This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-96SR18500 with the U. S. Department of Energy.

WSRC-TR-2004-00036

ADMP MIXING OF TANK 18F SLUDGE: HISTORY, MODELING, TESTING, AND RESULTS (U)

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KEYWORDS:
Sludge Removal
Turbulent Jets
Slurry Pump

RETENTION - Permanent

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2/24/04

APPROVED FOR PUBLIC RELEASE

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SUMMARY

Residual radioactive waste was removed from Tank 18F in the F-Area Tank Farm at Savannah River Site (SRS), using the advanced design mixer pump (ADMP). Known as a slurry pump, the ADMP is a 55 foot long pump with an upper motor mounted to a steel super structure shown in Fig. 1, which spans the top of the waste tank. The motor is connected by a long vertical drive shaft to a centrifugal pump, which is submerged in waste near the tank bottom. The pump mixes, or slurries, the waste within the tank so that it may be transferred out of the tank. Tank 18F is a 1.3 million gallon, 85 foot diameter underground waste storage tank, which has no internal components such as cooling coils or structural supports. The tank contained a residual 47,000 gallons of nuclear waste, consisting of a gelatinous radioactive waste known as sludge and particulate zeolite.

The prediction of the ADMP success was based on nearly twenty five years of research and the application of that research to slurry pump technology. Many personnel at SRS and Pacific Northwest National Laboratories (PNNL) have significantly contributed to these efforts. This report summarizes that research which is pertinent to the ADMP performance in Tank 18F. In particular, a computational fluid dynamics (CFD) model was applied to predict the performance of the ADMP in Tank 18F.

DISCUSSION

Essentially, this discussion consists of a brief summary of several publications for the American Society of Mechanical Engineers, 2004, Fluids / Heat Transfer Conference. Each of the papers, Parts I – IV, is included as an appendix to this report. Modeling, testing, and the historical performance of slurry pumps were all needed to predict the results obtained in Tank 18F.

CFD Modeling

The first paper is "Mixing in Large Scale Tanks, Part I, Flow Modeling of Turbulent Mixing Jets". This paper summarizes the CFD model used to analyze the ability of the ADMP centrifugal pump to slurry waste into suspension. The paper concludes that sludge may remain at the tank wall, depending on the material properties.

This model captures the complex fluid dynamics for two related processes. One process concerns the jet as it is discharged from the pump nozzle. The CFD model agrees with the available engineering literature. The other process concerns the same jet as it impinges on the wall of the waste tank. Adequate solutions are unavailable in the literature to solve this problem. The CFD model was shown to agree with experimental data collected during testing at a full scale testing facility. Once the CFD model was validated using the full scale test results, a separate CFD model was used to predict Tank 18F slurry performance. Separate models were required since the location of the pump is different at the test facility than at Tank 18F. The Tank 18F fluid model was then used in conjunction with sludge material properties to provide a prediction of the ADMP's ability to mix sludge.

Full Scale Testing of the ADMP

The second paper is "Mixing in Large Scale Tanks, Part II, Full Scale Testing". This paper describes slurry pumps including the ADMP, pump operation, the test equipment used to collect data, and summarizes the experimental data collected while the ADMP was operated at the Full Tank Facility. This test facility is an 85 foot diameter, eight foot deep, full scale tank, which contained 70 inches of water for testing the ADMP. The pump was mounted to an overhead platform which straddles the tank, and the pump was located 26.5 feet from the center of the tank. The velocity of the water jetting from one of the 5200 gallon per minute discharge nozzles was measured at numerous locations in the tank. The resulting velocity test data were used to validate the CFD model discussed in Part I.

Slurry Pump Performance

The third paper is "Mixing in Large Scale Tanks, Part III, Predicting Slurry Pump Performance". This paper describes the effective cleaning radius (ECR), which has long been used at SRS to predict a slurry pump's ability to slurry waste. The ECR is the distance to which the jet from a pump will shear the sludge into suspension. The ECR is a function of material properties and pump performance characteristics, each of which is described in detail. A brief description of the ECR performance of various slurry pumps is provided, including the ADMP. The local velocity required to slurry sludge at a point could be approximated, once the ECR equation was validated from test results and waste removal results from other tanks, such as Tank 8F. This velocity was estimated to be 2.27 feet per second and was used in the CFD model of Part I to predict the locations in the tank where sludge would be suspended.

Additionally, zeolite was not expected to be removed from the tank during ADMP operations. The difference between zeolite and sludge suspension is related to the much faster settling rate of zeolite. The sludge particles remain in suspension long enough to be transferred out of the tank, while the zeolite particles do not.

Quarter Scale Modeling

A PNNL report documents the fast settling behavior of zeolite using a one quarter scale model of a waste tank, the ADMP, and a transfer pump. Summarized in Appendix D of this paper, the report is titled "Recommendations for Advanced Design Mixer Pump Operation in SRS Tank 18F, PNNL-14443". In addition to settling behavior of zeolite, that report provides insight into the time dependence of slurrying kaolin clay, which is used as a sludge simulant.

Tank 18F Results

The fourth paper is "Mixing in Large Scale Tanks, Part IV, Cleaning Nuclear Waste From Tanks". This paper summarizes the requirements and results of operating the ADMP in Tank 18F. The installation is described for both the slurry pump at the center of the tank and the transfer pump that removes the sludge slurry from the tank. The slurry pump was operated for several cleaning cycles to remove the sludge, and these cycles are described. The pump was noted to clean the sludge throughout most of the tank all the way to the tank wall, but 4320 gallons of waste remained, which is graphically mapped. Apparently, the material properties of this waste were different than anticipated. High density materials were assumed to be the problem, coupled with zeolite that was found during sampling of the tank after the cleaning operations were complete.

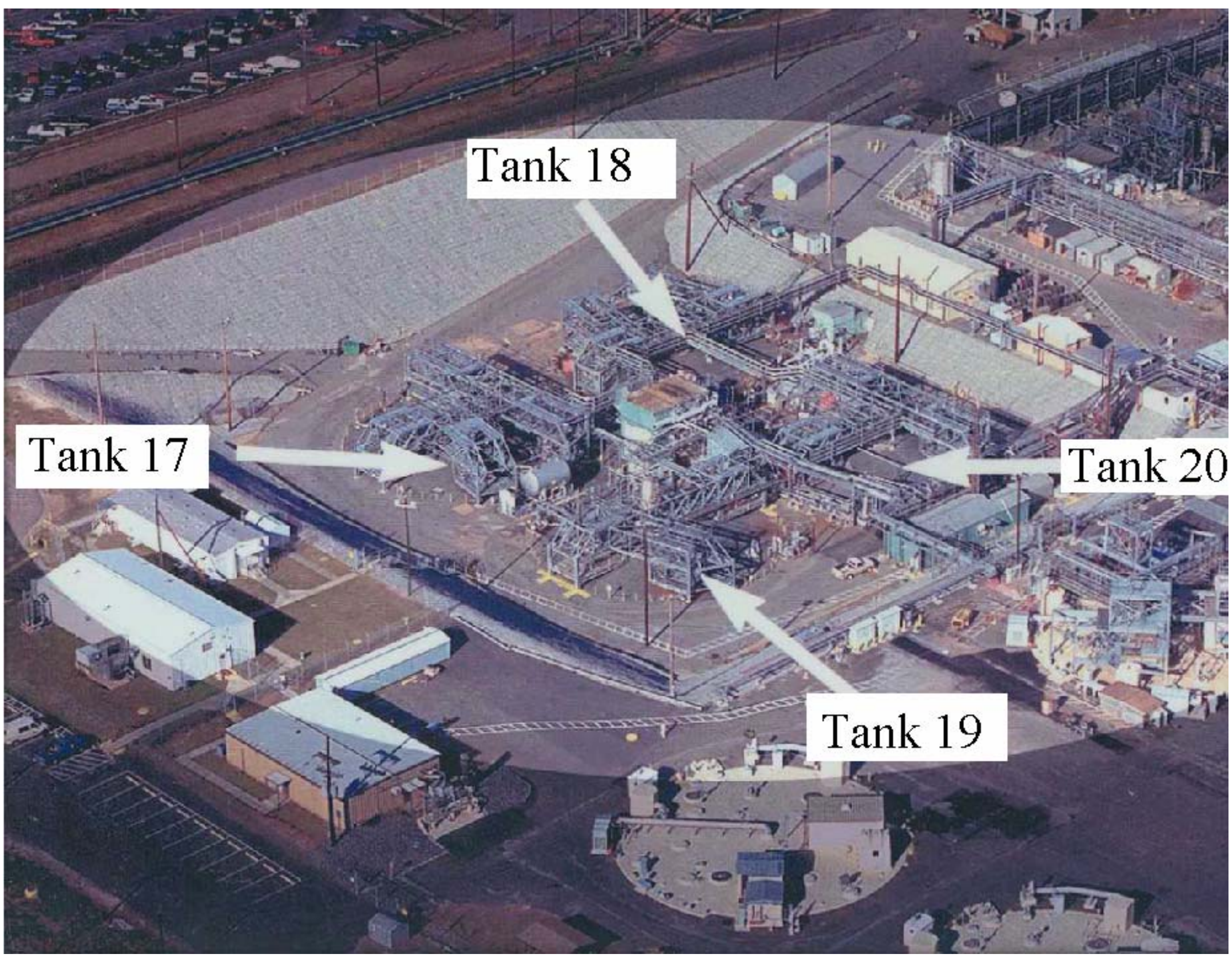

Figure 1: Location of Tank 18F in F-Tank Farm
Photo provided by Mark Lott, LWDP

Appendix 1

Mixing in Large Scale Tanks

I

Flow Modeling of Turbulent Jets

2004 ASME Heat Transfer / Fluids Engineering Summer Conference
Charlotte, N. C., July 11-15
HT-FED2004-56228

Mixing in Large Scale Tanks
Part I
Flow Modeling of Turbulent Mixing Jets

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ABSTRACT

Flow evolution models were developed to evaluate the performance of the new advanced design mixer pump (ADMP) for sludge mixing and removal operations in one of the large-scale Savannah River Site (SRS) waste tanks, Tank 18. This paper is the first in a series of four that describe the computational model and its validation, the experiment facility and the flow measurements used to provide the validation data, the extension of the computational results to real tank conditions through the use of existing sludge suspension data, and finally, the sludge removal results from actual Tank 18 operations using the new ADMP.

A computational fluid dynamics (CFD) approach was used to simulate the sludge removal operations. The models employed a three-dimensional representation of the tank with a two-equation turbulence model, since this approach was verified by both test and literature data. The discharge of the ADMP was modeled as oppositely directed hydraulic jets submerged at the center of the 85-ft diameter tank, with pump suction taken from below. The calculations were based on prototypic tank geometry and nominal operating conditions. In the analysis, the magnitude of the local velocity was used as a measure of slurrying and suspension capability.

The computational results showed that normal operations in Tank 18 with the ADMP mixer and a 70-in liquid level would provide adequate sludge removal in most regions of the tank. The exception was the region within about 1.2 ft of the tank wall, based on an historical minimum velocity required to suspend sludge.

Sensitivity results showed that a higher tank liquid level and a lower elevation of pump nozzle would result in better performance in suspending and removing the sludge. These results were consistent with experimental observations.

NOMENCLATURE

C_0, C_μ	constants
cp	centipoise (0.001 kg/m-sec)
D	diameter
d_0	nozzle diameter
H	height
ft	foot (0.3048 m)
g	gravitational acceleration
gpm	gallons per minute
k	turbulent kinetic energy
in	inch (0.0254 m)
m	meter
p	pressure
rpm	revolutions per minute
sec	seconds
SG	specific gravity
SRS	savannah River Site
t	time
U_0	nozzle velocity
$v(x)$	local velocity at point x
x	axial distance from nozzle
ε	rate of dissipation of turbulent kinetic energy
φ	nondimensional velocity
η	nondimensional axial distance from nozzle
μ	dynamic viscosity
ρ	density
τ	shear stress
Ω	vorticity

INTRODUCTION

Tank 18 is a 1.3 million-gallon capacity, single-wall waste tank located in the F-Tank Farmat Savannah River Site (SRS). It was placed into service as a receiver of low heat waste. The tank is an 85-foot diameter flat-bottomed, domed roof, cylindrical carbon steel tank with a height of about 34 ft with no cooling coils or internal supports. The waste in the tank was originally salt and sludge, but the salt has been dissolved and transferred to other tanks. The remaining sludge was hydraulically re-suspended and transferred to other tanks.

To suspend the settled sludge, water was added to Tank 18 as a slurry medium, and the ADMP was used to suspend the sludge. The ADMP has a bottom suction and two opposing discharge nozzles. The pump suction and nozzle diameters are 17.38 in and 6 in, respectively. The pump is immersed in the sludge layer, allowing a recirculating mixture of sludge and water to serve as the feed flow. The pump is located in the center of Tank 18. The cleaning pattern generated on the tank bottom when the pump rotates defines the effective cleaning radius (ECR). A maximum cleaning distance can be defined when the pump is stationary, and this distance is also used as the ECR. After the ADMP suspends the sludge, the waste is transferred to another tank. Detailed design and operating conditions are shown in Table 1. Waste removal operating conditions are discussed in Part IV, with the tank level maintained at about 70 inches as shown in Fig. 1.

The primary objective of the present work was to model Tank 18 with the existing ADMP mixer. The model was validated by benchmarking it against test data [1]. Then, the validated model was used to evaluate flow patterns in the tank and estimate the cleaning capabilities of the ADMP. Sensitivity analysis was performed to investigate key operating parameters. In addition, a smaller mixer with a 3-in nozzle diameter was evaluated for the sensitivity analysis as shown in Table 1. A schematic diagram for the Tank 18 system used in the analysis is illustrated in Fig. 1.

Parameters		Conditions
Tank dimensions (D_{tank} x H_{tank})		85 ft diameter x 70 in liquid level (or 40 in high$^+$)
Mixing Pump		ADMP
Pump nozzle diameter		6 in (or 3in$^+$)
Pump position	Vertical	27 in (23in$^+$) above tank bottom
	Horizontal	Center of tank
Tank fluid temperature		20^{o}C
Tank fluid		Water
		Slurry$^+$ (SG: 1.2, viscosity: 2 cp)
Flowrate for each nozzle		5200 gpm for ADMP (2600 gpm$^+$)
Nozzle velocity (U_o)		17.98 m/sec
Pump orientation		Indexed operation

Note:$^+$ This is for the sensitivity run.

Table 1: Reference design and operating conditions used for the analysis of Tank 18 model

The analysis results were used to evaluate hydraulic cleaning operations for waste removal. This information also assisted in the operating plan for Tank 18 waste removal and in identifying special requirements for sampling and monitoring the sludge suspension.

SOLUTION METHOD

The focus of the present work is suspending sludge particles with the ADMP. Prior to discussing the modeling approach, the literature results for a free turbulent jet flow are reviewed briefly, since the free jet flow is similar in many respects to the bounded wall jet. The previous work [2] and the literature data [3] show that when a turbulent jet of fluid is discharged from a nozzle with a diameter d_o, it both entrains fluids and expands. Most mixing action and entrainment takes place in the region of fully-developed flow which begins at a distance of approximately eight nozzle diameters from the exit plane. The non-dimensional velocity distribution φ_v along the jet axis of this region for a homogeneous fluid jet is given by [3]

$$\varphi_v = \left(\frac{v(x)}{U_o} \right) = C_o \left[\frac{x}{d_o} \right]^{-1} = C_o\, \eta^{-1} \qquad (1)$$

In Eq. (1), C_o is a constant determined by the turbulence characteristics of the jet, U_o the nozzle exit velocity, v(x) the local velocity at a point x, and x the distance from nozzle. Abramovich (1963) correlated experimental data for a free turbulent jet submerged in fluid using the non-dimensional form provided by Eq. (1). From his work, the proportionality constant C_o in Eq. (1) was determined to be 6.32. Equation (1) shows that the velocity at any point in the region of established flow is directly proportional to the product, $d_o \cdot U_o$. Thus, the axial entraining distance corresponding to minimum entrainment velocity can be estimated with nozzle diameter and flow rate.

The fluid domain for Tank 18 has both a solid boundary and a free surface boundary as the jet expands into the downstream region and ultimately recirculates via the suction on the bottom of the pump. The spreading fluid is retarded by the interaction with the wall, and the inner part of the flow may be expected to show a certain structural similarity to a boundary layer. Entrainment of quiescent fluid occurs near the outer edges of the flow, and accordingly resembles a free jet.

The decay of the axial jet velocity and the evolution of flow patterns are important phenomena affecting sludge suspension and mixing operations. A measure of the ability to shear the sludge layer, the scouring wall shear, is directly related to the local fluid velocity. The initial movement of solids deposited on the bottom of the tank identifies the critical condition or initial scour. It is usually described by two criteria, the minimum flow velocity and the frictional shear to scour and initiate movement of deposited solids particles. From these two criteria, a local fluid velocity can be determined as a performance indicator for adequate mixing or suspension.

When liquid flow passes over a stationary cohesive sludge mound containing solid particles, the flow results in hydrodynamic forces being exerted on individual particles in the mound. The initial movement of the top layer of the mound is called the critical or incipient condition of erosion. The degree of erosion resistance for a given particle to the hydrodynamic forces of the flowing fluid depends on the cohesion and adhesion forces. An increase in the fluid momentum causes an increase in the magnitude of the hydrodynamic forces. Hence, for a particular stationary sludge mound, a condition is eventually reached at which particles in the movable bed are not able to resist the hydrodynamic forces and solids in the top layer start to erode.

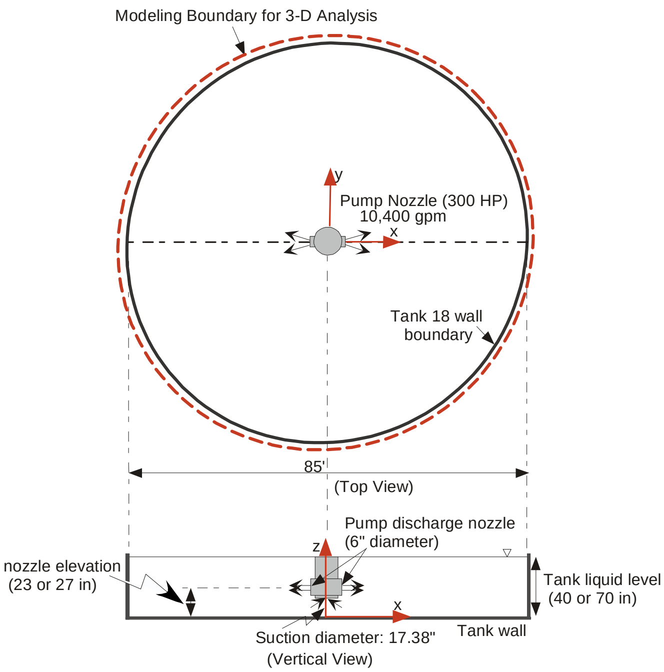

Figure 1: Schematic of Tank 18 operation system showing the present modeling boundary

The literature data show that large particles are more easily eroded by streams than smaller ones. This phenomenon is more pronounced with small particles since the cohesive forces increase with decreasing size.

Figure 2 shows for each particle size a certain velocity below which it will experience sedimentation, and a critical scour velocity, above which it will be eroded. Fluid velocity between these two velocities will suspend or transport solids of that size. A velocity of 2.27 ft/sec will erode the sludge layer for the particle sizes larger than clay material (about 5 microns). The literature data show that fluid velocity, particle size, specific gravity of particle, and tank liquid level are key parameters associated with particle suspension. It should be emphasized that the incipient velocity of erosion is actually dependent on the critical shear stress at which incipient sediment begins to move. The critical shear stress of actual cohesive materials contained in Tank 18 depends on the composition of the different sludge material, the particle-size distribution, particle shape, and packing. A minimum fluid velocity for suspending cohesive sludge at Savannah River Site (SRS) has been confirmed and established as 2.27 ft/sec.[5] Thus, the local fluid velocity at any distance from the nozzle can be employed as a measure of the slurrying capability of the ADMP.

Two types of materials are identified in Tank 18, both of which are discussed in detail in Part III of this four part series of papers. One is zeolite particles. Because it is fast settling, it can be suspended by the slurry pumps, but it cannot be effectively removed from the tank using a discharge pump. The other material is sludge, which can be removed because it remains in suspension longer. Unfortunately there are scant data available for particle dimensions in the sludge. However, studies of the ECR based on measured yield stress and density provide reasonable estimates for both the ECR and the velocity at the ECR required to suspend sludge. A complete discussion of material properties and their relationship to the minimum required velocity of 2.27 feet/sec is provided in Part III.

COMPUTATIONAL MODELING APPROACH

The analysis consists of two major parts. One part is to develop a model for the test facility used to simulate Tank 18 to benchmark the calculations with no sludge mounds. The second part is to calculate the flow for the turbulent jet induced by the mixer and to estimate the extent of the slurry mixing zone in Tank 18. Flow obstructions such as a cohesive sludge mound are also considered, but erosion of the sludge surface is not.

The modeling work considers four basic cases with different boundary conditions to investigate how sensitive the flow patterns are to different tank levels and pump elevations. Flow patterns were calculated to evaluate the effects on jet dissipation and suspension efficiency.

A three-dimensional CFD approach was used to calculate velocity distributions. The commercial finite volume code, FLUENT [7], was used to create a prototypic geometry file in a non-orthogonal mesh environment. The model geometry was created using the body-fitted coordinate system and structured multi-block grids. Reference design conditions including the mixing pump are given in Table 1. The ADMP has 6 inch nozzle, and was compared to a theoretical pump having a smaller nozzle diameter of 3 inches for the sensitivity study.

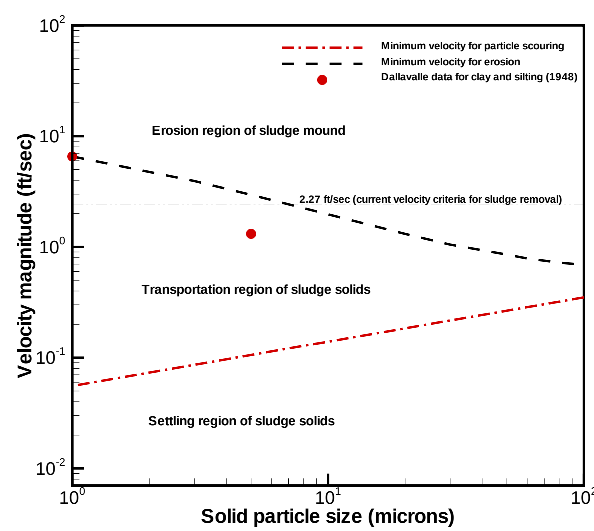

Figure 2: Velocity criteria for deposition, scouring, and erosion of sludge solids based on Graf's correlation [5] and Dallavalle's data [7]

Detailed wave motion of the free surface at the top of the tank was neglected for computational efficiency. That behavior does not have a significant impact on the flow patterns inside the slurry region in a deep tank [10]. The fluid properties of water were evaluated at room temperature (20°C). The flow conditions for the pump operations are assumed to be fully turbulent since Reynolds numbers for typical operating conditions are in the range of 10^8 based on the pump nozzle conditions. A standard two-equation turbulence model, the $k-\varepsilon$ model [7], was used since the benchmarking results showed that the two-equation model predicts the flow evolution of a turbulent jet in a large stagnant fluid domain with reasonable accuracy. This model specifies the turbulent or "eddy" viscosity μ_t by the empirical equation.

$$\mu_t = \left(\frac{C_\mu \rho_f k^2}{\varepsilon} \right) \tag{2}$$

C_μ is an empirical constant. In the present calculations, C_μ is 0.09. The turbulent viscosity is computed by solving two transport equations for k (turbulent kinetic energy) and ε (rate of dissipation of turbulent energy). The governing equations to be solved are composed of one continuity equation, three momentum equations for the three component directions (x, y, and z directions), and two constitutive equations for the turbulence parameters.

Water was used to simulate the fluid in the tank assuming that it would give an acceptable representation of the flow patterns. Sensitivity studies were performed using other fluid properties. For an indexed pump model, the pump is in a fixed orientation along a radial direction.

RESULTS AND DISCUSSION

Three-dimensional flow models were developed and calculations were benchmarked against the SRS test results. The benchmarked model was applied to the estimation of flow circulation patterns within Tank 18 and the investigations of steady-state and transient flow responses to jet velocities and tank liquid levels for the ADMP mixer submerged in Tank 18. A two-dimensional approach was initially tried to investigate computational times and numerical convergence, and to assess the ability of the code to capture important flow phenomena associated with the mixing behavior of a submerged jet. The results showed that the two-dimensional results overestimate the flow velocity by more than 40% when compared to test results. This stems partly from neglecting the presence of the tank bottom, and partly from the two-dimensional model not having the ability to capture viscous dissipation due to vertical flow rotation. This is shown mathematically in the viscous term in the fluid momentum equation,

$$\rho \frac{D\vec{v}}{Dt} = -\nabla p - \nabla \bullet \boldsymbol{\tau} + \rho \vec{g}$$

from which the viscous term can be expanded as

$$(\nabla \bullet \boldsymbol{\tau})_{shear} = \mu \nabla \bullet (\nabla \vec{v})$$

$$= \mu \nabla (\nabla \bullet \vec{v}) - \mu \nabla \times (\nabla \times \vec{v})$$
$$= \mu \nabla (\nabla \bullet \vec{v}) - \mu \nabla \times \vec{\Omega} \tag{3}$$

In Eq. (3), μ is dynamic viscosity and $\vec{\Omega}$ is the vorticity related to the fluid rotation. The first term on the right-hand side of Eq. (3) is associated with fluid compressibilty, and the second term is related to the vortex formation generated by the evolution of jet flow. For an incompressible liquid, the first term is zero. In the vorticity term, motion related to Ω_x and Ω_y cannot be captured, since these two components are zero in a two-dimensional model.

From a nodalization study, an optimum number of about 260,000 nodes was established. Very fine meshes, less than 0.2 in long, were used near the nozzle exit and suction inlet to capture the high velocity gradients in those locations. The results for the simulation showed that jet flows from the two nozzles were dissipated quickly along the principal discharge directions. As soon as the flow exits the nozzle, four main circulation cells are generated in the tank, one on each side of the centerline for each nozzle. Within about 10 seconds after starting, the nozzle facing the center of the tank created two dominant cells, but after that, all four cells developed to about the same size. Transient flow path lines created using the Lagrangian integral method along the flow direction are shown in Fig. 3. This circulating flow pattern help to understand the suspension and removal of waste sludge.

Flow tests at the full tank mockup facility [1] were conducted using the ADMP. The primary purpose of the tests was to obtain a database for benchmarking and validating the models. Flow tests were conducted in the 85 foot tank filled to a 70-inch liquid height. Flow velocities were measured at two different elevations, 3 inches and 27 inches from the bottom. At each elevation, velocities were measured at various locations near the centerline of the jet discharge using a Marsh-McBirney™ measurement probe [9]. A detailed mapping of the measurement sensor locations and a summary of numerical data are presented in a companion paper [1].

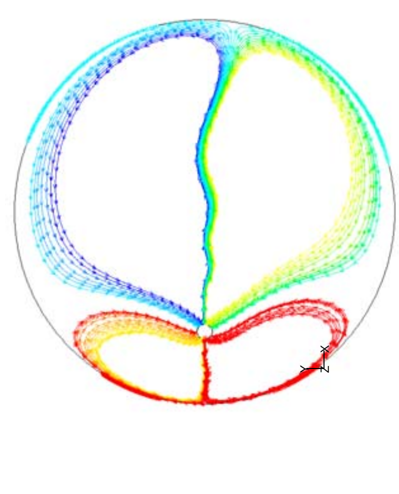

Figure 3: Flow paths around the tank at 10 seconds after the start of the pump on the discharge plane of the Full Tank facility for the initially quiescent tank

Comparison of CFD Results to Experimental Results

The results of the three-dimensional calculation are compared with the test results near the center of the discharge direction of the nozzle. The results at the 27 in plane are in agreement with the test data to within about 25%. The model predictions were also compared to test data measured at locations less than 25^o from the discharge direction at the 3 in elevation. The calculated results agree with data to within about 20% as shown in Fig. 4. The model results are benchmarked against literature data for the high velocity region not far from the nozzle exit. The predictions of fluid velocity along the axial direction of the jet agree with the data within about 10% as shown in Fig. 5. The model predictions are compared with all the Full Tank facility test data in Fig. 6. Several data points at remote locations far away from the central axis of the jet flow are significantly higher than the predictions, but the absolute velocities are much smaller than the minimum suspension velocity for zeolite observed in plant operations (~1.6 ft/sec). The differences are due to secondary flows created by pump oscillations and flow obstructions neglected in the computational model. The results show that jet velocity decays quickly near the exit of the nozzle due mainly to the turbulent dissipation through the fluid medium.

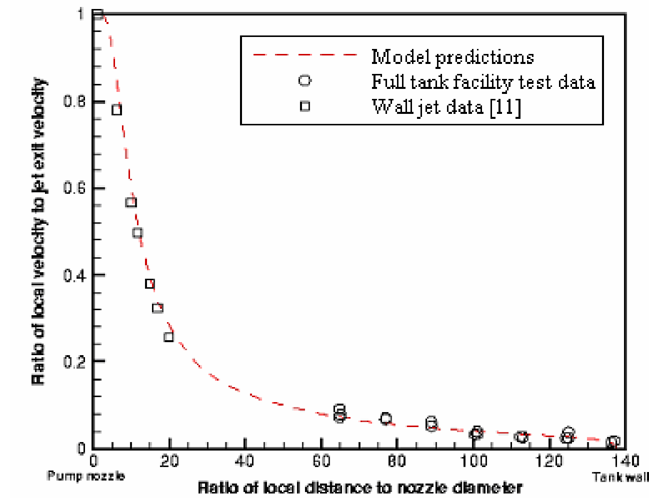

Figure 5: Benchmarking results of the Full Tank facility model against the SRS test data and literature data

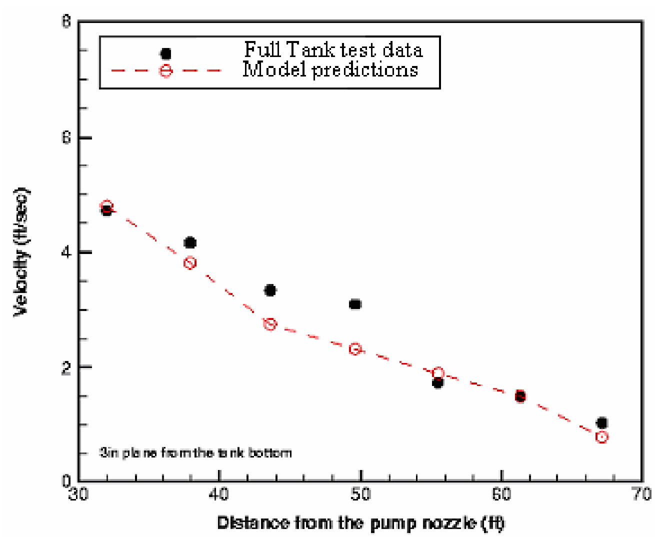

Figure 4: Comparison of the Full Tank facility model predictions of the discharge velocities with the test data near the centerline of the pump discharge direction at the plane 3 in above the tank bottom.

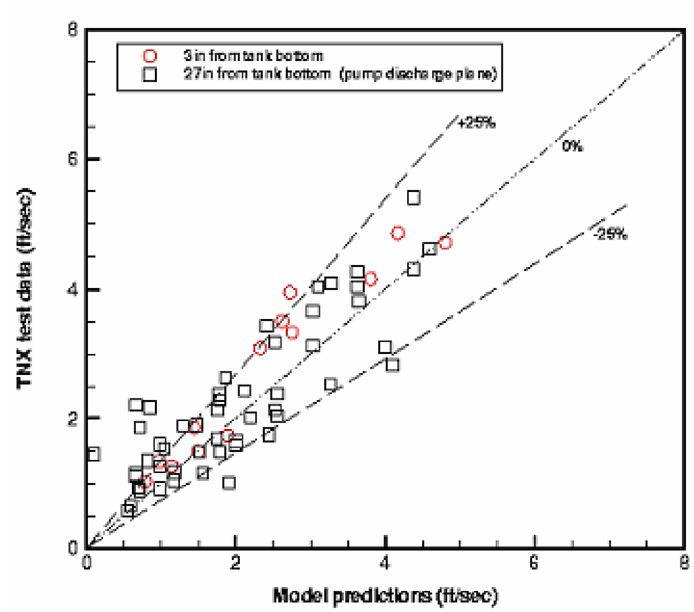

Figure 6: Comparison of the Full Tank facility model predictions with all of the Full Tank facility test data

Fluid Transients Following Pump Startup

Transient behavior of the flow evolution was examined to evaluate the development of the cleaning distance from a fixed pump. Figure 7 shows the development of the modeled flow patterns at the Full Tank facility. The model showed that the jet flow extended to about 19 feet from the nozzle within about 2 seconds, and that it reached the tank wall about 10 seconds after pump start.

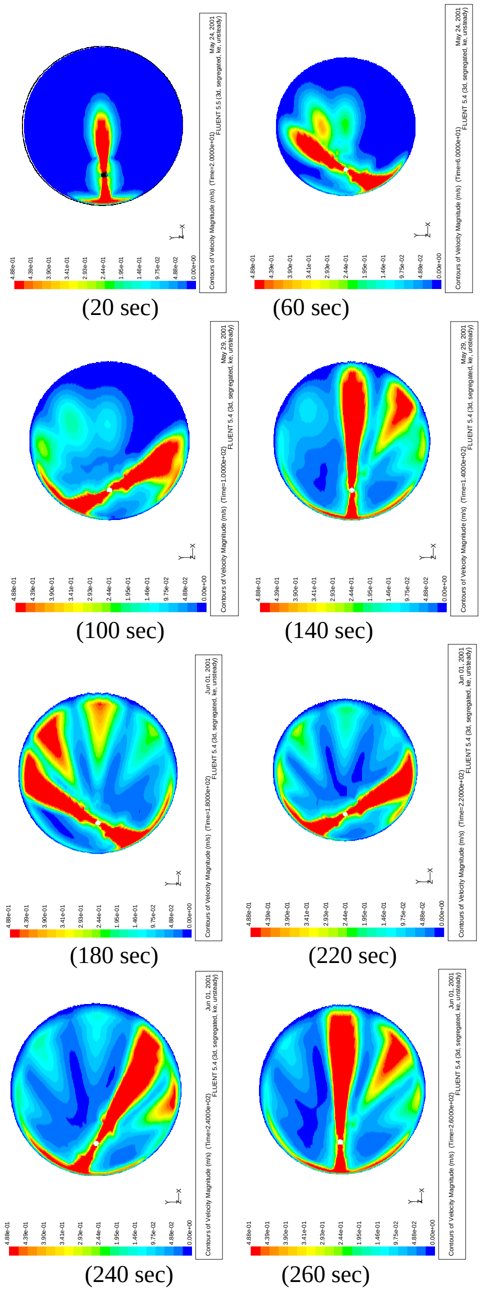

Figure 7: Transient flow evolution results of the TNX full tank model with 0.25 rpm counterclockwise pump rotation at the discharge plane 27 in above the tank bottom

Steady State Operation of the Pump

Steady-state flow patterns were established within about 1 minute. The steady-state flow patterns on the horizontal discharge plane follow a series of parabolic curves similar to that of a free jet as shown in Fig. 8. Vertical velocity profiles are changed from a bell-shaped curve near the exit of the nozzle to a near-uniform velocity near the tank boundary as shown in Fig. 9. This is consistent with literature data [4]. The results show that when the pump is located 27 inches above the tank floor, local velocity reduces to the 2.27 feet/sec minimum sludge removal velocity at about 40 feet distant from the nozzle exit.

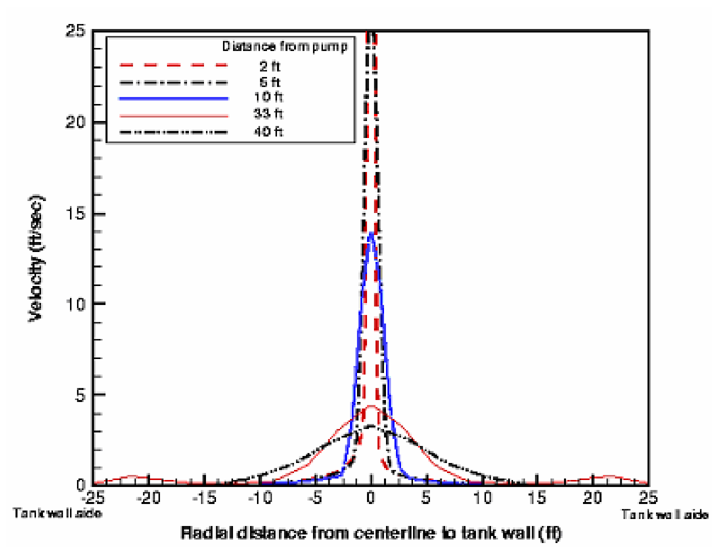

Figure 8: Steady-state horizontal velocity profiles for various distances from the pump at the nozzle discharge plane (27 inches above tank bottom): 3D Model Results for the Full Tank Facility with 70" liquid level

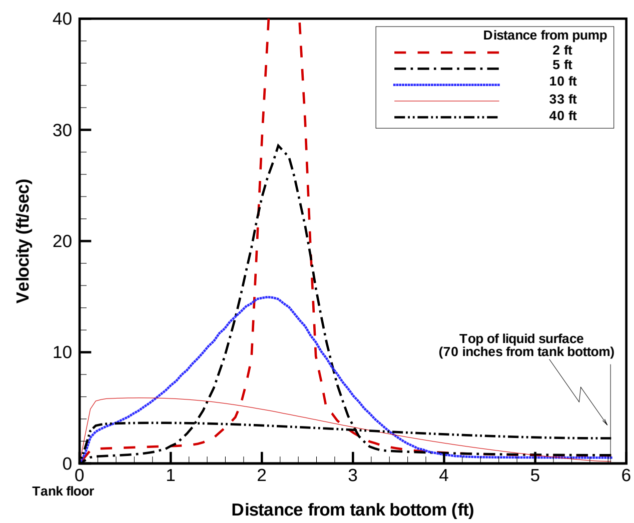

Figure 9: Steady-state vertical velocity profiles for various distances from the pump (pump nozzle is located 2.25 ft from tank bottom): 3D Model Results for the Full Tank Facility with 70" liquid level

Effects of Tank Liquid Level and Pump Nozzle Elevation on Sludge Mixing

Sludge removal capability was evaluated for two different liquid levels as listed in Table 1, 70 inches and 40 inches. The results are compared in Fig. 10. The high tank level is generally more efficient. The results showed that the sludge removal capability is about the same within about 5 ft of the pump (corresponding to about 10 nozzle diameters), but the velocity difference between the two cases becomes larger as the distance increases from 10 ft to 40 ft (near the wall boundary). This is mainly due to the larger momentum dissipation from the free surface in the case of a lower tank level as shown in Figs. 11 - 14. The sensitivity results [2] show that for a given tank level, the lower pump elevation provide a better mixing performance in terms of local velocity requirement for solid suspension.

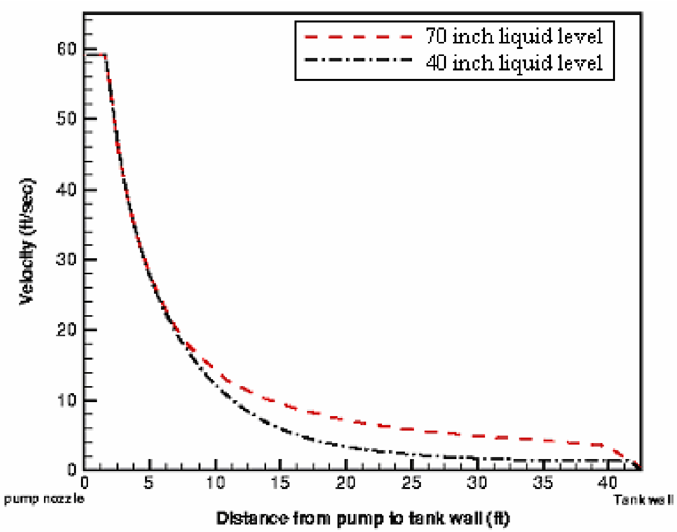

Figure 10: Velocity profiles for various distances from the pump at the nozzle discharge plane (27 inches above tank bottom)

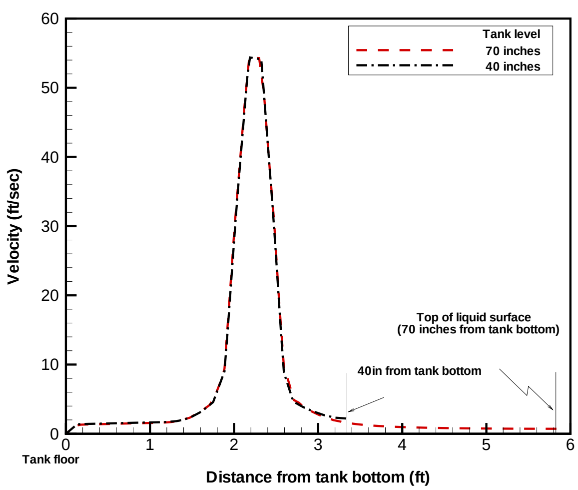

Figure 11: Velocity profiles for different tank levels (2 ft from the pump)

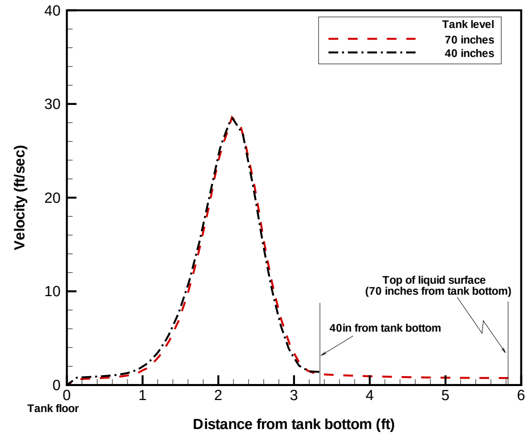

Figure 12: Velocity profiles for different tank levels (5 ft from the pump)

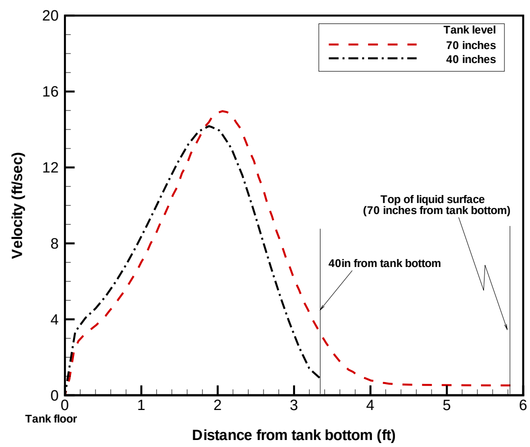

Figure 13: Velocity profiles for different tank levels (10 ft from the pump)

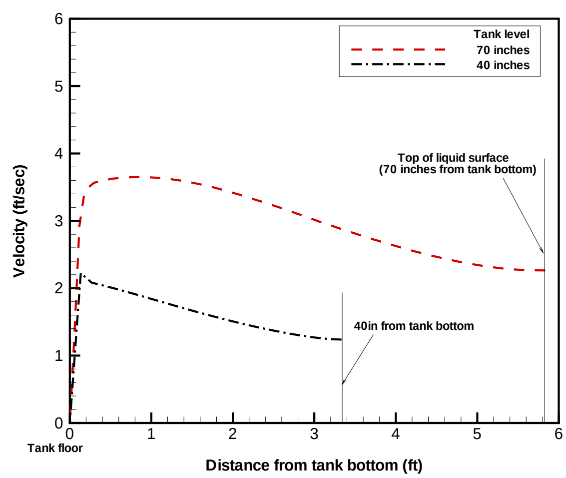

Figure 14: Vertical velocity profiles of two different tank levels (40 ft from the pump)

Effects of Pump Rotation on Sludge Mixing

Sensitivity results show that rotational effects on flow patterns are negligible for the 40 inch tank level. This is similar to the flow behavior seen for the high tank level. Graphical comparisons between the cases with and without pump rotation for the discharge plane and the plane 3 in above the tank bottom are shown in Fig. 15.

It is important to recognize that local velocity is not the only parameter affecting the ability of the liquid stream to suspend sludge or aggregate materials when tank sludge has a spatially non-uniform structure, or it is composed of cohesive aggregate. The length of time that the sludge is exposed to the liquid stream is also important in suspending cohesive sludge, and this effect is not captured in the present analysis. A longer exposure time, as would be the case for an indexed pump rather than a continuously rotating pump, could reasonably be expected to result in greater suspension or erosion of the sludge layer at a given pump position. Exposure time for an indexed pump is estimated from previous operational experience. Testing in Kaolin clay indicated a three percent increase in the ECR when the pump was not rotating [5]. Even so, the quarter scale pump testing indicated that better mixing is obtained during rotation.

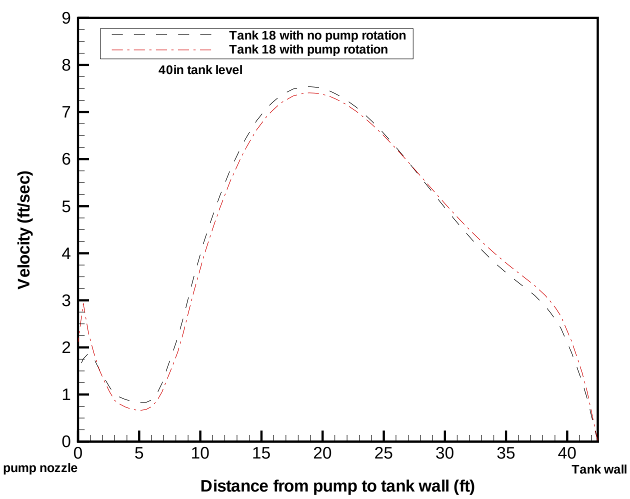

Figure 15: Downstream evolutions of Tank 18 ADMP with and without pump rotations for 40 in tank level at the discharge plane 3 inches above the tank bottom.

Effects of the Nozzle Diameter on Sludge Mixing

A smaller nozzle diameter was evaluated to examine its effectiveness for sludge removal. A reduced flow rate (2600 gpm per nozzle) and a 3-inch nozzle diameter were evaluated. Figure 16 compares velocity distributions at the plane 3 inches above the tank floor between the 6-inch nozzle and the 3 inch nozzle with no pump rotation. As shown in the figure, the hydraulic capability for sludge removal is improved by about 10% with the smaller nozzle.

Figure 17 shows comparisons of steady-state velocity profiles for the three cases at the discharge plane of the mixer. This figure also shows an empirical correlation and test data for free and wall jets available in the literature [4, 11]. The results show that a smaller mixer has better performance in terms of jet flow dissipation along the discharge direction. Transient flow evolution results of the full tank model with 0.25 rpm counterclockwise pump rotation at the discharge plane are shown in Fig. 15.

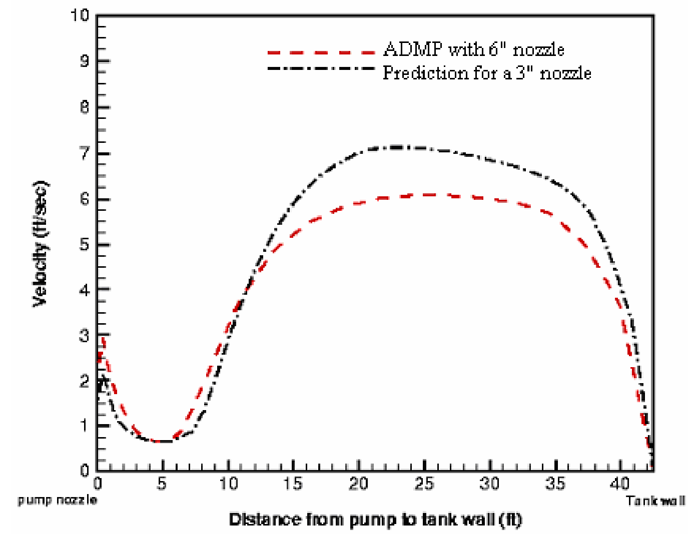

Figure 16: Horizontal velocity profiles along the downstream directions of the pump nozzles of Tank 18 with ADMP 6-in mixer and a mixer with a 3 inch nozzle. Velocities at the plane 3 inches above the tank bottom

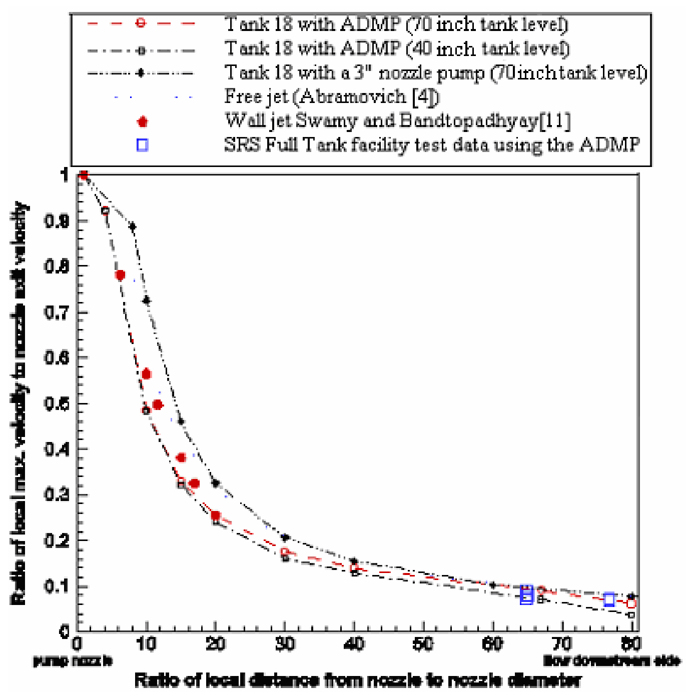

Figure 17: Comparisons of steady-state non-dimensional velocity profiles of Tank 18 at the discharge plane of ADMP mixer 27 in above tank bottom with literature data

Effects of Fluid Properties on Sludge Mixing

Most analyses were performed using water at the reference operating conditions. A fluid with a different Specific gravity is listed in Table 1, and was used to examine the sensitivity of the flow patterns to a change in specific gravity. Typically the fluid above the sludge, known as supernate, has a specific gravity of less than 1.2. The results show that the flow patterns are not sensitive to this change in specific gravity. At the discharge plane, there are no apparent differences in flow evolution. At the lower elevation 3 inches above the tank floor, slurry flow around the horizontal discharge direction of the nozzle dies out slightly more quickly than for water. The radial flow behavior induced by the slurry is larger than that of water because of the increased diffusion in the momentum transport. However, when the ECR is defined as the distance over which the jet velocity exceeds the minimum suspension velocity, differences between water and slurry are negligible for the conditions considered here.

SUMMARY AND CONCLUSIONS

Tank 18 simulation models with the ADMP mixer has been developed. Calculations have been performed to benchmark the models with full tank facility test data and to assess the efficiency of sludge suspension and removal operations during steady-state and transient pump operations. Solid obstructions other than the pump components, and free surface motion of the tank liquid were neglected.

A three-dimensional analysis with a two-equation turbulence model was performed with FLUENT™. The computed results were validated with Full tank facility test and literature data. Rotational effects of the pump were considered to estimate the impact on sludge suspension and removal assuming that local fluid velocity can be used as a measure of slurrying and mixing efficiency. For a minimum suspension velocity of 2.27 ft/sec, the results indicated that the existing ADMP mixer would provide adequate sludge removal from the tank with a 70 in liquid level except for a wall boundary of about 2 ft.

The CFD simulation results for the ADMP mixer showed that steady-state flow patterns were reached within about 60 seconds. The results also showed that when the pump was rotated in a continuous and one-way direction, the operational time to reach steady-state conditions was much longer. In addition, when the pump is off-center, times to reach steady-state flow patterns are much longer than the case with the pump located at the tank center.

The main conclusions are as follows:

- Model predictions agree with test data within about 25%. In the velocity ranges where sludge removal is required, the model provides a reasonable estimate when compared to actual test data. The predictions are in good agreement with wall jet data available in the literature.
- The difference between a fixed pump and a rotating pump is small, and is well within the uncertainty of the present calculations. A rotating pump is somewhat better than fixed because of secondary flows. The effect of pump rotation is more pronounced when the pump is located off-center and the tank liquid level is lower.
- A higher tank level results in better sludge mixing.
- A smaller nozzle size with an identical $Uo \cdot do$ has better performance for suspending and removing the sludge.
- The maximum clearing distance is not sensitive to the slurry fluid properties.
- Local velocities adjacent to the tank wall are potentially lower than those needed to remove sludge.
- Two dimensional models of the flow are inadequate.

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Appendix 2

Mixing in Large Scale Tanks

II

Full Scale Pump Testing

2004 ASME Heat Transfer / Fluids Engineering Summer Conference
Charlotte, N. C., July 11-15

HT-FED2004-56229

MIXING IN LARGE SCALE TANKS
PART II
FULL SCALE PUMP TESTING

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ABSTRACT
Velocities in the discharge jet of a submerged Advanced Design Mixer Pump (ADMP) were measured in an eighty-five foot diameter tank, and were successfully compared to predictions from a computational fluid dynamics (CFD) model. The ADMP is a 10400 gallon per minute, dual nozzle pump ultimately used to mix the contents of a nuclear waste tank prior to further processing. The pump was initially installed, operated, and tested in a full-diameter test facility tank containing seventy inches of water. The horizontal discharge jets of the pump established a steady flow pattern in the tank, and the resulting velocities were measured throughout the tank. The data from these measurements were statistically averaged to obtain local velocities at each of the measured points in the tank. This experimental velocity mapping was compared to the results of a CFD model and showed good agreement with the calculated velocities.

NOMENCLATURE

ADMP	advanced design mixer pump
CFD	computational fluid dynamics
SRS	Savannah River Site
gpm	gallons per minute
HP	horsepower
in	inches (0.0254 m)
ft	feet (0.3054 m)
m	meters
rpm	revolutions per minute
Hz	Hertz (cycles/sec)

INTRODUCTION
This paper focuses on the experimental validation of flow patterns induced by the jets of a single centrifugal pump in a full scale test facility 85-foot diameter tank, known as the Full Tank Facility. The use of centrifugal mixer pumps to slurry settled solids in nuclear waste storage tanks is a common practice at the Savannah River Site (SRS) in South Carolina. Solids were originally pumped into the waste storage tanks as radioactive slurry, which settled to the tank bottoms. Traditional waste removal methods involve shearing and re-suspending the sludge solids in a liquid with the jets of multiple mixer pumps. The suspended solids are then removed from the waste tank with a transfer pump. To mix the contents of Tank 18F, a single, larger slurry pump is used, and its installation in Tank 18F is discussed in detail in Part IV (Augeri [1]). This single pump is known as the ADMP and was tested at the Full Tank Facility. This paper compares the measurement of discharge jet velocities from the full-scale test results to the computational fluid dynamic results discussed in Part I (Lee, Dimenna [2]).

SLURRY PUMP HISTORY
Previous Pump Designs
SRS has successfully used numerous slurry pump designs from different manufacturers over the last 25 years to mix the contents of radioactive waste storage tanks (Sharpe, Stefanko [3]). One of these slurry pump designs is the model 91103, by Lawrence Pumps, Inc. [4], which is described in detail by Leishear and Stefanko [5]. Shown in Fig. 1, this pump is similar to the ADMP.

The model 91103 is a long shaft, vertical pump, which includes a top mounted motor, a rotating turntable, a segmented drive shaft, a centrifugal impeller, and a pipe column that surrounds the shaft and suspends the pump inside the tank. Power is provided to the motor through slip rings to permit the pump to rotate continuously at 1/5 to 1/4 rpm. A smaller separate motor drives the turntable. Shaft sections are coupled together between the motor and the impeller at the bottom of the pump. Enclosing the shaft, the column contains pressurized water to prevent diffusion of waste into the column through the lower seal and out onto the upper tank surface through the upper seal. These mechanical seals are mounted to the drive shaft at the top and bottom of the pump to contain the pressure in the column. Typically, several pumps are inserted into the waste tanks through cylindrical openings (risers) and mounted to the rotating turntables. Once installed in a waste tank, the pumps act as mixers by drawing nuclear waste into the pump suction and discharging a high velocity stream of liquid back into the tank. The discharge stream, or jet, entrains waste as it expands into the tank and erodes the sedimented waste, called sludge, from the tank bottom into suspension. The pumps typically have two tangentially opposed discharge nozzles. The dual nozzle configuration was validated during early testing of the pumps. A single nozzle design caused significant bending of the pump assembly, in the range of 5 - 6 inches. A four nozzle, or quad volute, design, of course, cut the flow in half at each of the nozzles since there were twice as many flow paths for the same impeller. Also, two radially opposed nozzles result in a decrease in discharge flow, since added friction losses occurr with the radial design. The model 91103 produces a 26.28 m/sec (86.2 ft/sec) discharge velocity at each of the 1.5 inch diameter nozzles at an operating speed of 1785 rpm at 150 HP. A similarly designed model VRP 2x15, by Sulzer-Bingham, Inc. [6], has a discharge velocity of 16.62 m/sec (54.5 ft/sec) at an operational speed of 1750 rpm at 150 HP. The performance for these pumps is covered in detail in Part III (Leishear, et. al. [7]) of this series.

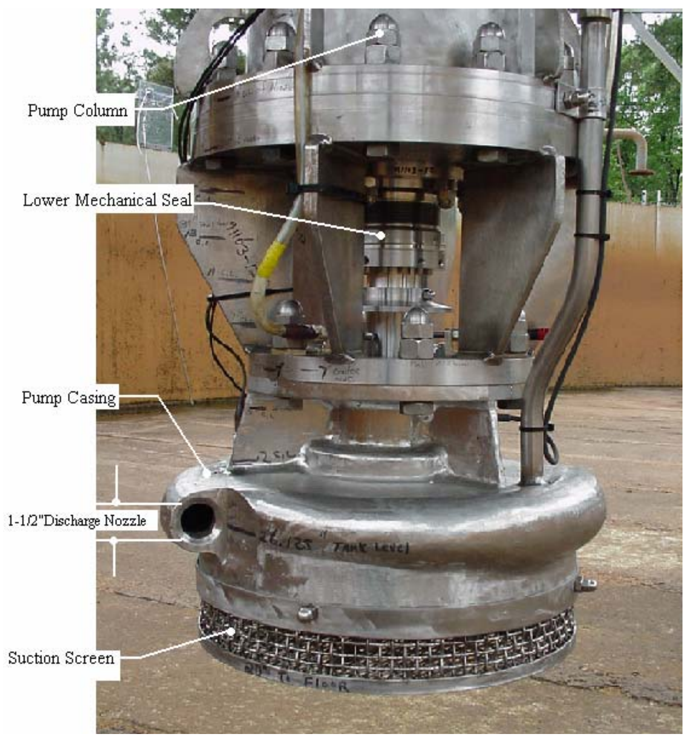

Figure 1: Model 91103

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Parallel to the operation of the 91103 and VRP 2x15 model pumps, a program to resolve technical issues with long-shaft pumps led to the design of two developmental pumps of equal capacity. One was a submersible pump built by Hazleton pumps, which was successfully installed and operated to remove sludge from a tank at the DOE Hanford facility. The two dimensional model that predicted the pump performance is documented by Onishi, et. al. [8]. The other developmental pump was the ADMP, which had several new features. The column was pressurized with air rather than water. Oil lubricated ball bearings were used to restrain lateral shaft motion rather than water lubricated journal bearings. Also, the higher flow of the ADMP was obtained by using a mixed axial / radial flow impeller rather than a radial flow impeller used in the earlier models. The ADMP rotates back and forth through a 180 degree angle rather than continuously rotating. The ADMP has a larger diameter than the earlier pumps. Otherwise, the ADMP design was similar to the existing designs. The ADMP is the focus for the remainder of this paper.

ADMP Description

The ADMP is a 55 foot long pump built by Lawrence Pumps, Inc [9] and is shown in Fig. 2. Examination of the figure reveals that the pump is made up of several shaft sections and column sections. Each column section is individually removable and has one thrust bearing, one radial bearing, and one splined shaft. Column sections are bolted together at flanges. Bearings are oil lubricated and fed by the individual bearing housing. Shaft sections connect to each other by flexible couplings. The column was filled with dried filtered air while installed at both the Full Tank Facility and when later installed in the waste tank. Air containment is achieved through mechanical seals, metal o-rings, and graphite gaskets.

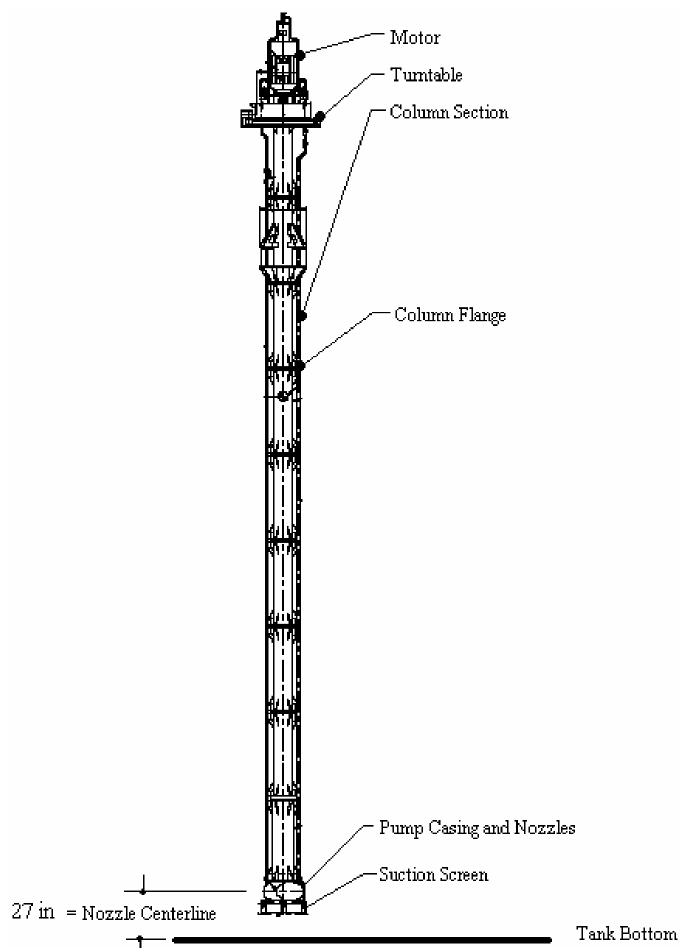

Figure 2: ADMP Elevation

The ADMP column is made up of 16 and 18 NPS, Schedule 40 pipe. The pump has a 39-inch diameter casing, an 18-inch diameter mixed flow impeller, and a 300 HP (6 pole) induction motor. Figure 3 shows the pump casing and impeller, and the two tangential nozzles which are part of the casing. Figures 4 and 5 respectively show a side view and an end view of the pump and the impeller with the pump casing removed. Each nozzle is 6 inches in diameter and faces an opposing direction. Performance is 5200 gpm (per nozzle) at 1185 rpm and 52 feet of head. The nozzle discharge velocity is 17.97 m/sec (58.9 ft/sec). This is a high velocity pump, which is evident by the nozzle discharge shown in Fig. 6. This particular photo was obtained while the tank level was significantly below the typical operating level for the Full Tank Facility or the waste tank. A photo of the pump operating at a typical liquid level is provided in Part IV.

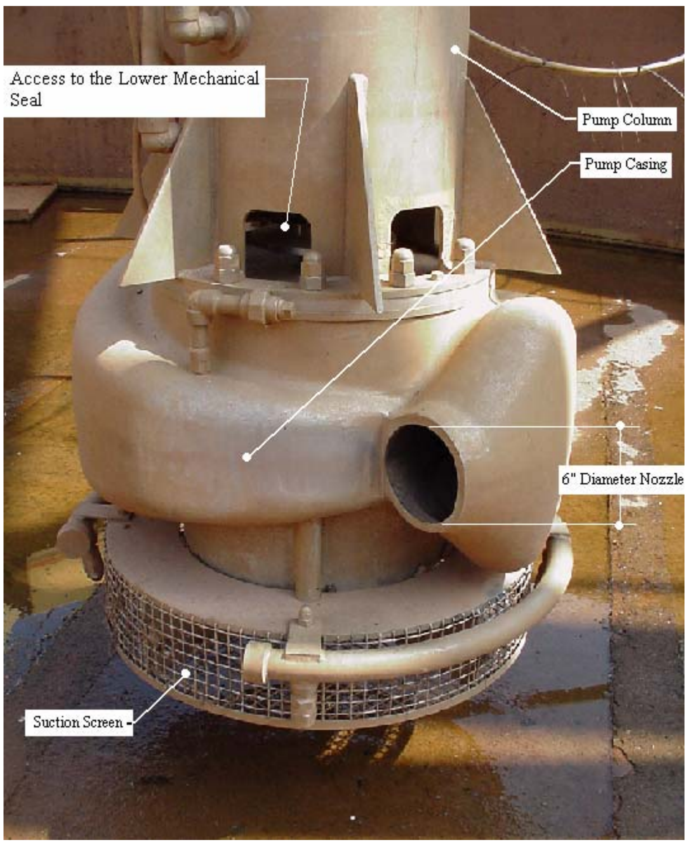

Figure 3: ADMP Pump Casing, Nozzle, and Suction Screen

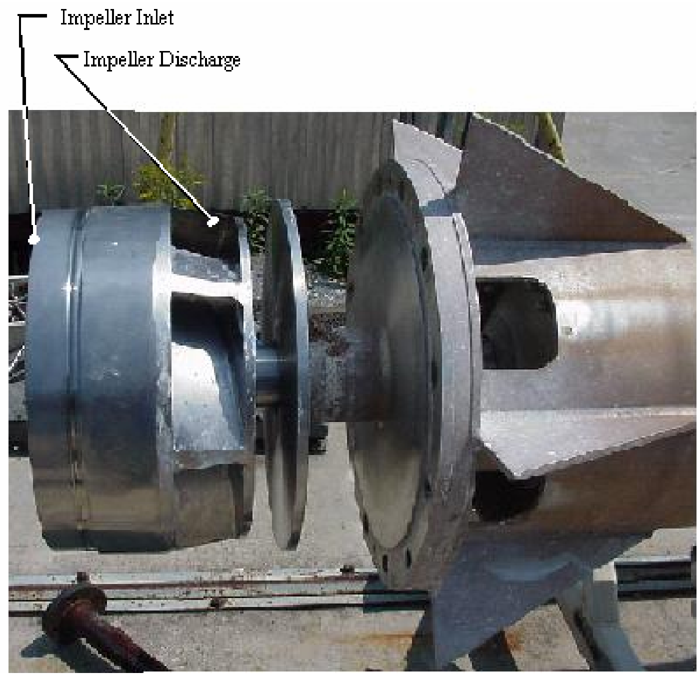

Figure 4: ADMP Side View with the Pump Casing Removed

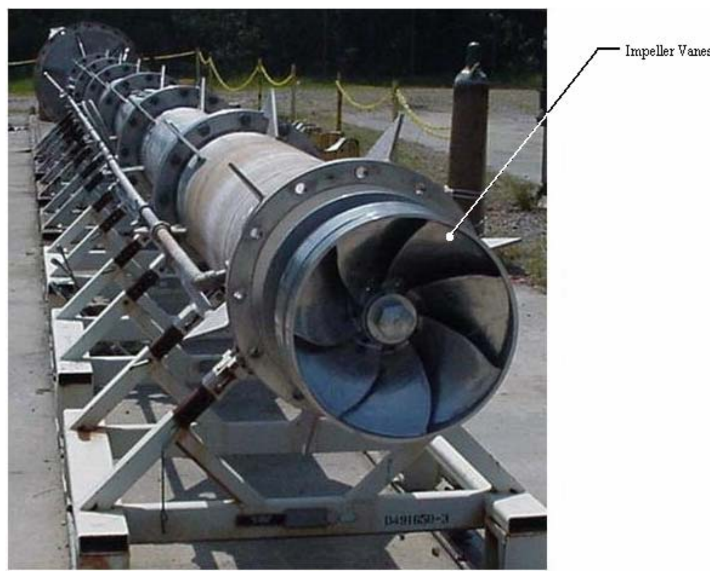

Figure 5: ADMP End View with the Pump Casing Removed

ADMP FLOW TESTS IN THE FULL SCALE TEST TANK

Equipment Setup

To set up the ADMP for flow velocity tests, the pumping system was mounted to an overhead platform at the test facility, similar to the setup shown in Fig. 6. A turntable supplied with the pump was first mounted to the overhead structural steel platform that spans the 85 foot diameter by eight foot deep tank. Two column sections were removed from the pump to shorten the length to meet the structural steel mounting requirements of the Full Tank Facility, and the ADMP was then bolted to the turntable. The closest horizontal distance between the pump centerline and tank wall was 4.88 meters (16 ft). The nozzle centerline height to the tank floor was 27 inches, as shown in Fig. 2

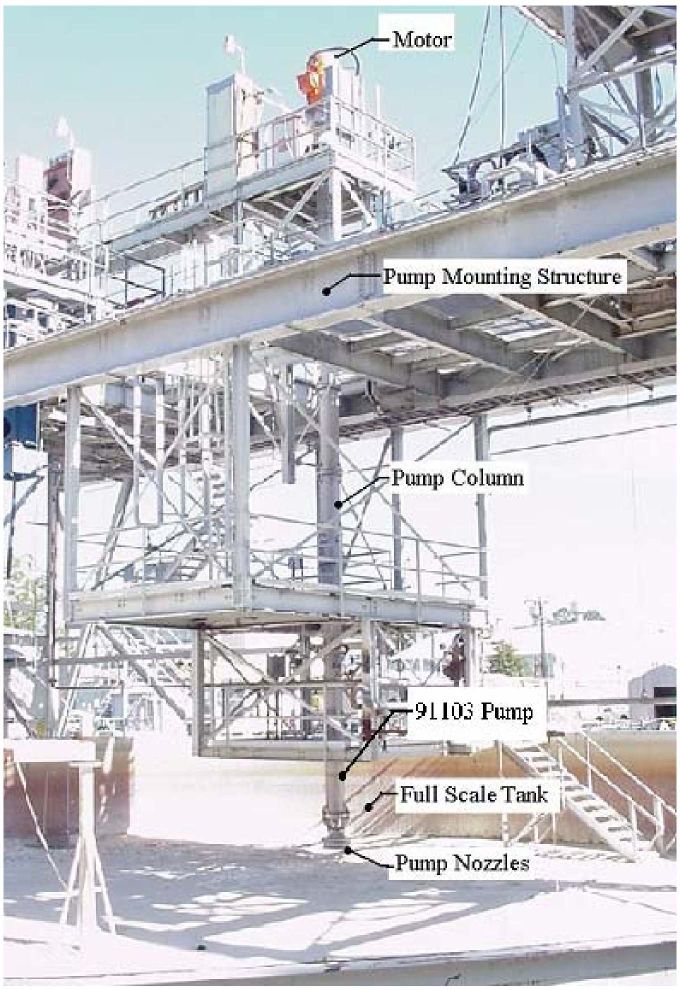

Figure 6: Typical Pump Installation at the Full Tank Facility

Data Collection

Fluid velocities were measured using the walkway over the test tank (Fig. 7) and the measurements were obtained using a Marsh McBirney, model 511 [10], electromagnetic velocity probe. The walkway spanned from the tank wall to a pole at the tank center and could be repositioned by rotating the walkway about the tank centerline. A steel rod was braced between the walkway and the tank bottom to prevent vibration of the velocity probe. The probe was bolted to the rod.

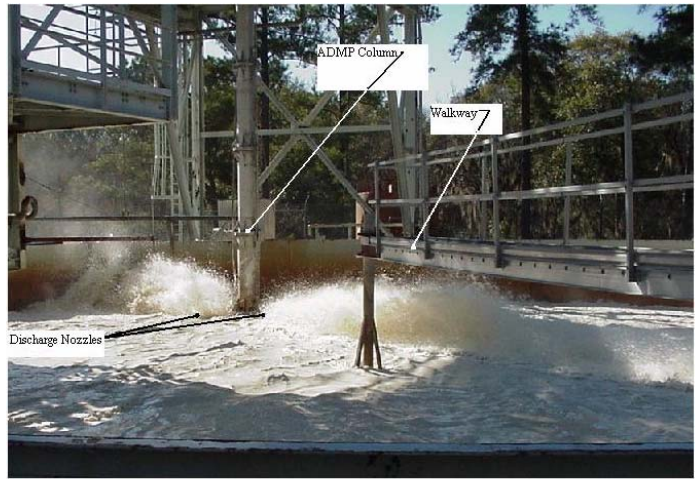

Figure 7: ADMP Operating at the Full Tank Facility with the Water Level Near the Pump Discharge Centerline

Figure 8 shows the factory calibrated Marsh McBirney equipment, used to collect velocity data. The equipment consisted of a transducer probe, cable, and signal processor housed in a portable case. The instrument sensed two dimensional flows in a plane normal to the longitudinal axis of the electromagnetic sensor, which was parallel to the tank bottom. The panel meters provided visual observation of flow, and the consequent analog output voltages were recorded with a Strawberry Tree data acquisition system [11] at 10 Hz for 3 minutes. The full scale output range of velocity components is +/- 3.0 m/second (10 ft/second) when measured along the X and Y orthogonal axes of the electromagnetic sensor. The probe was positioned to ensure that one of the two orthogonal directions was normal to the pump centerline. The X and Y velocity vectors were then added to obtain an absolute velocity. In other words, 1800 discrete velocity measurements were obtained at each data point over a three minute time span.

Figure 8: Marsh McBirney Velocity Probe

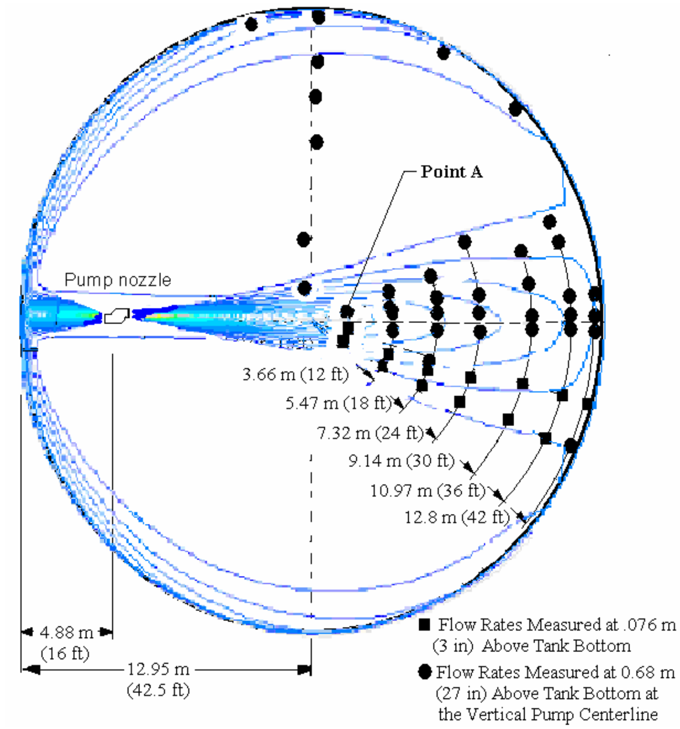

Figure 9: Velocity Measurement Data Points

Numerous data locations were selected to capture an array of velocities across the pump's discharge jet to assess whether the ADMP could effectively suspend sludge. In particular, velocities were measured on the discharge plane of the pump and close to the tank bottom. The flow measurement tests were performed with the ADMP operating at full speed and the test tank filled to a 1.78 m (70 inch) liquid level. The pump was held at a fixed, or indexed, position (i.e., without the turntable moving) throughout the tests. Fluid velocities were measured at both 0.076 m (3 inches) and 0.68 m (27 inches) from the tank bottom in different locations. The velocity locations are mapped in Fig. 9.

Flow Test Results

The experimental data was favorably compared to the CFD model in Part I, and therefore limited results are presented herein. Even so, the data reduction techniques bear some discussion. The test data fluctuated sinusoidally, since the installed pump was observed to oscillate about its axis through a $\pm 10^{o}$ angle with a period of ≈10 seconds.

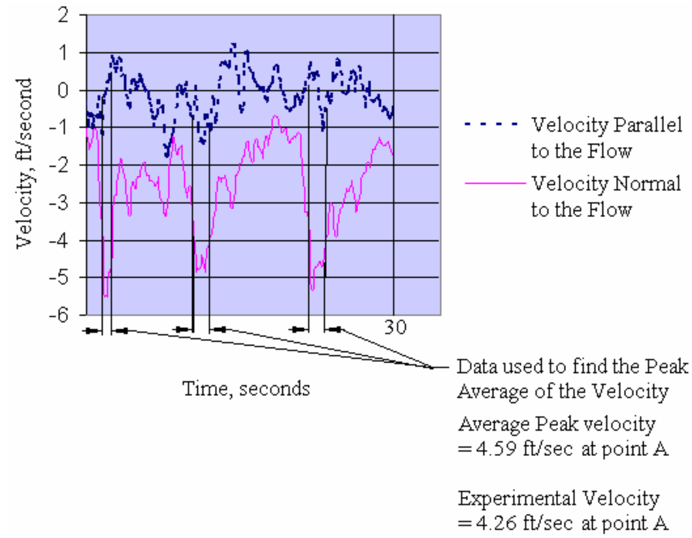

Figure 10: Velocity Data at an Arbitrary Point in the Flow

Considering this factor, the average of the peak data readings was assumed to be the actual data, rather than the arithmetic average of the data. Point A was arbitrarily selected for discussion. The location of this point in the Full Tank is shown in Fig. 9, and the velocity data associated with the point is shown in Fig. 10. The data is observed to reach a well defined maximum every 10 seconds. This observation corresponded to the situation when the sensor was aligned directly with the primary discharge flow. Consequently, only that data near the peak value was required for the analysis. To obtain a single peak average value, the parallel and normal velocity components were simply added vectorially at each data point and averaged. As noted above, the velocity probe was mounted to the rod. This mounting resulted in vibrations at approximately 80 Hz. These vibrations had a negligible effect on flow measurements, since any vibration effects due to the rod would be averaged with respect to the velocity measurement. Similar results for the flow measurements were obtained throughout the tank and plotted in Fig. 11, using peak data averages.

As might be expected, the deviations between the peak and arithmetic averages are reduced as the distance from the pump increases. Factors such as proximity to the tank bottom and wall, return flow, and distance from the nozzle tend to diminish the effect of oscillations in the nozzle orientation in the far-downstream region.

Results at the Pump Discharge Plane. The CFD results on the discharge plane are in agreement with the test data to within 25%, as shown in Fig. 11. Again, the measured data is closer in magnitude to the CFD predictions at a distance from the pump. As a comparative example, the experimental velocity for Point A is compared to the CFD prediction in Fig. 11.

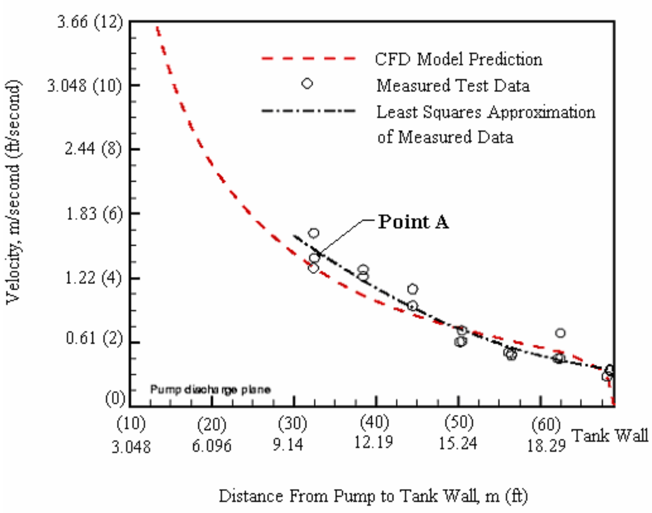

Figure 11: Comparison of Measured Data to the CFD Predictions on the Pump Discharge Plane, Lee and Dimenna [12]

Results Near the Tank Bottom. The results 3 inches above the tank bottom agree with the data to within about 20%, as discussed in Part I. These model predictions were obtained from test data measured at locations less than 25^o from the pump discharge direction.

CFD Validation. In Part I, the model predictions were compared with the experimental test data. Several data points at remote locations far away from the central axis of the jet flow were significantly higher than the predictions, but their absolute velocities are much smaller than the minimum sludge suspension velocity (≈2.27 ft/sec). The differences are assumed to be due to secondary flows created by the pump oscillation, eddies in the flow, unmeasured vertical turbulence, and flow obstructions neglected in the computational model. The model results were also benchmarked against literature data for the high velocity jet region not far from the nozzle exit where the predictions were shown to agree with the data to within about 10%. In short, the experimental results provided reasonable agreement with the CFD model.

Pump Rotation Effects on Flow Patterns. The effects of the 180 degree pump rotation on the flow patterns at a distance from the pump could not be effectively measured. However, observations of the jet in the Full Tank clearly discerned that the jet tends to bend slightly during rotation. This bending of the jet causes an asymmetrical flow pattern similar to that observed in the CFD models. Figure 12 shows the typical effects of pump rotation. Further details were provided by Lee and Dimenna [12].

CONCLUSION

The experimental velocities obtained during full-scale testing agreed with the CFD results. That is, experimental velocity mapping results observed in a full scale facility were compared to the results of a CFD model, which was discussed in Part I of this four part series of papers. Good agreement was seen between the measured and calculated velocities.

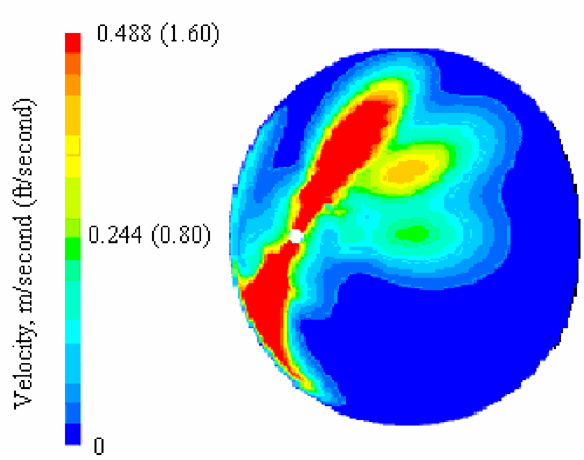

Figure 12: Flow Patterns One Minute After the Pump Starts With the Pump Rotating, Lee and Dimenna [12]

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Appendix 3

Mixing in Large Scale Tanks

III

Predicting Slurry Pump Performance

2004 ASME Heat Transfer / Fluids Engineering Summer Conference
Charlotte, N. C., July 11-15

HT-FED2004-56209

MIXING IN LARGE SCALE TANKS
PART III
PREDICTING SLURRY PUMP PERFORMANCE

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ABSTRACT
This third in a series of four papers (Parts I - IV) presents the equations used for the initial evaluation of a pump's ability to suspend solids and extends those equations to establish the minimum local velocity required to suspend those solids. This minimum velocity was used in a finite difference model in Part I to predict the ability of a pump to suspend, or slurry, solids that had settled on the bottom of a nuclear waste tank. To slurry waste, the Advanced Design Mixer Pump (ADMP) discharges a fluid jet that impinges on, shears, and then suspends the waste. Prior to the pump's installation in a waste tank, the local velocity at a point in the flow required to suspend solids was found from available equations, material properties, and empirical data for similar pumps. Also, the computational fluids dynamics (CFD) model was validated in Part II by comparing it to flow rates measured in a full scale test facility where the ADMP was operated. The CFD fluid model could then be used to predict flow rates throughout the actual waste tank where the pump was to be installed, and the ability of the pump to adequately slurry the waste could be shown. All that needed to be done was to compare the local velocity of the fluid required to shear the waste into suspension to the velocities modeled throughout the waste tank. In short, this paper validates the theoretical and experimental basis for the derivation of a minimum velocity required for the flow stream to shear the waste into suspension. The final installment to this series of papers (Part IV) validates the application of the CFD model, by concluding that a nuclear waste tank is effectively cleaned to the wall throughout most of tank, using the ADMP.

NOMENCLATURE

A	area, m^2
ADMP	advanced design mixer pump
C	constant
CFD	computational fluid dynamics
F_j	force due to a jet, N
F_s	force due to shear, N
D_0, D_P	diameter, m
ECR	effective cleaning radius
L	liquid
N	newtons
P	pressure
SRS	Savannah River Site
V_0	velocity, m / second
V_{ECR}	velocity, m / second
V_S	particle settling velocity, m / second
V	volume, m^3
cm	centimeter
g	grams
g_c	gravitational constant, m / second^2
in	inches
ft	feet
m	meters
ml	milliliter
p	particle
Δ	change in
μ	fluid viscosity
ρ	density, g/ml
τ	yield stress, dynes/ cm^2 = g · cm / s^2 ▪ cm^2

INTRODUCTION
Predicting the ability of a pump to slurry settled solids into suspension, depends on the effective cleaning radius (ECR) and the settling rate of the particles after they are suspended. The ECR is the horizontal distance from the pump centerline to which a material may be eroded into suspension, and the settling rate is the velocity at which the particles fall out of solution. The material under consideration here is nuclear waste, which has settled to the bottom of nuclear waste tanks.

Specifically, two waste forms are considered here. One is sludge, which is a highly viscous material. The other is a granular solid known as zeolite. The materials are stored in waste storage tanks having 0.75 to 1.3 million gallon capacities.

Sludge behavior will be discussed first in this paper. The ECR equations for sludge have been validated repeatedly. Churnetski [1,2] presented the original ECR equation, which was documented in tests using kaolin clay as a simulated sludge. Following that research, the ECR equation was successfully applied to sludge mixing at Savannah River Site (SRS) for different waste tanks, using multiple slurry pumps. ECR data is available from several of the numerous waste tanks in the H-Area and F-Area Tank Farms at SRS. In the H-Area Tank Farm, the ECR equation was successfully used for Tank 15H, which is not discussed here. The equations were then applied to Tank 42H by Motyka [3], and later validated in the F-Area Tank Farm for Tank 8F by Freed, et. al. [4]. Motyka also provided experimental data for the settling rates of sludge. Since this previous research is the foundation of the present research for the slurrying of sludge in Tank 18F, that research will be discussed prior to the Tank 18F discussion.

The present research focuses on the slurrying of Tank 18F, using the ADMP. The ADMP is a long shaft pump with its motor mounted on the top of a 1.3 million gallon waste tank at SRS. The vertical shaft connects the motor to the impeller which was submerged in the waste below. As shown in Fig. 1, the suction at the bottom of the pump draws fluid into the pump and then horizontally discharges the fluid through two opposing nozzles into the waste. The two jets then impinge on the waste and slurry the material within the ECR.

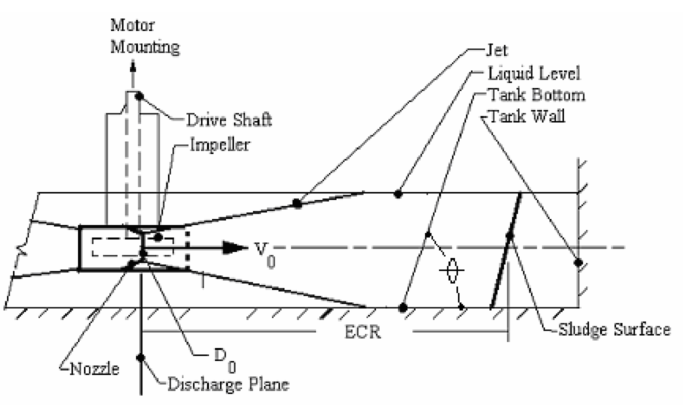

Figure 1: Relationship of the ECR to the Pump Installation

The volume of sludge in Tank 18F was conservatively estimated to be 47,000 gallons and was distributed throughout the tank bottom in varying heights ranging from an estimated minimum of 4 inches to a peak of 23 inches (Lilliston, et. al. [5]). Zeolite was also a constituent of the waste. Tank 18F was unique in that it contained a single slurry pump, rather than multiple slurry pumps that were used in the aforementioned tanks. The pump was mounted in the center of the tank. A question needed to be answered, "What are the effects of the wall on the ECR?"

To address this question, the velocity, V_{ECR}, which was required to suspend sludge in Tank 18F was determined from the existing ECR data, (Leishear [6]) and was used in a computational fluid dynamics model. The CFD model is presented in Part I (Lee, et.al.[7]) of this series of papers, which models the ADMP. The CFD model was needed since wall effects were expected to potentially reduce the ECR below that predicted by ECR equations for a jet in a free, or unimpeded, stream. In other words, a single-phase CFD model was adapted to this two fluid process. The single fluid CFD model established the flow rates throughout the tank, and these flow rates were compared to V_{ECR} to establish the point at which sludge suspension occurred.

Zeolite suspension will also be briefly discussed below, following the sludge discussion. Powell [8] investigated zeolite to establish the minimum horizontal velocity that is required to suspend zeolite particles and the settling rate required for those particles. Enderlin [9] performed tests using zeolite to find the settling rate of large particles in a quarter scale tank. The results from Poirier and Enderlin were applied to Tank 18F. The velocity required for suspension was considered to be V_{ECR} for zeolite suspension. Again, this velocity was used as the local velocity in the Tank 18F CFD model. In this case, it was the initial horizontal velocity required for particle suspension. Thus, a local velocity was established for both sludge and zeolite suspension for comparison to flow rates in the CFD. The CFD model was found to be reasonably accurate.

Predictions of the flow rates that were modeled in the CFD were validated in Part II (Stefanko, et.al.[10]) with experimental results from full scale testing that were performed in a 25.9 meter (85 foot) diameter test tank referred to as the Full Tank Facility, using the ADMP. Part II also describes several other slurry pumps used at SRS.

The CFD model is further validated in Part IV (Augeri, et. al. [11]), which concludes that the ADMP successfully removed sludge to the wall throughout most of the waste tank as predicted by the CFD model. Part IV also provides details on the installation and operation of the ADMP, during slurry processing. The suspension of sludge begins the discussion about the Tank 18F CFD model.

SLUDGE SUSPENSION

The initial suspension of sludge depends principally on the ECR. The ECR due to a free jet which is unaffected by the tank wall has been investigated. Historical data is available for different pump types and materials. The equations for the ECR follow, and will be considered for clay used in the test facility and for sludge in waste tanks, i.e., Tank 8F and 42H. These historical results will then be applied to the Tank 18F analysis.

The ECR Model

The ECR equation was derived from the equations for a jet impinging on a wall (Perry [12]) and is expressed as

$$ECR = C \cdot D_0 \cdot V_0 \cdot \sqrt{\frac{\rho}{\tau}} \qquad (1)$$

where the metric value of the constant, C, was experimentally validated for kaolin by Churnetski to be

$$C = 0.40 \qquad (2)$$

Then, $$\text{ECR} = 0.40 \cdot D_0 \cdot V_0 \cdot \sqrt{\frac{\rho}{\tau}} \cdot \left(100 \frac{\text{cm}}{\text{m}}\right) \tag{3}$$

where D_0 is the diameter of the jet at the discharge plane as shown in Fig. 1, V_0 is the discharge velocity of the pump at the discharge plane, ρ is the density of the sludge, and τ is the yield stress of the sludge.

Sludge Material Properties

Material properties of the sludge need to be considered before test results are considered. The sludge is a gelatinous material, shown in Fig. 2, which consists of soluble solids predominated by $NaNO_3$, $NaNO_2$, $NaAlO_2$, Na_2CO_3, and Na_2SO_4. The insoluble solids contain small quantities (< 1% each) of radioactive and stable fission products, but the principle insoluble components are $Fe(OH)_3$, $Al(OH)_3$, MnO_2, $CaCO_3$, zeolite, and SiO_2.

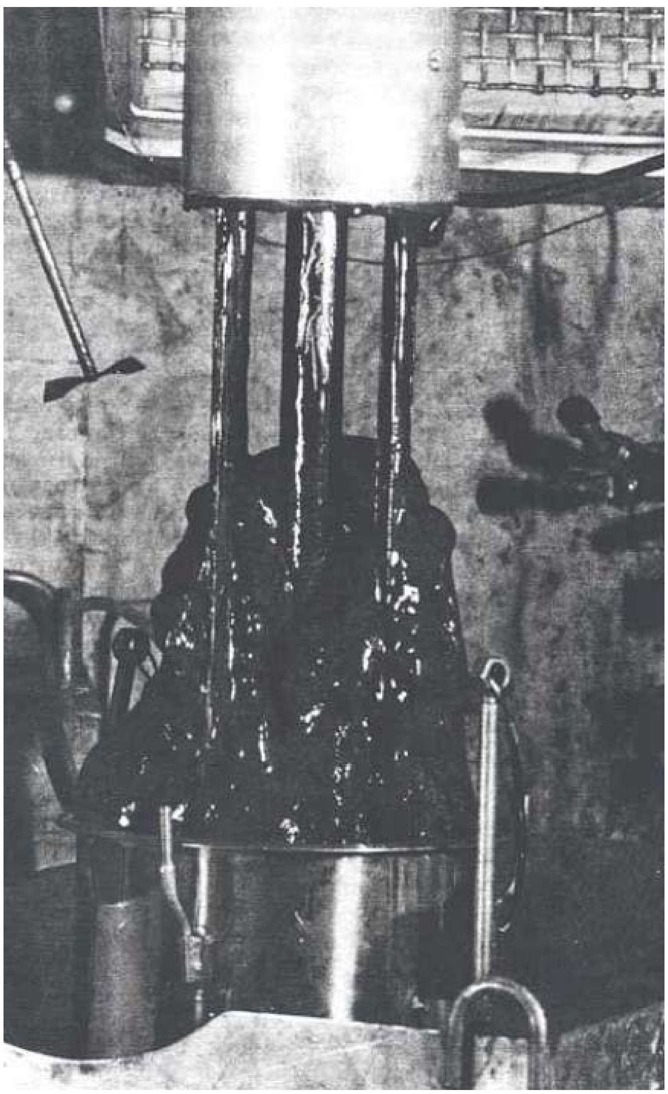

Figure 2: Typical Sludge Sample, Stone, et. al. [13]

Testing has shown that the sludge acts like a Bingham plastic. That is, the material flows when its yield stress, τ, is reached. The sludge flows freely like water after the initial yielding of the sludge. The difference between a free flowing Newtonian fluid, such as water, and a Bingham plastic is shown in Fig. 3. The value of τ is, of course, required for the ECR calculation.

Material properties were experimentally obtained by Hamm [14] for shear stress, weight percent solids, and density, which are summarized in Figs. 4 and 5. Samples of waste were obtained from the waste tanks and diluted to obtain rheological properties for different solids loadings. The highest solids loading from a sample was used to find the ECR and is recorded in Appendix 1.

The yield stresses and densities are assumed to be similar for Tanks 8F and 18F in that their respective yield stresses were 330 and 270 dynes / cm^2, and the waste resulted from similar processing at SRS. Consequently, the conservative material property values of Tank 8F were used to approximate the required quantities needed in the ECR calculation for Tank 18F. Again, the values are summarized in Appendix 1and shown in Fig. 4.

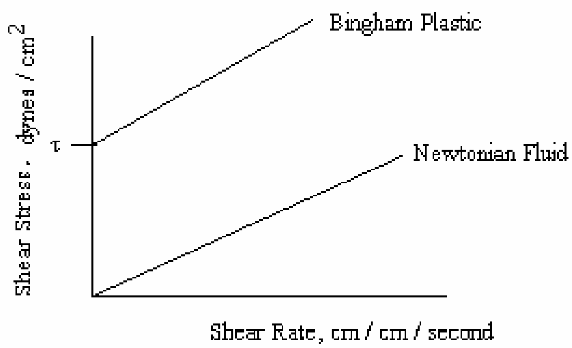

Figure 3: Comparison of a Bingham Plastic to a Newtonian Fluid

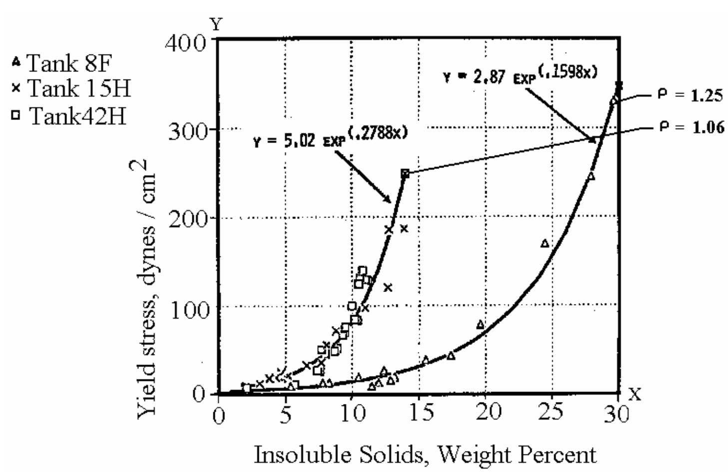

Figure 4: Yield Stress Dependence on Insoluble Solids, Hamm and Ebra [14]

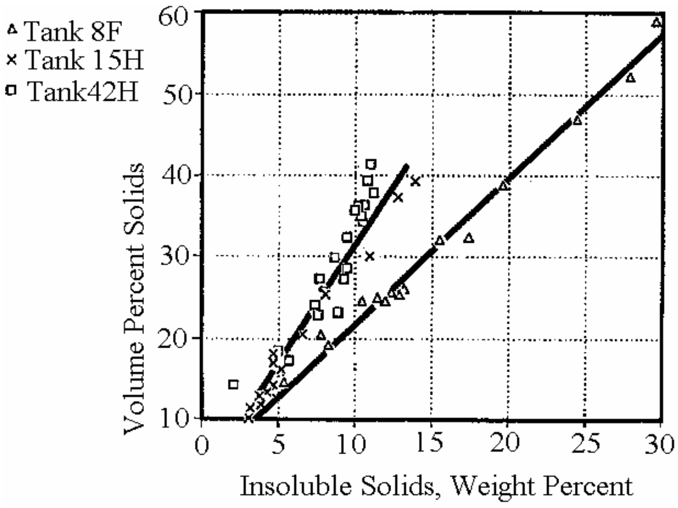

Figure 5: Volume Percent Solids Dependence on Insoluble Solids, Hamm and Ebra [14]

ECR Tests in a Kaolin Clay Water Mixture

Testing of kaolin slurries was performed using both the ADMP and a smaller capacity Sulzer pump for use in Tank 42. Churnetski's initial validation of the ECR equation was performed with the Sulzer pump, while the recent ADMP testing evaluated the effects of pump rotation on the ECR and the effects of fluid flow beyond the ECR. The results are summarized in Appendix 1 along with the performance results for the various pumps discussed herein.

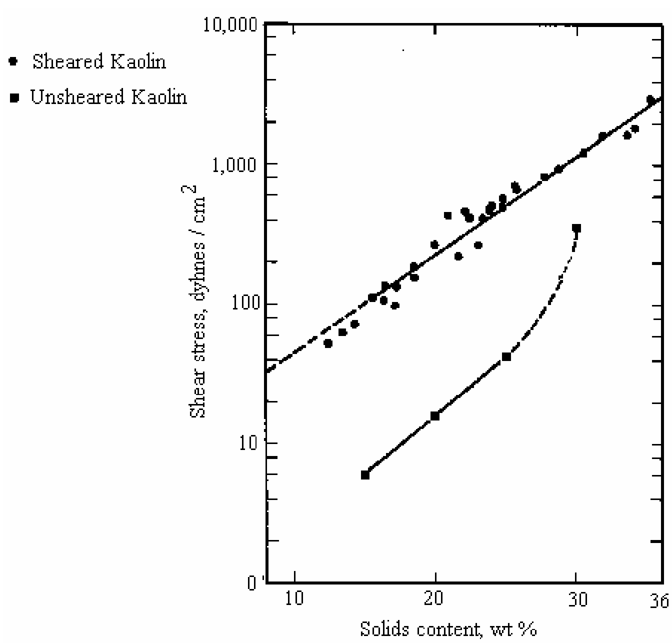

Figure 6: Kaolin Rheology, Selby [15]

ECR Validation. When kaolin is fully sheared by pumping, its properties can be used to simulate waste. Selby [15] showed that the yield stress, τ, is a function of the weight percent of solids in the kaolin simulant, as shown in Fig. 6. Using this relationship in 1981, Churnetski was able to select an appropriate solids content to imitate the actual sludge properties prior to waste mixing. Her ECR results are shown in Fig. 7. These were obtained by operating the pump at different speeds, using kaolin in a test tank and a Tank 42 pump. Similar results were obtained for another pump, which is the quad-volute pump manufactured by Sulzer but is not discussed here.

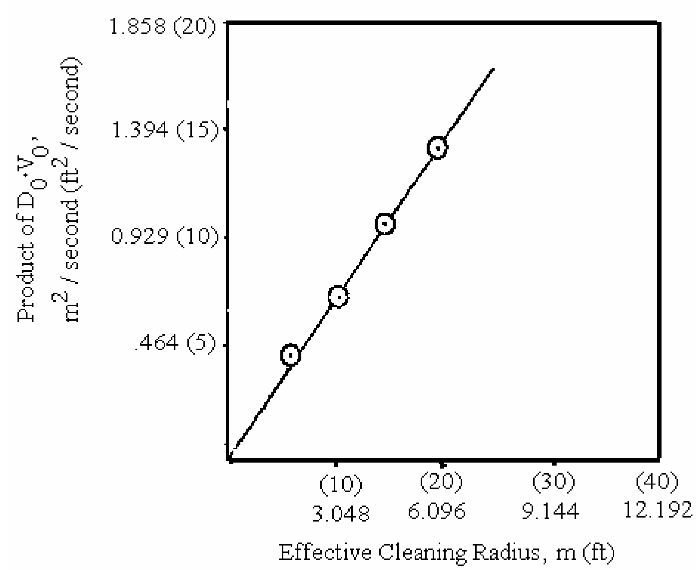

Figure 7: ECR Dependence on the Pump Discharge Velocity and Nozzle Diameter, Churnetski [2]

ECR Effects Due to Pump Rotation. In 2001, the ADMP was operated at the Full Tank by operating the jets both in a fixed position and by rotating the pump back and forth. Several tons of Kaolin clay and sand were added to the Full Tank and the effects of pump rotation on the ECR were evaluated.

The ADMP installation was different at the Full Tank than at the waste tank installation. Rather than being centered in the tank, the ADMP was suspended from an overhead platform and the center of the pump was located 4.88 meters (16 feet) from the wall of the tank. This location ensured that one of the jets would be in the free stream 21.03 meters (66.7 feet) from the opposite wall) and would thus be nearly unaffected by wall effects, as shown in Fig. 8. The flow from this jet was used to measure the ECR for both the fixed and rotating jet. Frictional effects due to the tank bottom were shown to have negligible effects on the flow by the CFD model.

The required constant, C, in the ECR equation was somewhat reduced due to the extremely high density and yield stress for this particular test. A kaolin / sand mixture was used that had settled and partially dried outdoors for several months in the Full Tank. Material properties of this mixture were measured and provided by Hansen [16]. The percent solids of the clay / sand mixture were obtained by drying the material in a conventional oven and measuring weights after the material was dried. The yield stress was measured using a Haake RS 150 rheometer, which is shown in Fig. 9. The ECR was measured at the Full Tank, and was used along with the material properties and Eq. 1 to find the value of C. The initial ECR was established, while the pump rotated at 0.25 rpm back and forth. To further understand the effects of rotation, the pump was later held stationary, or indexed, to evaluate the effect of indexing.

Little added effect on the ECR was observed after eight hours of indexed operation and the increase in the cleaning radius was noted to be approximately 3%. Basically, the change in the ECR is small due to indexing. The change in ECR is negligible when considered near the tank wall for an impinging jet. Data for both indexed and rotating pump operation for the ADMP using kaolin / sand is listed in Appendix 1.

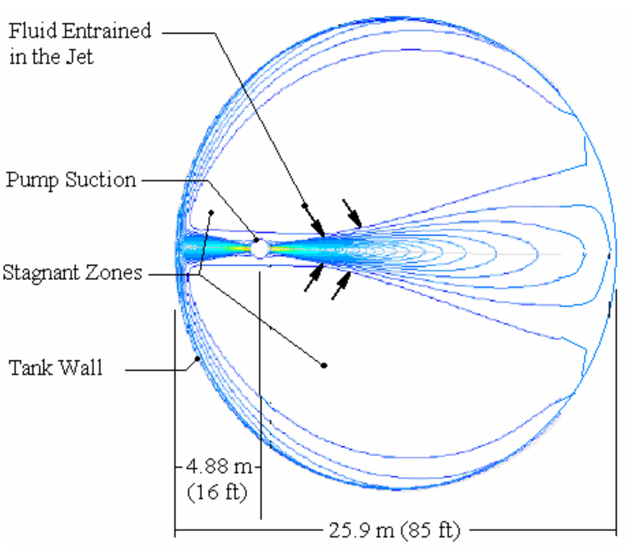

Figure 8: Flow Patterns Due to the ADMP in the Full Tank Facility, No Rotation

Figure 9: Rheometer and Vane Rotor for Measuring the Yield Stress of Kaolin Clay, Hansen [16]

Sludge Suspension Outside of the ECR. Beyond the ECR, the kaolin was unaffected by flow of the fluid over the surface. A minimum flow rate was required at the ECR to suspend sludge. At lower flow rates, the material is not suspended regardless of how long the flow passes over the surface of the sludge. That is, the flow rate of the liquid is inadequate to induce erosion at the surface of the sludge. The ADMP was operated for weeks at the Full Tank, and the kaolin level did not measurably change. In other words, diffusion of the heavy solids into suspension will occur, but diffusion will be so small that the depth of the Bingham plastic remains virtually unaffected. The validation of the ECR equation for clay set the precedent for the ECR validation for sludge.

ECR Application in Tank 42H

The ECR equation was used to predict sludge mixing in Tank 42H, and is shown in Fig. 10. The slurry pumps operated successfully to mix the tank. A 125,000 gallon volume of sludge was mixed with 1.04 million gallons of water with added corrosion inhibitors. This mixing yielded a slurry, which had one weight percent of insoluble solids. This slurry is not only a demonstration of the ECR equation, but is the basis for the settling rates discussed below.

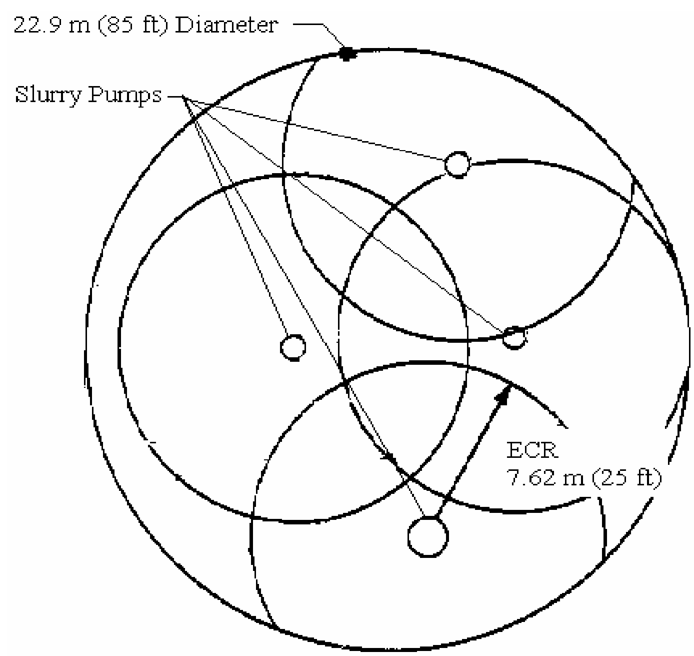

Figure 10: ECR for Tank 42H
Adapted from Motyka [3]

ECR Validation in Tank 8F

The ECR was predicted by Poirier [17] and confirmed by Freed, et. al. [4]. During a Tank 8F waste removal project, four Lawrence Pumps, model number 91103, were installed in the 22.86 meter (75 feet) diameter tank to slurry approximately 1.25 m of sludge (173,000 gallons) of waste in the tank. The pumps were sequentially lowered into the tank to operate at five different heights as water was added to remix the waste. The waste was removed from the tank except for the residual sludge shown in Fig.11.

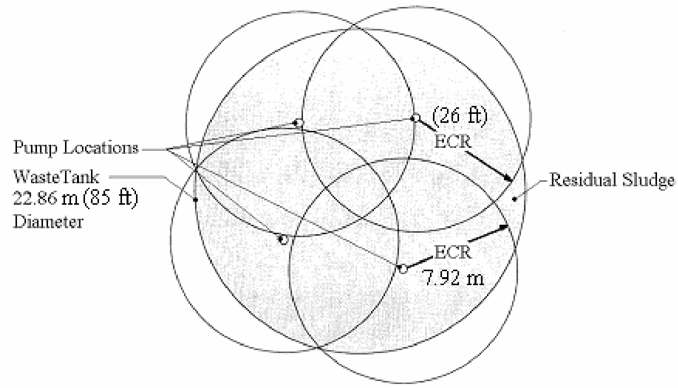

Figure 11: Validation of ECR Calculations Using Tank 8F Results, Adapted from Freed, et. al. [4]

The waste had completely dried during storage. The effect of drying the waste apparently had a negligible effect on the material properties with respect to the ECR as the material was rewetted. Remote camera inspections showed that the ECR was met at the centerline elevation of the jet. However, the angle of the waste, θ, with respect to the tank bottom was approximately sixty degrees as shown in Fig. 1.

ECR Data Results

To summarize earlier experience with the ECR equation, numerous pumps and materials have been tested and operated at SRS to establish the parameters required to predict the ECR. Several representative examples of slurrying were summarized from selected SRS reports. These examples demonstrated the validity of the ECR equation, Eq. 3,

$$ECR = 0.40 \cdot D_0 \cdot V_0 \cdot \sqrt{\frac{\rho}{\tau}} \cdot \left(100 \frac{cm}{m}\right)$$

using the material density, the yield stress, and the experimentally verified constant, C. The ECR equation has been shown to provide good results for ECR predictions for most commonly encountered materials. One exception was a very high density kaolin / sand mixture, which had a different value for C.

Tank 18F Slurry Pump Evaluation

Recently, Tank 18F was evaluated for slurrying. A CFD model was used to evaluate the pump for use in slurrying the sludge in Tank 18F, since equations to describe the ECR near the tank wall are unavailable. To perform the CFD, the model needed to be related to shearing of the sludge in the waste tank. At any point in the flow, the velocity may be found using the CFD. If the velocity required to shear the sludge into suspension is known, the ECR may then be found. That is, the velocity required to shear the sludge is the velocity at the ECR.

Velocity at the ECR. The local velocity, V_{ECR}, at the ECR required to suspend sludge may be calculated. From Churnetski, the force, F_j, on the sludge surface due to a jet is

$$F_j = \frac{\rho \cdot V_{ECR}^2 \cdot A}{2 \cdot g_c} \quad (4)$$

where V_{ECR} is the velocity at the ECR, A is the area on which the force acts, and g_c is the gravitational constant. When F_j exceeds the resistive shear force, F_s, of the sludge, the sludge will be suspended. That is,

$$F_s = \tau \cdot A \quad (5)$$

and

$$F_j = F_s \quad (6)$$

Therefore,

$$\tau \cdot A = \frac{\rho \cdot V_{ECR}^2 \cdot A}{2 \cdot g_c} \quad (7)$$

Equation 7, the material properties for Tank 18F in Appendix 1, and Fig. 4 yields

$$V_{ECR} = 0.69 \text{ m/second (2.27 ft/second).} \quad (8)$$

ECR Estimate for the ADMP Installed in Tank 18F. Using V_{ECR} in the CFD of Part I, the ECR was determined. Actually, a zone for all velocities above V_{ECR} can be established. This limit of the ECR is shown in Fig. 12. The predicted ECR without wall effects is listed in Appendix 1 as 21.73 meters, and the ECR was expected to reduce to 12.64 meters due to wall effects. As noted above, the ECR is negligibly affected by rotation in Tank 18F, and the effect of rotation can be compared in Figs. 13 and 14. A cross section of the jet is shown in Fig.15.

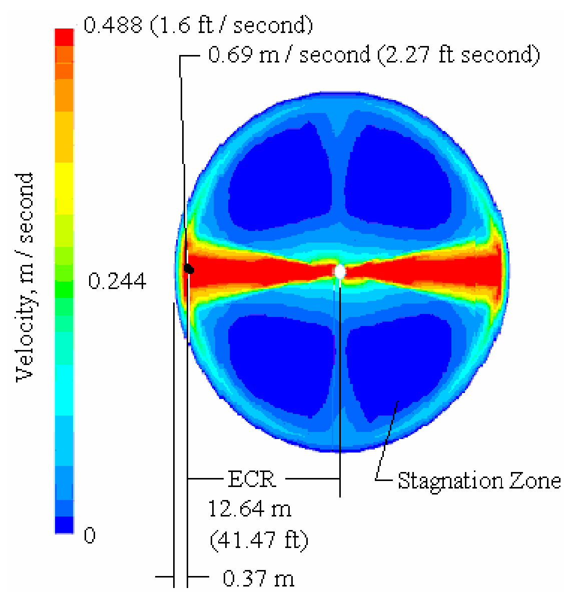

Figure 12: CFD Model of Tank 18F Pump Discharge Plane, Without Pump Rotation, adapted from Lee and Dimenna [18]

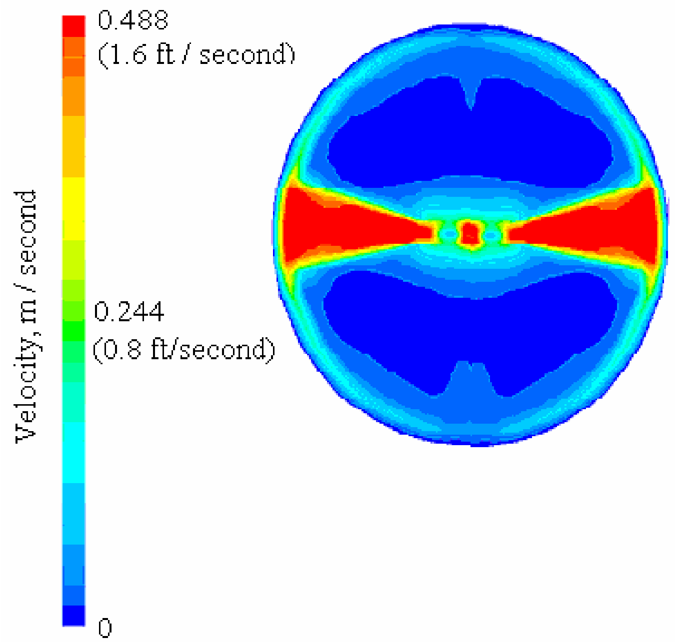

Figure 13: CFD Model of Tank 18 Near the Tank Bottom, Without Pump Rotation, Lee and Dimenna [18]

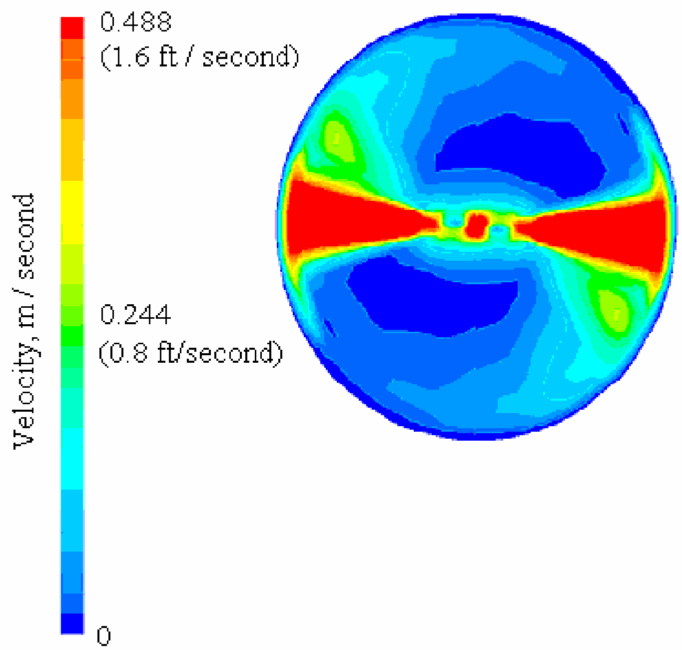

Figure 14: CFD Model of Tank 18 Near the Tank Bottom, With Pump Rotation, Lee and Dimenna [18]

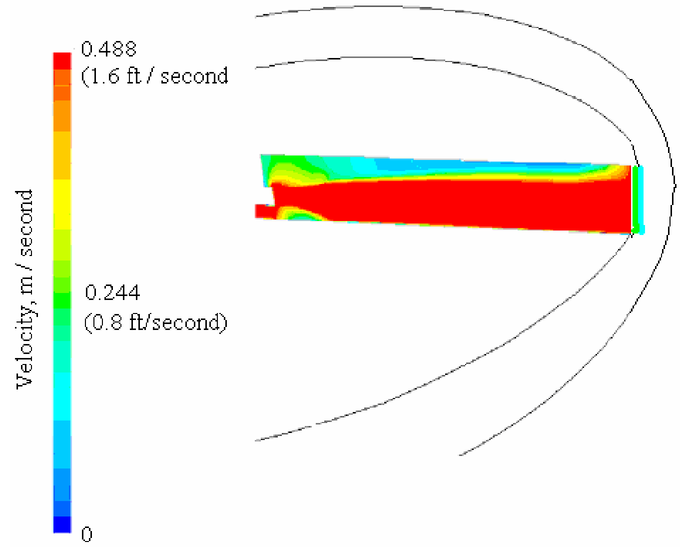

Figure 15: Cross Section of the Jet, Lee and Dimenna [18]

Shear Angle of the Sludge. The CFD model provides a good prediction for the effects of the impingement of the jet on the waste near the wall. But, as the waste is removed it may actually settle down and toward the tank center. To understand this phenomenon, the angle of shear, θ, was considered, as shown in Fig. 16.

For an isotropic, homogeneous material, the only forces in the material are due to the material's own weight. The downward force on a shear plane acting on a unit area is $\rho \cdot \tan(\theta) / 2$. The total shear stress acting on the plane is $\tau \cdot \sin(\theta)$, where τ is the yield stress required to shear the material for a Bingham plastic. For Tank 18F material, the shear stress is assumed to be 33 pascals = 330 dynes / cm^2, and the density is 1.25 grams / milliliter.

Since the sum of the forces equals zero in Fig. 15,

$$\tau \cdot \sin(\theta) = \rho \cdot \tan(\theta) / 2. \quad (9)$$

Then, on substitution, the shear angle for Tank 18F is

$$\theta = \cos^{-1}(\rho \cdot g_c / \tau) = 83° \quad (10)$$

where ρ is the sludge density, g_c is the gravitational constant, and θ is the shear angle.

Thus, the remaining sludge was predicted to form an annular ring in the tank with a volume between zero and 1400 gallons, depending on the actual rheological properties of the sludge. Figure 17 shows a cross section of the maximum potential residual sludge at the tank wall. The residual waste at the wall was actually slurried in tank 18F. Presumably, a lower shear stress existed in the material than that which was modeled, or an additional erosion mechanism is at work near the wall. An erosion mechanism is likely, based on the results of quarter scale modeling.

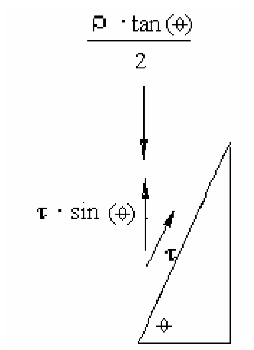

Figure 16: Shear Angle of the Sludge

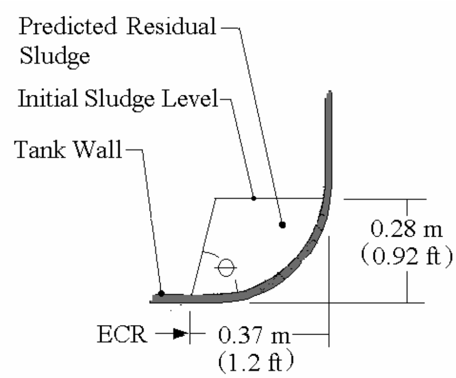

Figure 17: Potential Residual Sludge for a High Density Material

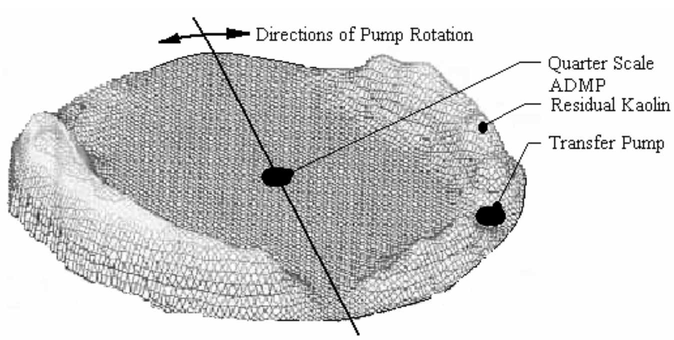

Figure 18: Residual Kaolin Clay in a Quarter Scale Model After 12 Hours of Operation, Adapted from Enderlin, et. al. [9]

The ECR as a Function of Time

The ECR is, of course, a function of the time that the jet impinges on the free surface of the sludge. So far, this paper has focused solely on the steady state ECR, which is obtained at the end of the mixing process. Enderlin's work [9] provides some insight into the process.

A one quarter scale tank was fabricated to model the ADMP performance in Tank 18F, using similarity laws to design the quarter scale facility. A uniform layer of a fourty-nine weight percent kaolin clay / water mixture was placed in the tank to model the sludge. Also modeled, were the ADMP and a transfer pump to remove solids from the tank. A typical profile of the kaolin, which remained after operating the pumps, is shown in Fig. 18. The sludge was cleaned all the way to the wall by the jet. In short, an erosion mechanism apparently provides added cleaning of the waste near the wall for some materials, like the sludge observed in Tank 18F and the kaolin in the quarter scale tests. Erosion typically requires a lower velocity to simply move particles, rather than lift the particles into suspension. But, for other materials discussed above, like the dried sludge of Tank 8F and partially dried kaolin in the Full Tank Facility or sludge, the erosion mechanism has a negligible effect. For wetted sludge or kaolin, erosion is the mechanism that explains why the sludge is cleared all the way to the wall. Erosion occurs at 5 to 10 percent of the yield tress of kaolin. A discussion of the erosion process is dependent on particle size as discussed in Part I, and at present is inadequate for use in predicting slurry pump performance, since the velocity required to erode sludge is presently unknown. Use of the ECR equation provides an under estimate of sludge removal, i. e., a conservative estimate.

Tank 18F Sludge Slurry Results

Approximately 42,680 gallons of the initial 47,000 gallons of waste were removed from Tank 18F, as shown in Fig. 19. The actual mixing of nuclear waste requires weeks, and the processing details for the slurry results are described in Part IV. That paper concludes that the sludge was removed all the way to the tank wall throughout most of the tank. The predicted results therefore are in reasonable agreement with the theoretical results. Even though the sludge was removed to the wall, the non-homogeneous nature of the sludge and the difficulties of obtaining accurate material properties when sampling from million gallon tanks is credited with this difference between predictions and results. Another possibility for the discrepancy is an error in the modeling assumptions. For the small volume of solids trapped near the tank wall, the flow rates near the sludge may cause additional erosion, which was not credited. Regardless, the CFD model provides considerable insight into the flow phenomena near the wall, and can be used to establish a conservative estimate of the ECR for slurry pump performance.

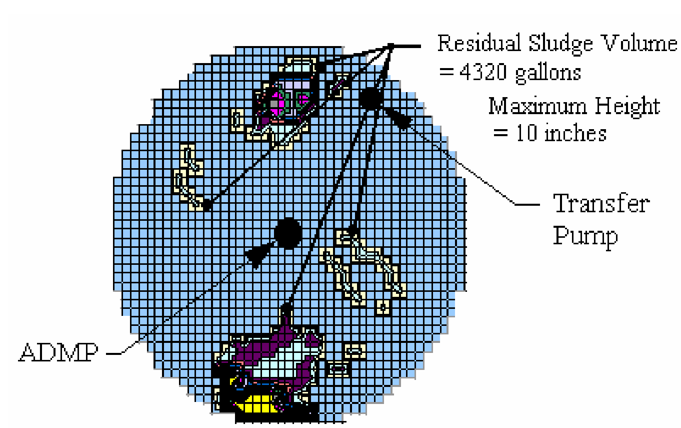

Figure 19: Tank 18F Residual Sludge, Augeri, et. al. [11]

SLUDGE SETTLING RATES

Once the sludge is suspended, it needs to stay suspended for processing. Suspension of the waste depends on the settling rate of waste particles. Tank 42H is the only waste tank for which experimental data for settling rates is available. To consider Tank 18 F settling rates, Stokes' equation for a settling rate of a particle can be used to extrapolate the Tank 42H data to some limited Tank 18F data.

Tank 42H Experimental Settling Rates

Settling rates as a function of weight percent insoluble solids for Tank 42H are presented in Fig. 20. The data for sludge settling was obtained by Motyka, using optical and sonar techniques.

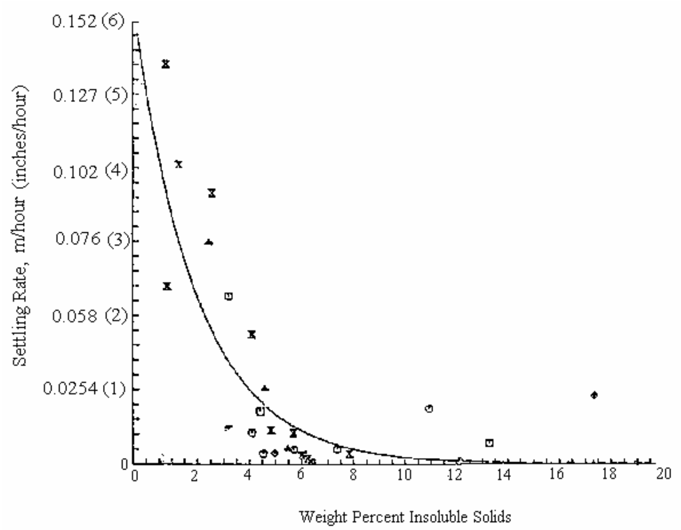

Figure 20: Settling Rate Dependence on Weight Percent Solids for Tank 42 Sludge
Motyka [3]

Tank 18F Sludge Settling Rates

Motyka noted that the settling rates for F-Tank Farm sludges are expected to be faster than those in the H-Tank Farm. The wastes are similar since the slurries are comprised of large low density agglomerates of fine particles, known as flocculated particles. However the densities of the sludges in the two tank farms differ, as shown in Fig. 4. The difference in density of the sludge is due to the percentage of entrained aluminum in the waste and equals 1.25 for Tank 18F and 1.06 for Tank 42H. Hamm noted that the typical particle diameter is 80 microns, which is the approximate diameter of a human hair. Assuming the flocs for the different sludges are approximately the same, and the liquid is water, a crude comparison of the settling rates for the H and F-Area sludges may be obtained by using Stokes' relationship for the terminal velocity of a particle. That is, Motyka noted that Stokes' equation is valid for waste settling rates at values below 1 % solids concentration, and the equation is expressed as

$$V_s \propto D_p \cdot g_c^2 \cdot \left(\frac{\rho_p - \rho_L}{18 \cdot \mu} \right) \tag{11}$$

where V_S is the settling velocity of a particle, D_p is the particle diameter, μ is the fluid viscosity, ρ_L is the fluid density, and ρ_p is the particle or sludge density.

A crude comparison of the settling velocities may now be performed. Substitution of the densities of 1.70 from Thomas's report [19] and 1.06 from Fig. 4 into Eq. 11 for Tank 18F and Tank 42 H respectively, and comparing them proportionally, shows that the settling rate of the F Area sludge may be as high as 11.7 times the settling rate of the H Area sludge. That is,

$$\frac{V_S(\text{Tank18F})}{V_S(\text{Tank42H})} \cong \frac{1.70 - 1.00}{1.06 - 1.00} = 11.7 \tag{12}$$

A maximum settling rate of 0.43 m / hour (17.1 inches per hour) is then found by using Eq. 12 and Fig. 20. No subsequent experimental settling data was obtained for Tank 18F sludge after Tank 18F cleaning.

ZEOLITE SUSPENSION AND SETTLING RATES

Zeolite suspension was evaluated for the Tank 18F slurry, since approximately 15,500 pounds of zeolite was contained within the sludge. Zeolite is a porous, granular alumino-silicate solid, which may have its interstitial voids filled with large unattached molecules or water. Poirier investigated particulate zeolite at the conditions expected in waste tanks. He found that the horizontal velocity required to lift 0.7 millimeter zeolite particles was 0.488 meters / second (1.6 feet / second). He also found that the settling velocity of zeolite was 0.04 meters / second. These values are consistent with the observation of Harnby, et. al. [19]. That is, the lift velocity for particles is typically one tenth of the settling velocity for those particles. When settling results are compared to the Tank 18F geometry and the CFD model, settling dominates the particle behavior. The pump rotates back and forth through a 180 degree angle at a velocity of 0.25 revolutions per minute, which means that the jet will return to its original position every four minutes. For a typical tank level of 1.78 meters (70 inches), the zeolite will be lifted in the jet, as implied by the velocities depicted in Fig. 12. But, the zeolite will completely settle out of solution in a maximum time of 44 seconds after it leaves the jet, long before the jet returns to suspend the zeolite. The zeolite is effectively lifted by the jet, and redeposited behind the jet after it passes.

This settling behavior was validated by Enderlin, again using the quarter scale model. His results showed that the particles were swept up into the jet but settled out of solution immediately after exiting the jet and were deposited back on the tank floor. Essentially, the jet will not slurry the particles, but will simply lift the particles and then move the particles around on the tank floor. Based on this data, conclusions were drawn that transfer of zeolite from another tank was unlikely, and any zeolite concentration in Tank 18F was, for the most part, unaffected by slurry processing. There is some evidence in Enderlin's report that zeolite may be swept toward the pump, and that some transfer of material may be accomplished after the material is collocated with the pump. However, Enderlin concluded that slurry pumps will not effectively remove sludge, since zeolite should be fed directly into the transfer pump inlet.

CONCLUSION

The ability of a pump to suspend sludge in nuclear waste tanks may be affected when the jet from the pump impinges on the free surface if the sludge. The equation for the distance to which the pump will suspend sludge is the effective cleaning radius (ECR) and has been repeatedly validated in other research. However, an equation is unavailable for the effects of the wall on the ECR. For the Tank 18F example considered here, a minimum velocity of 0.69 meters / second (2.27 feet / second) was established as the velocity required for sludge suspension. This velocity was applied to an experimentally validated CFD model in Part I to establish the wall effects. That model predicted a residual sludge volume at the wall between zero and 1400 gallons. The actual pump cleaned most of the sludge all the way to the wall, and the initial prediction is considered to be reasonable. In addition to the ECR prediction, limited experimental results were discussed from the work of other researchers. This work provided sludge and zeolite settling velocities. The rotation of a centrally located discharge jet is adequate to maintain suspension of the smaller diameter sludge particles in a 25.9 meter (85 feet) diameter waste tank. But, this installation will not keep the larger zeolite particles suspended after they exit the jet. In short, the complete cycle of initial suspension, and the ensuing settling behavior of nuclear waste sludge was considered.

APPENDIX 1: ECR'S AND MATERIAL PROPERTIES FOR DIFFERENT PUMP INSTALLATIONS

Pump Type & Conditions	Material	ECR M (ft)	C	D_0 m (in)	V_0 m/sec (ft/sec)	ρ g/ml	τ dynes/ cm^2
ADMP, Lawrence, Rotation, Full Tank	kaolin/ sand	11.58 (38)	0.34	0.152 (6.0)	17.97 (58.9)	1.73 (65.2 weight %)	11750
ADMP, Lawrence, No Rotation, Full Tank	kaolin/ sand	11.89 (39)	0.40	"	"	"	"
91103, Lawrence, Rotation, Tank 8F	sludge	7.93 (26)	0.40	0.038 (1.5)	26.28 (86.2)	1.25	330
ADMP, Lawrence, No Rotation, Tank 18F	sludge	21.73 (71.3)	0.40	0.152 (6.0)	17.97 (58.9)	"	330 / 270
Sulzer, Rotation, Tank 42H	sludge	7.62 (25)	0.40	0.038 (1.5)	16.62 (54.5)	1.06	130
Sulzer, Rotation	kaolin	7.62 (25)	0.40	0.038 (1.5)	16.62 (54.5)	(30 weight %)	134

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Appendix 4

Quarter Scale Modeling of the ADMP

QUARTER SCALE MODELING OF THE ADMP

ABSTRACT

Quarter scale modeling of the Advanced Design Mixer Pump (ADMP) was performed at Pacific Northwest National Laboratories to evaluate sludge mixing in tank 18F. Two materials were evaluated during the tests. The first material was kaolin clay which was used to simulate the radioactive sludge in the waste tank. Testing showed that sludge mixing resulted from an erosion process that removed the simulant all of the way to the outer wall of the tank. The second material was zeolite which was shown to rapidly settle to the tank bottom following suspension by the centrally located ADMP. This rapid settling prevents efficient zeolite removal from the tank.

INTRODUCTION

The quarter scale tank, the ADMP used for mixing, and the transfer pump used to remove material from the tank are shown in Figs. 1 and 2. The details of modeling, construction, operation, and testing are available in a report by Enderlin, et. al. [1]. A summary of his results are provided here to provide further insight into the sludge mixing process. Both the mixing of kaolin clay simulant and zeolite are considered herein as they apply to sludge removal from Tank 18F. Specifically, the fast settling characteristics of the zeolite are demonstrated, and the erosion process is related to the the effective cleaning radius (ECR) that is typically used to predict slurry pump performance. The ECR is the distance to which a pump will effectively clean sludge from the bottom of a tank.

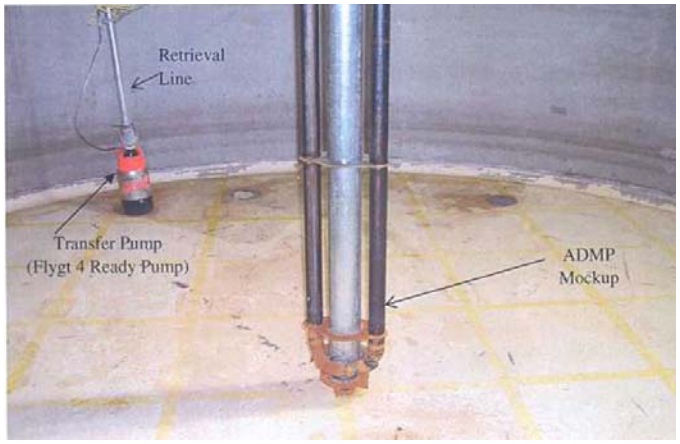

Figure 1: Quarter scale model of Tank 18F, the ADMP mounted at the tank center, and the transfer pump,
Enderlin, et. al.

Figure 2: Details of the quarter scale ADMP model
Enderlin, et. al.

Summary of Quarter Scale Kaolin Mixing

The erosion mechanism that exists during mixing is clearly evident in Figs. 3 - 6. A sludge stimulant was mixed using a ratio of 49.1 weight percent kaolin clay to 50.9 weight percent water. The 2993 pounds of kaolin formed the lower layer of material and water was added to the tank to obtain a 17.2 inch liquid level. The pump was oscillated about 80 percent of the operation time and held stationary at different positions for the remaining time. Again, Enderlin's report provides specific details. The figures clearly show the effectiveness of sludge removal and the diminishing sludge mixing ability with respect to time. A lot of sludge is removed quickly, and the rest takes longer and longer to remove.

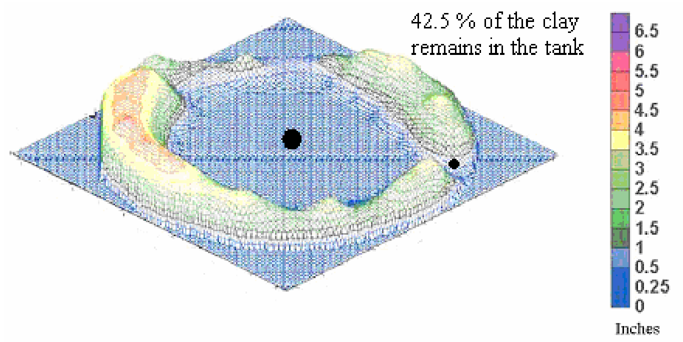

Figure 3: Residual kaolin after 2.23 hours of pump operation,
Adapted from Enderlin, et. al.

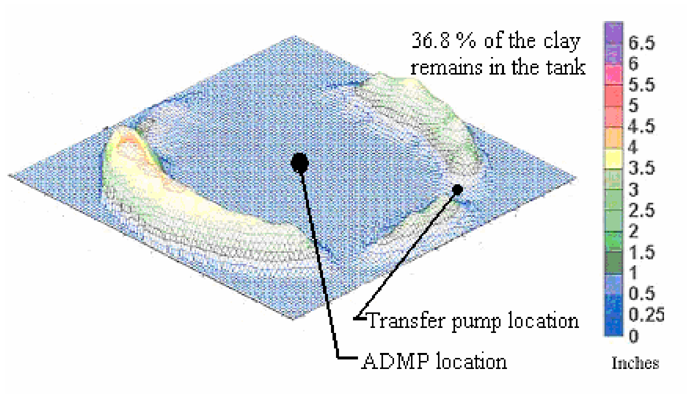

Figure 4: Residual kaolin after 9.81 hours of pump operation,
Adapted from Enderlin, et. al.

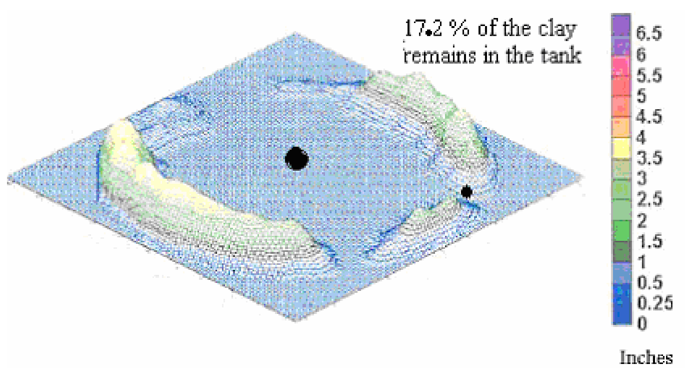

Figure 5: Residual kaolin after 15.8 hours of pump operation,
Adapted from Enderlin, et. al.

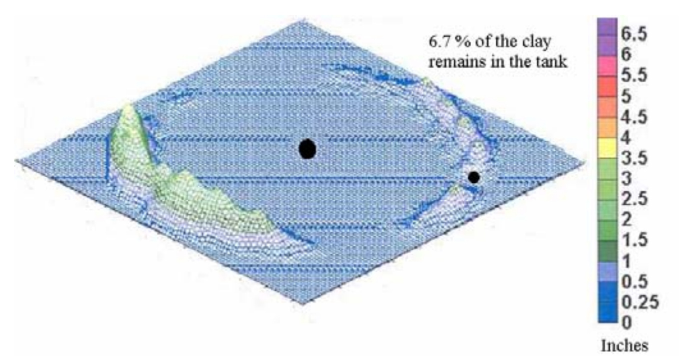

Figure 6: Residual kaolin after 42.6 hours of pump operation,
Adapted from Enderlin, et. al.

Relationship between the ECR and erosion

The ECR as calculated in Appendix C of this paper conservatively predicts sludge removal. Therefore, the ECR equation can be used as a conservative estimate. The ECR equation is expressed as

$$ECR = C \cdot D_0 \cdot V_0 \cdot \sqrt{\frac{\rho}{\tau}} \qquad (1)$$

where C is an experimentally determined constant, D_0 is the diameter of the jet at the discharge plane as shown in Fig. 7, V_0 is the discharge velocity of the pump at the discharge plane, ρ is the density of the sludge, and τ is the yield stress of the sludge.

This solution technique assumes that the sludge is sheared directly into suspension and was shown in Appendix C to accurately predict the performance of a pump in a tank containing dry sludge, but was not concise for the quarter scale model, as shown in Figs. 3 – 6, or the actual performance of the ADMP in Tank 18F. In each of these cases, the pump cleaned the sludge all the way to the tank wall, while the CFD model predicted a residual ring of waste at the wall.

This cleaning behavior can be explained by considering erosion. Powell, et. al. [2] performed tests using kaolin stimulant. They demonstrated that erosion of the clay occurred through a sloughing process that created particles at the clay surface less than 1 millimeter in diameter. These particles are then entrained in the flow where they are further reduced in diameter. This process occurs at shear stresses of five to ten percent of the yield stress of the clay.

The fact that erosion occurs at stresses less than yield explains the difference between ECR predictions and actual results for sludge mixing. Erosion removes sludge in the wake of the jet from the pump, even though the sludge particles may not go directly into suspension. The particles are moved along the tank bottom. Unfortunately, the erosion process is not well defined for nuclear waste sludge. Therefore, the ECR technique is used to provide a conservative solution. The sludge can be expected to be removed to a distance at least equal to the ECR for dry sludge and all the way to the wall for wetted sludges.

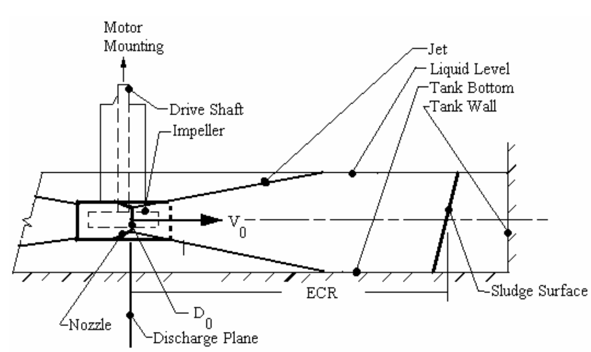

Figure 7: Relationship of the ECR to the Pump Installation

Zeolite Mixing

The fast settling of zeolite is discussed in Appendix C of this report and Enderlin's report documents the effects of settling rates. Less than seven percent of the zeolite was removed from the tank after three hours of pump operation. This sludge removal rate is rather small when compared to the 57.5 percent removed per 2.23 hours for the kaolin discussed above. Figures 8 and 9 demonstrate the performance of the quarter scale ADMP when mixing zeolite. Enderlin concluded that transfer pumps will not adequately remove zeolite.

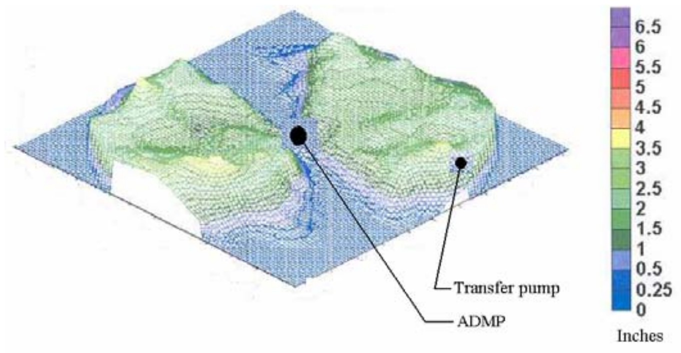

Figure 8: Residual zeolite after 11 minutes of pump operation, Adapted from Enderlin, et. al.

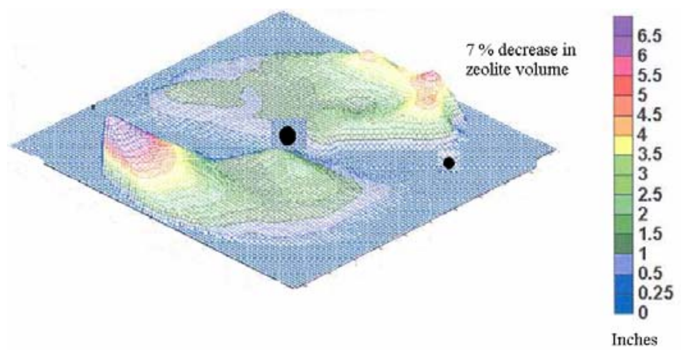

Figure 9: Residual zeolite after 179 minutes of pump operation, Adapted from Enderlin, et. al.

CONCLUSION

Quarter scale modeling demonstrated two clear conclusions. One, zeolite will not be efficiently removed using a transfer pump. Two, the ECR equation will provide a conservative estimate of slurry pump performance. The equation will under estimate the residual sludge volume, since erosion effects are inadequately considered in the ECR equation.

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Appendix 5

Mixing in Large Scale Tanks

IV

Cleaning Nuclear Waste Tanks

2004 Heat Transfer / Fluids Engineering
July 11 – 15, 2004 Charlotte NC

HT-FED2004-56333

Mixing in Large Scale Tanks
Part IV
Cleaning Nuclear Waste From Tanks

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ABSTRACT

The prototypical Advanced Design Mixer Pump (ADMP) was installed in the center of a nuclear waste tank to suspend settled solids, allowing removal of the solids from the tank with a separate transfer pump. Traditional waste removal methods use multiple (up to four) long shaft vertical pumps for suspending the waste solids. A combination of Computational Fluid Dynamic (CFD) modeling, scale modeling, and equipment testing were used to predict the capability of a single mixer pump to suspend radioactive waste solids in liquid using a forty mile per hour discharge jet velocity . Modeling and testing predicted the cleaning effectiveness of the mixer pump to ensure that the majority of waste solids throughout the tank would be suspended for removal to the extent technically and economically practical. In spite of unexpected field conditions and pump phenomena that hindered performance, observation showed that the pump performed as predicted by the modeling and testing.

INTRODUCTION

The Savannah River Site near Aiken, South Carolina has fifty-one nuclear waste storage tanks in various phases of operation and closure. These tanks were originally constructed to receive, store and treat the nuclear waste created in support of the missions assigned by the United States Department of Energy (DOE). Both federal and state environmental agreements require the nuclear waste to be removed from the tanks followed by tank closure. The focus of this article is the technology and strategy used to remove the majority of waste from one of the waste tanks.

The nuclear waste stored in these tanks consists of various forms and constituents, primarily the byproduct of nuclear material processing. One of the waste forms is commonly called sludge. Sludge is a mixture of oxides and hydroxides and may contain manganese, iron, some aluminum, zeolite, with traces of uranium, plutonium, and mixed fission products. The exact composition and radioactive content of sludge in any tank depends upon the process history of materials in the waste, and upon the age of the sludge (Hill, A. J. [1]). The solids are originally pumped into the tank as slurry and settle to the bottom of the tank over time. If allowed to remain undisturbed, the sludge can become compacted and cohesive. It is best described as a dark brown sticky mass of both loosely settled and compacted material. Interspersed throughout the sludge can be small chunks of insoluble salt solids, piles of steel measuring tapes, and industrial debris such as gasket material, plastic, hoses, etc. Rheological data on sludge is limited and is likely to vary between waste tanks.

Tank 18 is a 1.3 million-gallon single wall storage tank built in 1958. The tank contained an estimated 551,000 gallons of sludge solids in 1986 at the start of the first waste removal campaign (Abell, G [2]). Traditional waste removal methods used multiple mixer pumps to suspend sludge solids in liquid to form a slurry allowing it to be pumped out of the tank. This technology was used in the 1986 campaign. Three mixer pumps were used in 1986. After this campaign and after receipt of solids from other similar style tanks undergoing waste removal, the tank contained an estimated 47,000 gallons of sludge solids (Hubbard, M [3]). An effort was started to remove as much of this remaining waste as technically and economically feasible. Original methods used to remove waste solids are no longer considered cost effective. An engineering evaluation was performed to evaluate various methods and technologies for application to Tank 18 (Abell, G [2]).

The concept of the Advanced Design Mixer Pump (ADMP) originated as a joint program between Hanford and Savannah River Site (SRS). The intent of the ADMP program was to develop technology directed at resolving technical issues associated with traditional long-shaft slurry pump designs. The prototypical pump was built by Lawrence Pumps, Inc. and subsequently tested at the SRS Full Tank Test Facility [10]. The engineering evaluation for Tank 18 considered the ADMP as an option for suspending the remaining sludge solids, concluding that it was a viable alternative (Abell, G [2]). The ADMP was subsequently selected because it could meet functional requirements and was readily available. A Computational Fluid Dynamic (CFD) analysis was performed to estimate the Effective Cleaning Radius (ECR) of the ADMP to aid in waste removal process planning (Lee, S. Y., et. al. [5,6]). After refurbishment and pre-operational testing, the ADMP was installed in Tank 18. Although unexpected waste conditions and pump phenomena hindered waste removal performance, the ADMP successfully suspended the majority of sludge solids into a slurry allowing transport from the tank via a separate transfer pump (Thomas, J. L., [7]).

NOMENCLATURE AND ABBREVIATIONS

ADMP	Advanced Design Mixer Pump
Amps	amperage
CFD	computational fluid dynamics
DOE	United States Department of Energy
ECR	effective cleaning radius
gpm	gallon per minute
mRem/yr	millirem per year
NE	north east
NPSH	net positive suction head
pCi/L	picocurries per liter
psig	pounds per square inch
rpm	revolutions per minute
SRS	Savannah River Site
SW	south west

TANK AND EQUIPMENT DESCRIPTION

Tank 18 is a 1.3 million-gallon single wall storage tank built in 1958. It is cylindrical in shape with a domed roof and flat bottom. It is 85 feet in diameter with walls 34.25 feet high. The sides and bottom are made of steel plate backed by reinforced concrete. The domed roof is made of reinforced concrete and is approximately 45 feet high from the center to the bottom of the tank. There are manholes, commonly called risers, spaced around the roof for access into the tank, however access is limited or nonexistent through most risers because of abandoned equipment that can not be removed economically. The intersection between the sides and bottom is curved to a twelve-inch radius. There are no internal cooling coils or structural supports that would impede flow within the tank. See Fig. 6 and 7.

The ADMP is a long shaft centrifugal pump with a motor at the top and the impeller at the bottom. The drive shaft is 55 feet long and is segmented into sections. Each shaft section is individually removable and is mounted to a thrust bearing and a radial bearing. The bearings are oil lubricated. The drive shaft is contained in equally segmented cylindrical columns. The top and bottom columns are equipped with gas lubricated mechanical seals. The column is pressurized with air to prevent liquid waste from entering the column and contaminating the bearings. Approximately two standard cubic feet per minute (scfm) of air continually purges through the column and out through the mechanical seals when the pump is operating. The pump drive is a 300 horsepower, 1200 rpm, vertically mounted electric motor. The motor is controlled by a variable frequency drive (VFD) allowing the pump to operate at speeds between 700 and 1200 rpm. The pump casing has two diametrically opposed, horizontally aimed discharge nozzles. Each nozzle is six inches in diameter and located on the perimeter of the casing such that the discharge produces a tangent force vector with respect to the centerline of the pump in opposing directions. The pump generates 10,400 gpm (5200 gpm per nozzle) at full speed. The pump inlet configuration is similar to a sump pump, located beneath and in-between the discharge nozzles. An inlet screen covers the pump inlet. The inlet screen is approximately 39 inches in diameter, five inches deep and is made of light gage (approximately 1/8 inch) stainless steel perforated plate. The openings are approximately 5/16 diameter and cover the top, sides and bottom of the screen. The entire pump assembly is mounted on an oscillating turntable such that each nozzle discharge sweeps roughly 180 degrees of the tank. See Figs. 1 - 7.

A submersible pump is located in the northeast tank riser to pump the slurry out through a transfer line once the ADMP has suspended the sludge at a rate of 200-250 gpm. The transfer pump inlet is approximately seven inches off of the tank bottom.

INITIAL CONDITIONS

The volume of sludge in Tank 18 was conservatively estimated to be 47,000 gallons and was distributed throughout the tank bottom in varying heights ranging from an estimated minimum of 4 inches to a peak of 23 inches. The majority of waste appeared to be located in the south and northeast portions of the tank. See Fig. 10. Approximately 27,000 gallons of 40% sodium nitrite was added to the tank for corrosion control followed by well water to achieve an initial liquid level of ninety inches (approximately 318,000 gallons total volume).

During installation of the ADMP it was found that the pump would not fully insert into the tank due to unknown obstructions at the bottom of the tank. It was known that there was approximately twenty-two inches of sludge in the area of the ADMP inlet screen, but it was believed to be sufficiently loose such that it would disperse under the weight of the pump. It was later determined to be compacted sludge and steel tapes. The original design would result in the centerline of the discharge nozzles being approximately 23 inches off of the tank bottom with the bottom of the inlet screen approximately six inches off of the tank bottom. A mounting modification was implemented allowing the ADMP to be located at a higher elevation to avoid the interference. The final position resulted in the centerline of the discharge nozzles being approximately 39.3 inches off of the tank bottom. The ADMP discharge nozzle orientation with the tank resulted in a sweeping pattern between NE and SW.

Tank Cleaning Requirements

Requirements for tank cleaning are that the waste be processed to remove key radionuclides to the maximum extent that is technically and economically practical (DOE, [8]). In addition, the remaining waste must comply with US Nuclear Regulatory Commission Class C low level waste concentration limits and environmental performance objectives for tank closure stemming from South Carolina drinking water standards for contaminants at the point of compliance (the seepline). These regulations require that the tank farm beta-gamma radioactivity dose be no greater than 4 mrem/yr and the concentration of alpha emitting radionuclides be no greater than 15 pCi/L at the point of compliance. Compliance with all of the performance objectives is confirmed by a groundwater fate and transport model of the remaining contaminant inventory, as measured by process knowledge and sample data. The model calculates the contaminant concentrations at the seepline and the radiation dose received to a hypothetical individual at the seepline over the 10,000 year period following tank closure.

WASTE REMOVAL PROCESS

Fundamentally, removing sludge from a waste tank involves mixing the sludge solids with a liquid to form a pumpable slurry followed by pumping the slurry out of the tank. Based on the studies and evaluations, a waste removal process plan was developed for Tank 18. The process plan included multiple slurry mixing operations and transfers in order to suspend and remove the waste to other storage tanks. Figure 8 provides a relative timeline and the original plan for the waste removal operation (Hubbard, M. [3]). This figure includes the tank fluid operation levels and waste transfer planning. Four cleaning cycles were estimated as required. A cleaning effectiveness was estimated at 75% for each cleaning cycle with inspections for cleaning effectiveness planned after the first and fourth transfer. These transfers would include complete transfer of all of the tank waste as capable by the transfer pump.

For this discussion, a cleaning cycle consists of ADMP slurry operation followed by pumping the slurry out of the tank. The process of pumping liquid or slurry from a tank is called a “transfer”. All referenced liquid levels are liquid depths measured from the tank bottom.

The first cleaning cycle was planned to be performed with the tank filled to a depth of 90 inches and the ADMP run for 10 days. Tank fill levels to support mixing were driven by several factors. These tank level factors include:

- Administrative controls not to expose nozzles during operation (1 inch above nozzle or greater than 43 inches) to avoid aerosolization of waste.

- Evaluation showing that the cleaning radius is optimized with a tank level greater than 65 inches.
- Sludge settling rates for low weight percent sludge is fast, therefore the tank level is maximized to allow for ADMP operation during bulk quantities of the transfers.
- Process controls not related to mixing technology, e.g. waste water generation limits and flammability controls.

The 10 days of mixing was determined by CFD studies and past waste removal experience. Similar waste removal programs using standard slurry pumps monitored gas release rates during mixing. This data provided evidence that sludge suspension and cleaning radius was achieved in 9 to 10 days.

After 8 days of the initial 10-day run, a waste sample was to be obtained. Sampling requires a short shut down of the ADMP to allow for safe access of sampling tools. This sample was to provide baseline sample data of tank contents and to meet corrosion control monitoring requirements. After completion of the 10 day mixing cycle, transfer of the tank contents is initiated. The ADMP would be monitored and run during the transfer process to maximize waste removal, but shut down upon pump cavitation indication or 43 inches of tank depth to avoid nozzle exposure. ADMP monitoring consists of video inspection of the tank interior and monitoring of motor current. For the first and last transfer, the transfer pump is run until suction head is lost. Based on testing of the transfer pump, it was expected to pump down to approximately 7 inches from tank bottom. During the final 20 inches of the transfer process, the tank sludge levels are constantly monitored by video inspection and compared with the known liquid level. This inspection is called sludge mapping and is used to estimate the quantity of sludge remaining within the tank. The sludge mapping is used as a basis to measure waste removal and cleaning effectiveness.

The second and third cleaning cycles were planned to be shorter as compared to the first. To reduce waste water generation, the tank liquid level is limited to 60 to 65 inches and the transfer is stopped at 43 inches. The mixing time was estimated at 5 days each; however, sludge mapping results from the first transfer was used to alter the plan. Since the transfer of waste is stopped at 43 inches, cleaning effectiveness cannot be measured by inspection.

The fourth cycle was originally estimated to be the last cleaning cycled required. The tank would again be filled to 60 to 65 inches followed by ADMP operation for 5 days and a transfer of the slurry, continuing until transfer pump suction was lost. Sludge mapping is performed during the end of the transfer to estimate final cleaning effectiveness. Based on the evaluation of the cleaning effectiveness, the transfer pump is replaced by a dewatering pump to allow further tank liquid removal and mapping.

As noted in the following section, the waste removal process operation was adjusted to address initial poor mixing and sludge removal performance (Hess, B. R., [9]). These operational adjustments included indexed mixer pump operation and additional cleaning cycles combined with adjustments to the mixer pump height and orientation.

WASTE REMOVAL PERFORMANCE

The ADMP was initially operated for 3 hours to mix and distribute corrosion inhibitor (approximately 27,000 gallons of sodium nitrite) previously added to the tank. The pump was then run for 8 continuous days. This run was originally intended to be the first cleaning cycle, but was stopped and deferred due to changes in process planning priorities. Two slurry samples collected at the end of the 8-day run contained only trace amounts of sludge solids. Planning estimates predicted at least two weight percent solids in the first batch operation, much more than that found in the samples. Questions regarding the sample bottles used (small mouth) and sample collection method made the reason for the low percent-solids unclear, however it raised concern regarding the ADMP mixing effectiveness during the eight day run. The tank liquid level of 90 inches prevented a visual estimate of the ADMP effectiveness on the sludge solids. Sludge soundings within three feet of the ADMP centerline contacted the tank bottom indicating some sludge had been moved.

The ADMP was restarted approximately two months after the initial 8-day run to begin the first cleaning cycle. The ADMP was operated continuously for 10 days with the turntable operating at ½ rpm prior to starting the transfer pump. ADMP operation continued during the transfer until the tank liquid level reached approximately 43 inches in depth. The target final liquid level in the tank was 7 inches, however the transfer was terminated at approximately 22 inches. Camera inspection during the transfer showed that the transfer pump was located in a “sludge well” such that the transfer pump suction became starved requiring termination of the transfer sooner than planned to prevent overheating of the transfer pump.

As previously discussed, estimates predicted that the majority of waste should be removed during the first cleaning cycle, therefore a substantial reduction in visible solids was expected when the first transfer was complete. Although a detailed estimate of the remaining sludge was not possible given the 22 inch liquid level, sludge mounds were observed on the north and south sides of the tank, peaking at elevations of 23 and 25 inches respectively. The visible size of the two mounds indicated that the ADMP had not suspended as much sludge as expected. Conservative estimates show that as little as 3000 gallons of sludge may have been removed, versus an expected 30,000 gallons.

An effort was initiated to lower the ADMP to it's original design elevation (approximately 23 inches) to improve pump discharge impingement on the sludge mounds. After allowing time for sludge solids to settle, an underwater camera was inserted into the tank and used to inspect below the ADMP inlet screen. A large tangled mass of steel measuring tapes in sludge directly below the inlet screen was observed with an outside diameter roughly the same as the inlet screen. Measuring tapes are used to routinely measure the tank liquid level and are dropped into the tank due to wear, excessive contamination, etc. Over time the old tapes accumulate into a pile, particularly on older tanks. A special tool was developed and deployed to relocate the measuring tapes. The ADMP was then successfully lowered to the original design elevation. As noted earlier, the entire pump assembly is mounted on an oscillating turntable causing each nozzle discharge to sweep roughly 180 degrees of the tank. The position that the nozzles change direction with respect to the tank may not experience the maximum discharge jet velocity. Equipment limitations prevent the start / stop points from overlapping. The original nozzle start / stop points (NE to SW) coincided with areas of the tank that contained the largest mounds of sludge. The orientation of the ADMP was adjusted to provide a NW to SE nozzle sweeping pattern to increase the discharge jet contact time with the visible sludge mounds. The speed of the turntable was lowered to .2 rpm to reduce discharge jet shearing losses and maximize the effective cleaning radius. In addition to these changes, a strategy to operate the ADMP in a fixed position (i.e. without the turntable operating) was developed to increase the impingement time of the pump discharge jet at targeted mounds. This is commonly called "indexed" operation. A thermocouple was also installed in the waste tank to periodically monitor slurry temperature to confirm the temperature rise predicted by thermal analysis and ensure there was no detrimental effect on the ADMP NPSH. Tank liquid level during the remaining cleaning cycles was limited to between sixty and sixty-five inches due to space constraints in receiving tanks.

The second cleaning cycle was started shortly after the adjustments noted above. ADMP operation was initiated in a fixed (indexed) position. The ADMP was operated for approximately two days at each of 7 indexed positions. At this point, the ADMP had operated sufficiently to begin trending of the pump operating data. Very limited data is available compared to more traditional centrifugal pump systems. Because the pump inlet and discharge is in an open tank, typical pump performance data such as discharge head and flow rate are not available. The only data available for this application is pump speed, motor load in amperage, and temperature of the waste. Video of the liquid surface is available to qualitatively assess the magnitude of surface turbulence generated by the mixer pump. Analysis of this data showed the ADMP current was reducing over time. A typical start up load would be approximately 250 - 290 amps at 1185 rpm, but would drop to approximately 210 amps within one hour of start up. Data from the first 10 day mixing cycle showed that the load settled to approximately 200 - 190 amps after approximately 56 hours of operation. "No-load" amperage was measured to be approximately 166 amps at 1185 rpm during testing. See Fig. 9. There were no other indications of problems with the ADMP operation. The drop in load was considered undesirable because it indicates the ADMP may not be doing as much work as expected, resulting in less cleaning effectiveness. Surface turbulence appeared to reduce as motor loading dropped. A 72 hour endurance test run in water prior to installation showed a steady load of approximately 266 amps. The pump operating speed was lowered to reduce the potential for pump damage from cavitation or vortexing while the loss of pump load was being investigated. Initially the pump operating speed was lowered to 1050 rpm and later lowered to 900 rpm. There was no significant change in pump performance at the lower speeds, as measured by the pump current, other than expected lower start up loads. The operating speed was subsequently increased back to 1050 rpm. An operating strategy of shutting the ADMP down when the amps dropped below a minimum load value specified by Engineering (typically 230 to 210 amps) was implemented. The ADMP would remain down for 1 to 4 hours prior to restarting. A minimum of one hour was specified by the motor vendor to allow for cooling prior to restart. Experience showed that shutting down for longer than one hour would occasionally result in longer run-times before the minimum amp loading was reached. Cleaning cycle 2 was completed in this fashion. The remaining cleaning cycles were also performed this way, however the ADMP speed was increased back to 1185 rpm. Although the ADMP cleaning effectiveness was still not as predicted, substantial improvement was noted based on remaining solids volume estimates at the end of the second cleaning cycle. An estimated 23,000 gallons of sludge was removed.

Other efforts were initiated to improve ADMP mixing performance. Potential causes, indicators, confirmation methods, and corrective actions for the decrease in ADMP performance were identified. Inspections to confirm proper ADMP operation did not identify any other pump anomalies or malfunctions. Video at the end of the first two cleaning cycles showed significant debris accumulation on the inlet screen, leading to the theory that the pump was becoming starved, possibly to the point of cavitation, although no other signs of cavitation had been noted (such as excessive noise and vibration). The pump manufacturer stated that up to fifty percent of the inlet screen could become clogged before impacting the pumps performance. Although subjective, video inspection indicated that this amount of screen pluggage was possible. See Fig. 3. A high velocity water lance (60 –65 gpm at 800 psig) was deployed to flush the screen and the area around and below the ADMP. The mixing performance did not improve after lancing with 7500 gallons of water. A second attempt had the same result. The inlet screen openings were sized to prevent the steel measuring tapes from entering the pump inlet and becoming entangled with the impeller. In another attempt to prevent screen pluggage, a portion of the inlet screen was modified to increase the open surface area allowing smaller debris to pass through the pump. The open surface area was increased by approximately 20%. See Fig. 4. When ADMP operation resumed, no significant improvement in ADMP performance was noted based on motor amp loading. Other actions were considered that could possibly identify the root cause of the loss of ADMP load, but these were not considered technically and economically feasible (Augeri, M. J., et. al. [10]).

After six cleaning cycles of varying volumes and mixing duration, an estimated 4320 gallons of sludge remained in the tank, with a maximum mound height of approximately 10 inches. An evaluation was conducted that concluded that further waste removal was not technically and economically practical. See Figs. 11 and 12. The 4320 gallons of waste remaining meets all environmental performance objectives and can be disposed of in a form that complies with class C concentration limits for low level waste.

To improve future slurry pump performance, actions to consider should include:

1. Maintain a higher NPSHA value and operate the pump in a lower NPSHR range, by operating the pump in the following conditions:
    - Higher tank fluid level
    - Lower fluid temperature
    - Increased suction screen flow through open areas.
    - Clean fluid approach area to the pump suction.
    - Reduced discharge nozzles size.
    - Lower pump speed operation.
2. Prevent air entrainment to the pump suction due to vortexes and fluid splashing at the nozzle discharge.
3. Divert column air discharge away from the pump casing and the pump suction.
4. Test the pump under the identical operation conditions as that of the installed pump.
5. Characterize the tank waste for chemical and physical properties, to determine fluid foaming and air bubble retention capabilities of the waste.
6. Characterize the tank waste to establish erosion properties of the sludge material.

CONCLUSION

CFD modeling predicted that the ADMP was capable of suspending sludge particles to the waste tank wall. The CFD model predicts the liquid velocity distribution within the tank and compares those calculated velocities with expected velocities required to suspend particles of a particular size and mass. Based on the amount of sludge solids removed from the tank and the reduction in sludge mound height near the tank wall, it can be concluded that the modeling accurately predicted the mixer pumps capability to suspend sludge particles in the waste tank.

The poor cleaning efficiency experienced in cycle 1 was likely due to a combination of factors, such as low pump loading, the mixer pump nozzle discharge elevation being approximately 14 inches higher than the peak of the sludge mounds, high turntable speed causing excessive shear of the discharge streams, and the original orientation of the pump resulted in the largest sludge mounds being in the least turbulent zones of the tank. Corrective actions taken after the first cleaning cycle improved the estimated cleaning efficiency from 6% to approximately 52%. Resolution of the loss of pump loading would likely improve the pump mixing efficiency even further.

As mentioned earlier, there is limited rheological data available for the sludge material. The assumed minimum velocity required to suspend the sludge (2.27 ft/sec) (Lee, S. Y. [6]) is primarily based on limited analytical data and previous sludge handling experience, but it is possible for the sludge properties to be different between waste tanks and even within a waste tank. Observation of the sludge in Tank 18 showed that some portions appeared cohesive while other more loose portions settled rapidly into dense layers, suggesting that higher velocities may be required to break apart cohesive portions and maintain suspension of larger particles. Sampling of the remaining sludge indicated the presence of zeolite. Zeolite is known to be fast settling and difficult to remove with this technology (Enderlin, C. W., et. al. [11]). The initial quantity of zeolite in Tank 18 sludge was unknown. These factors may have also contributed to the cleaning efficiency being less than originally predicted.

FIGURES

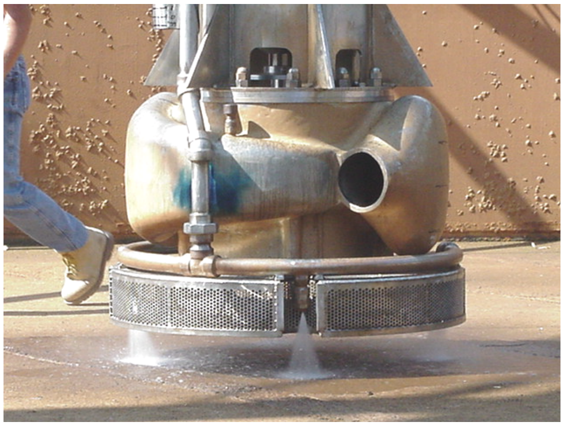

Figure 1: Pump with Mining Ring Operating

Figure 2: ADMP Operating in Water in Test Tank

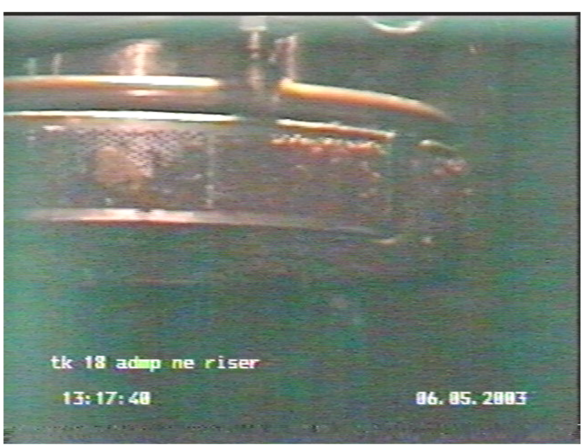

Figure 3: ADMP Inlet Screen Plugged with Trash

Figure 4: Modified ADMP Inlet Screen

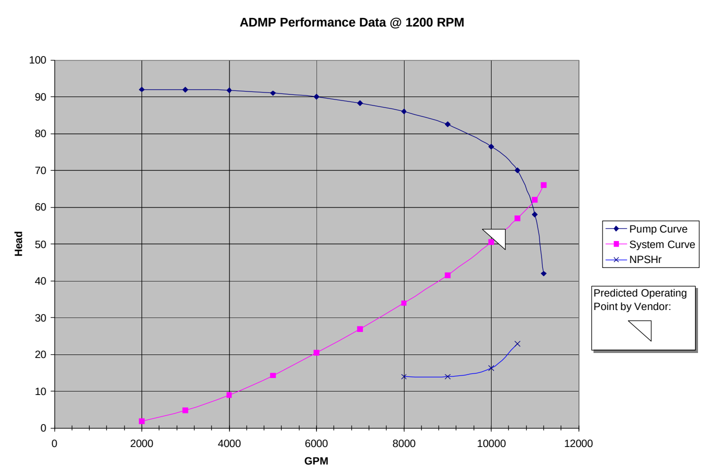

Figure 5: ADMP Manufacturer Performance Curves

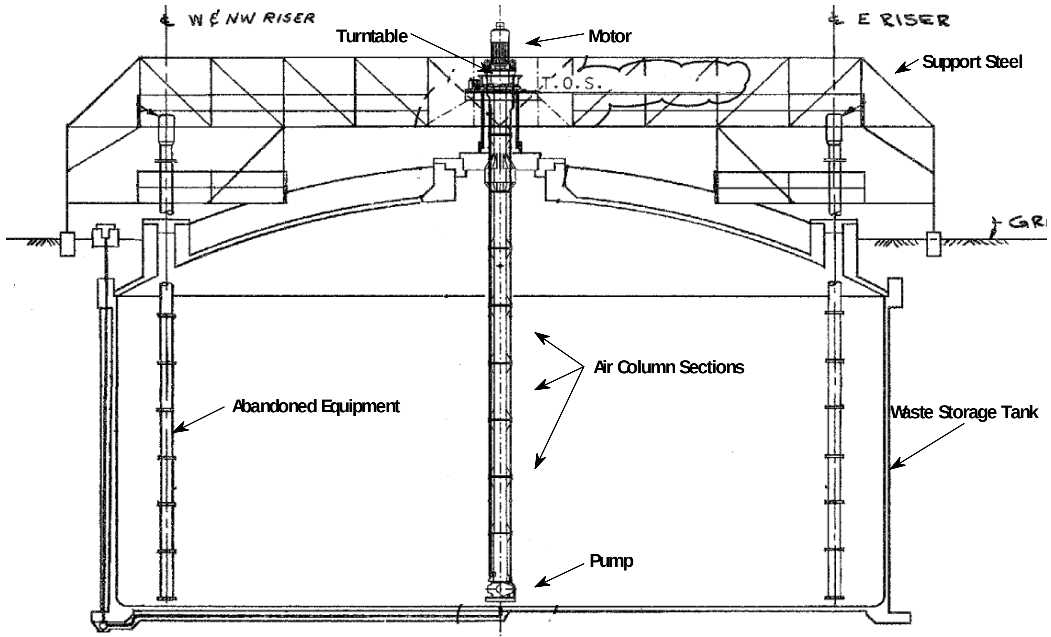

Figure 6: Elevation View of Waste Storage Tank with ADMP Installed in Center Riser

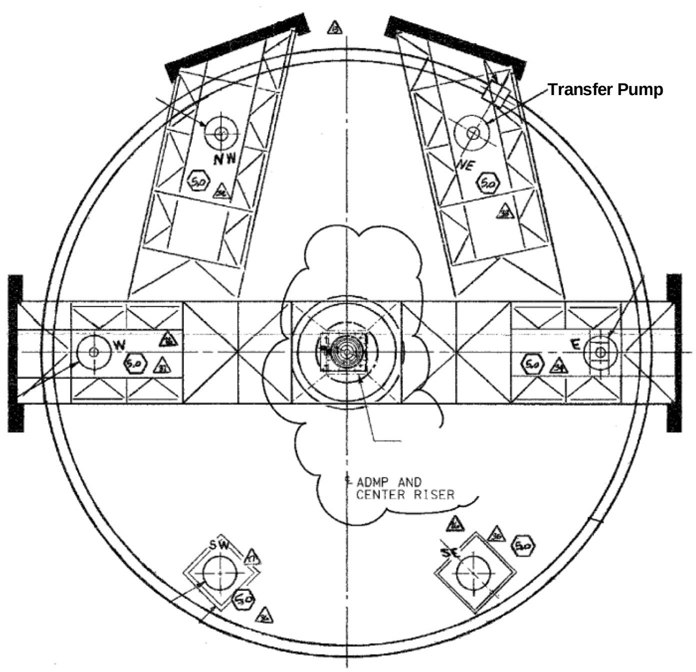

Figure 7: Plan View of Waste Storage Tank

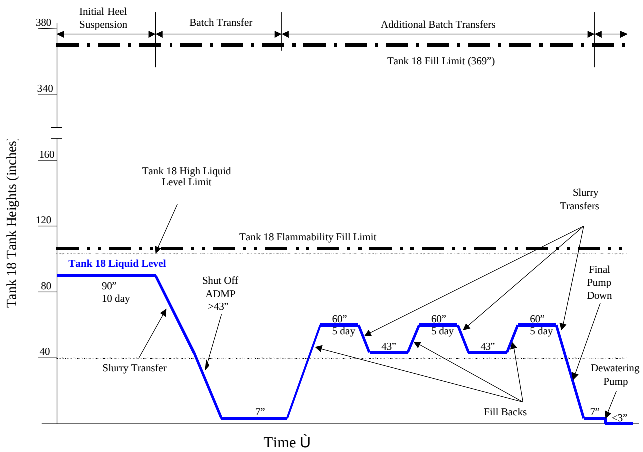

Figure 8: Planned Waste Removal Process

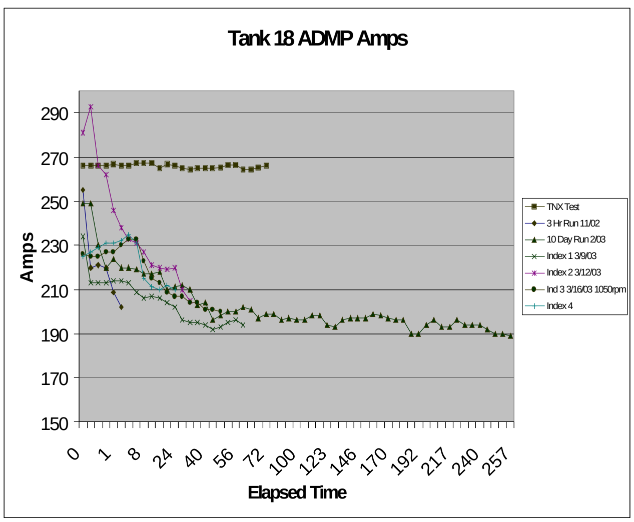

Figure 9: ADMP Amp Loading vs. Time

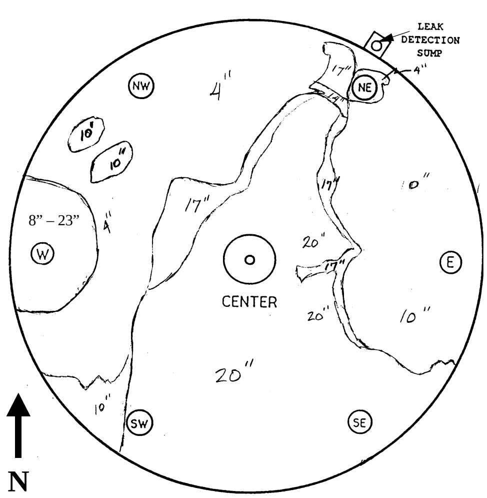

Figure 10: Plan View of Initial Sludge Level Map

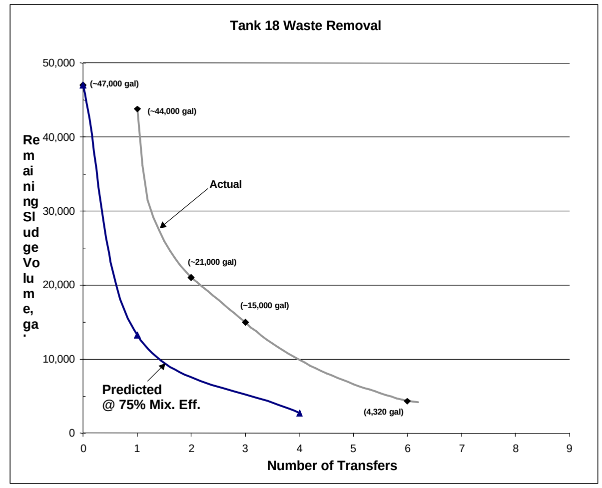

Figure 11: Sludge Removed Per Cleaning Cycle

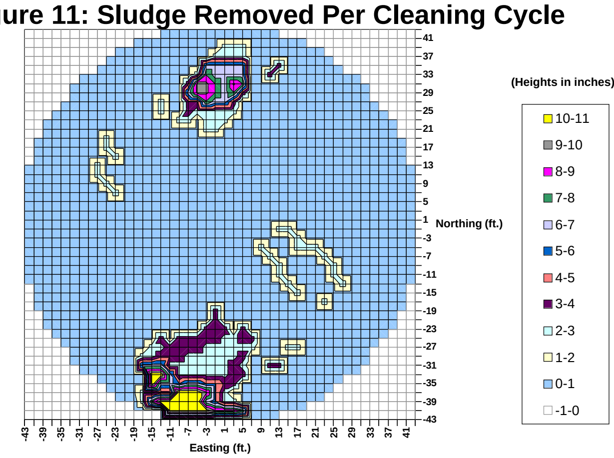

Figure 12: Final Sludge Topography

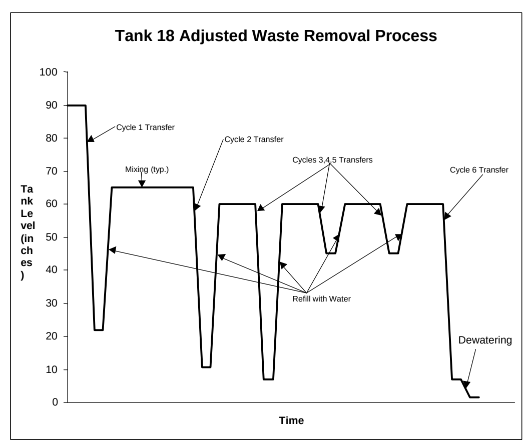

Figure 13: Adjusted Waste Removal Process

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