. Entrainment of the solvent into the pump above the air entrained vortexing level will generate droplets as described below.

The author performed calculations to determine the impact of the pumps on Isopar L® drop size. The standard slurry pumps have two nozzles with an inner diameter of 1.5 inches. The 3 inch straight discharge section of the nozzle[28] contains 86.9 cm^3 of liquid. The two nozzles contain 173.8 cm^3 of liquid. Given a supernate density of 1.26 g/cm^3, the nozzles contain 220 g of supernate. Equation [9] calculates the power produced at the jet nozzle[29]

$$P = \left(\frac{\pi}{8}\right)\rho D^2 U_o^2 \qquad [9]$$

where ρ is the fluid density, D is the nozzle diameter, and U_o is the nozzle discharge velocity.[30] Since the pump has two nozzles (i.e., two jets), the calculated power should be multiplied by 2. Using equation [9], the power produced by a standard slurry pump is 5.26×10^{11} g cm^2/s^3. Given a supernate mass of 220 g in the nozzles, the power per unit mass is 2.4×10^9 cm^2/s^3 (2.4×10^5 m^2/s^3). Li and Garrett investigated the relationship between oil droplet size and ocean turbulence and correlated the oil droplet size with the power per unit mass (see Figure 3 in reference [31]).[31] Figure 5 shows the relationship. While the droplets in Li and Garrett's work had a viscosity of 100 cp versus a viscosity of 3 – 5 cp for MCU solvent[32], their work provides a rough estimate of the size of solvent droplets that should exit the standard slurry pumps. For the power per unit mass produced by the standard slurry pumps, the predicted drop size is approximately 1 micron. Droplets of approximately 1 micron size will follow the liquid and be dispersed in Tank 50H.

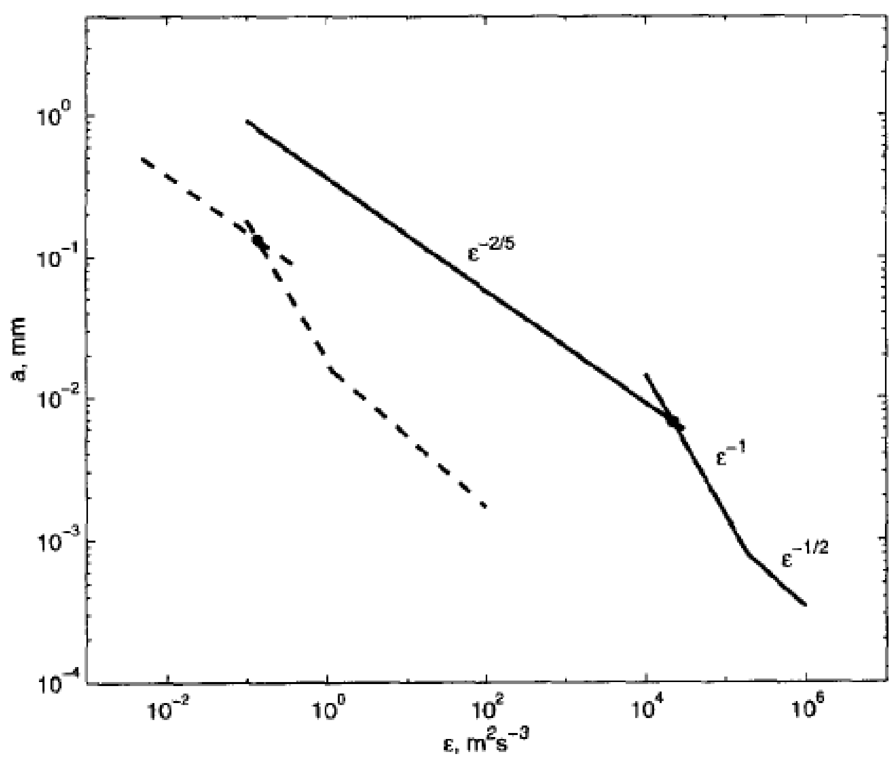

Figure 5. Relationship between Applied Energy (ε) and Drop Size (a)

Another approach is to use the internal volume of the pump rather than the volume of the discharge section of the pump nozzle. The impeller region of the pump has a diameter of 18.5 inches and a height of 4.0 inches.[26] The internal volume is approximately 17,600 cm^3. Given a supernate density of 1.26 g/cm^3, the impeller region contains approximately 22,200 g of supernate. Since the power produced by the pump is 5.26×10^{11} g cm^2/s^3, the power per unit mass is 2.4×10^7 cm^2/s^3 (2.4×10^3 m^2/s^3). Based on Li and Garrett's work[31], the expected drop size is approximately 10 micron. Droplets of approximately 10 micron size will follow the liquid and be dispersed in Tank 50H.

Reduction of the Isopar L® droplet size will occur in the pump and from turbulence generated by the jet leaving the pump. Floating Isopar L® will also be size reduced by the wave action created at the surface of the tank.[31] Droplet sizes can be determined by either turbulent inertial or turbulent viscous regimes.[33] In the inertial regime, the droplets are larger than the smallest turbulent eddies and are considered the largest droplets that can be present and in the viscous regime, the droplets are smaller than the smallest turbulent eddies. The maximum stable droplet size due to the turbulent inertial regime, given that the droplet and carrier fluid have similar viscosities is described by equation [10]

$$D_{max} = A_1 \varepsilon^{-2/5} \left(\frac{\sigma}{\rho} \right)^{3/5} \qquad [10]$$

where A_1 equal 0.725, ε is the mean kinetic energy dissipation, σ is the interfacial surface tension, and ρ is the density of the carrier fluid.[34] This droplet size is dependent on interfacial surface tension.

The smallest droplet size from viscous turbulent regime, based on the "Kolmogorov scale", is described by equation [11]

$$D_{max} \approx \varepsilon^{-1/4} \left(\frac{\mu}{\rho} \right)^{3/4} \qquad [11]$$

where μ is the viscosity of the carrier fluid.[33]

The mean kinetic energy dissipation for a turbulent round jets has been reported as

$$\varepsilon = 36 \frac{U_o^3}{D} \left(\frac{X}{D} - \frac{X_o}{D} \right)^{-4}, \ \frac{X_o}{D} = 5.47 \qquad [12]$$

where X is the distance down stream of the nozzle discharge.[35] The mean kinetic energy dissipation can be calculated using this equation [12] when $\frac{X_o}{D}$ greater 10.[36] Prior to this location, the mean kinetic energy dissipation is flat. The maximum mean kinetic energy in the jet stream is then evaluated at $\frac{X}{D}$ = 10. As the jet further develops, the mean kinetic energy dissipation decays to the 4th power.

The maximum mean kinetic energy in the standard slurry pump discharge jet is calculated with equation [12]

$$\varepsilon = 36\frac{(109\,ft)^3}{0.125\,ft}(10-5.47)^{-4} = 895{,}000\,ft^2/s^3 = 8.32x10^8\,cm^2/s^3$$

Using an interfacial tension (with salt solution) of 18.7 dynes/cm and salt solution density of 1.26 g/cm^3, a maximum drop diameter can be calculated with equation [10][32,25]

$$D_{\max} = A_1\varepsilon^{-2/5}\left(\frac{\sigma}{\rho}\right)^{3/5} = 0.725\left(8.32x10^8\right)^{-2/5}\left(\frac{18.7}{1.26}\right)^{3/5} = 0.00099cm = 9.9\mu$$

Using a fluid viscosity of 3 cp. and a fluid density of 1.26 g/cm^3, a maximum drop diameter can also be calculated with equation [11]

$$D_{\max} \approx \varepsilon^{-1/4}\left(\frac{\mu}{\rho}\right)^{3/4} = \left(8.32x10^8\right)^{-1/4}(0.024)^{3/4} = 0.00036cm = 3.6\mu$$

With the above approaches maximum drop sizes of 1, 3.6, 9.9, and 10 micron are calculated for Isopar L® or solvent that passes through a standard slurry pump. These drop sizes are smaller than the maximum sized drop that will flow the liquid motion in Tank 50H Therefore, any drops that are drawn into the pump suction will be reduced to a size that will allow them to follow the liquid motion throughout Tank 50H. In addition, drops smaller than 1 – 10 micron will be further reduced in size as they pass through the pump.

The Isopar L® or other solvent components could adhere to solid surfaces in stagnant regions of the tank. MCU has not observed any issues with the solvent adhering to the process walls or equipment. Any Isopar L® that does adhere to tank internal surfaces could be removed by high shear jets (i.e., the pumps) or by slowly dissolving into the supernate solution. The Modifier will not evaporate. However, it is present in lower concentration than the Isopar L®.

5.0 CONCLUSIONS

The conclusions from this analysis follow.

- A single rotating standard slurry pump (with a 13.6 ft^2/s U_0D) will be able to blend miscible liquids (i.e., salt solution) in Tank 50H within 4.4 hours.
- Two rotating standard slurry pumps will be able to blend miscible liquids in Tank 50H within 3.1 hours.

- Three rotating standard slurry pumps will be able to blend miscible liquids in Tank 50H within 2.5 hours.
- A single rotating standard slurry pump (with a 13.6 ft^2/s U_0D) will disperse Isopar L® droplets that are less than or equal to 15 micron in diameter. If the droplets are less than 15 micron, they will be dispersed within 4.4 hours. Isopar L® provides a lower bound on the maximum size of droplets that will be dispersed by the slurry pumps in Tank 50H.
- Two rotating standard slurry pumps will disperse Isopar L® droplets less than 15 micron within 3.1 hours, and three rotating standard slurry pumps will disperse Isopar L® droplets less than 15 micron within 2.5 hours.
- If the Isopar L® droplets are drawn through the pump, they will be further reduced in size, with a maximum drop size less than 15 micron.

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