Methods for Determining Agitator Mixing Requirements for a Mixing & Sampling Facility to feed WTP

P.W. Griffin

Washington River Protection Solutions, LLC

Richland, WA 99352

U.S. Department of Energy Contract DE-AC27-08RV14800

EDT/ECN: DRF

UC:

Cost Center:

Charge Code:

B&R Code:

Total Pages: 45

Key Words: Mechanical mixer, Mixing and Sampling Facility, Zwietering correlation, suspension, high level waste mixing.

Abstract: The following report is a summary of work conducted to evaluate the ability of existing correlative techniques and alternative methods to accurately estimate impeller speed and power requirements for mechanical mixers proposed for use in a mixing and sampling facility (MSF). The proposed facility would accept high level waste sludges from Hanford double-shell tanks and feed uniformly mixed high level waste to the Waste Treatment Plant. Numerous methods are evaluated and discussed, and resulting recommendations provided.

TRADEMARK DISCLAIMER. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors.

Nancy A Fouad
Release Approval

8-27-09
Date

Release Stamp

Approved For Public Release

Methods for Determining Agitator Mixing Requirements for a Mixing & Sampling Facility to feed WTP

P.W. Griffin

Washington River Protection Solutions, LLC

August, 2009

P.O. Box 850
Richland, WA 99352

EXECUTIVE SUMMARY

The following report is a summary of work conducted to evaluate the ability of existing correlative techniques and alternative methods to accurately estimate impeller speed and power requirements for mechanical mixers proposed for use in a mixing and sampling facility (MSF). The proposed facility would accept high level waste (HLW) sludges from Hanford double-shell tanks (DST) and feed uniformly mixed HLW sludge to the Waste Treatment Plant (WTP). Numerous methods are evaluated and discussed, and resulting recommendations provided. Due to the complexity of the task and the lack of available, applicable correlations and techniques, the final recommendation is to consult professional mixing personnel for the purpose of developing a scaled model test plan to determine system requirements. The consultant must have notable experience developing mixing systems that process broad particle size and density distributions, ideally in the nuclear industry. One such consultant considered in this report is Philadelphia Mixing Solutions, Ltd. (PMSL). PMSL has extensive experience designing mixing systems for the nuclear industry with successful product deliveries currently in use at Savannah River Site, Oak Ridge, and IHI in Japan. They are the NQA-1 certified supplier of mechanical mixers for the WTP Project managed by Bechtel National Inc..

Calculations contained herein are preliminary and served to guide the problem of sizing mechanical mixers for mixing Hanford tank HLW sludge toward a more empirical approach to determine proper mixer sizing/configuration. Note also that the industry accepted approach is to use scaled model testing to determine proper mixer sizing for complex applications, not generalized correlations. Further, the risk to the WFD Project resulting from incorrect calculations is low due to the very low probability that incorrect conclusions were drawn from these calculations. While the preliminary calculations contained herein do not fit the definition of "computation" per TFC-ENG-DESIGN-C-10 (thus requiring no documented calculation check), it was determined that little value would be added by performing a calculation check commensurate with an informal calculation. Users must recognize this limitation and engage in calculation verification as per TFC-ENG-DESIGN-C-10 if results from calculations are used explicitly.

TABLE OF CONTENTS

1.	Introduction.....	1
1.1	Background.....	1
1.2	Objective.....	1
1.3	Overview of MSF Requirements	2
1.4	An Introduction to Mechanically Agitated Mixing Systems	2
2.	A Discussion on Complexity	3
2.1	Vessel Geometry	3
2.2	Impeller.....	4
2.3	Process Constituents and Process Requirements	4
3.	Analytical Techniques – The Zwietering Correlation.....	5
3.1	Application of The Zwietering Correlation	5
3.2	Comments on Applying Zwietering’s Correlation.....	7
3.3	Zwietering Results	9
3.4	Zwietering Correlation Conclusion.....	11
4.	Analytical Techniques -- The Oldshue Technique.....	11
4.1	The Oldshue Technique.....	11
4.2	APPLYING THE OLDSHUE TECHNIQUE.....	11
4.3	Oldshue technique conclusion	13
5.	Analytical Techniques -- Modified Froude Number Correlation	14
6.	Conclusion on Correlative Techniques	14
7.	Alternative Methods.....	15
7.1	Computational Fluid Dynamics	15
7.2	Scaled Modeling	15
7.3	Expert Appeal – Philadelphia Mixers	16
8.	Conclusion and Recommendations	18
9.	References.....	20

LIST OF APPENDIXES

A	Notes on Calculations.....	A-1
B	Data from Philadelphia Mixers.....	B-1
C	Unpublished Reference Material.....	C-1

LIST OF FIGURES

Figure 1-1. Standard mechanically agitated vessel.....	2
Figure 1-2. Degrees of suspension.....	3
Figure 6-1. Parameter range comparison.....	15

LIST OF TABLES

Table 3-1. Operating conditions over which the Zwietering correlation was obtained.....	7
Table 3-2. Best-recommendation waste property parameters of average HLW.....	8
Table 3-3. Zwietering correlation results for 1 PBT4-45 impeller.....	10
Table 3-4. Zwietering correlation results for 2 PBT4-45 impellers.....	10
Table 4-1. Particle free-settling velocities.....	12
Table 4-2. Power and impeller speed predictions.....	13
Table 4-3. Power consumption based on Oldshue Technique.....	13
Table 7-1. PSD as utilized by Philadelphia Mixers.....	17
Table 7-2. Philadelphia Mixers' recommended speed and power.....	17

ABBREVIATIONS AND ACRONYMS

BR	Best Recommendation
CFD	Computational Fluid Dynamics
HLW	High-level waste
MFN	Modified Froude number
MSF	Mixing and Sampling Facility
NQA	Nuclear quality assurance
PBT	Pitched-blade turbine
PBT4-45	4-blade pitched-blade turbine, blade angle = 45°
PMSL	Philadelphia Mixing Solutions, Ltd.
PSDD	Particle size and density distribution
WTP	Waste Treatment Plan

VARIABLES AND CONSTANTS

B	Baffle width
C	Impeller clearance from vessel base
c_w	Solids concentration percentage by weight
D	Impeller diameter
d_p	particle diameter
$\Delta\rho$	Density difference ($\Delta\rho = \rho_s - \rho_l$)
g	Gravimetric constant ($g = 9.81 \frac{m}{s^2}$)
k	Scale up equation constant
μ_L	Liquid dynamic viscosity
N	Impeller speed
n_b	number of impeller blades
N_{JS}	Agitator “just-suspended” speed
N_U	Agitator speed for uniform suspension
ν	Liquid kinematic viscosity
P	Power
P_O	Power number
$P_{O,E}$	Equivalent power number
$P_{O,H}$	Hydrofoil power number
$P_{O,PBT}$	Pitched-blade turbine power number
π	geometrical constant, pi ($\pi = 3.14\dots$)
R	regression line correlation coefficient
ρ_l	Liquid density
ρ_s	Solids density

ρ_{slurry}	Slurry density
s	Impeller geometry constant
T	Vessel diameter
Tq	Shaft Torque
V_s or V_s	Settling velocity
v_s	solids volume fraction
W	Blade width
X	Solid to liquid mass ratio
Z	Liquid level height

MATHEMATICAL UNITS

ft/min	feet per minute
ft	foot
gal	gallons
g/mL	grams per milliliter
HP	horse power
$\frac{kg}{m^3}$	kilograms per cubic meter
m	meter
μm	micron
mm	millimeter
mPa s	millipascal-seconds
ln	natural logarithm
Ns/m ²	Newton-seconds per square meter
rpm	revolutions per minute
rev/s	revolutions per second
m ² /s	square meters per second

1. INTRODUCTION

1.1 BACKGROUND

When stored over time, Hanford tank waste segregates into various phases in an attempt to reach equilibrium. These phases are known as supernatant, saltcake, and sludge, and exist in varying concentrations in most tanks. Supernatant refers to waste that exists as a liquid, generally floating above any solid matter. Saltcake is comprised of chemicals which have crystallized to form solids. Finally, insoluble solids which have settled at the tank bottom comprise what is known as sludge. In the interest of mobilizing this waste for transfer to other tanks or the WTP, saltcake and sludge must be mixed back into solution. With the help of hot water, saltcake can be remixed fairly easily. Sludge waste, on the other hand, poses a greater challenge. Because tank waste is removed by pumping, the sludge must be vigorously mixed to suspend it in a carrier fluid; pure solids cannot be pumped. Current plans for mixing DST sludges include mixing via jet mixer pumps. Jet mixer pumps offer a limited degree of mixing that may be quite acceptable for mobilizing and transferring waste, but possibly too crude a procedure to meet some proposed receipt requirements of the WTP.

WTP has numerous requirements that all waste must satisfy prior to being received (ICD-19). To characterize and certify any waste intended for processing, a sample must be taken and endure a testing period of more than 180 days. It is essential to safe and efficient operations that the sample is representative of an entire tank's contents, if possible. The most dependable solution is to provide mixing capability that yields a uniform sludge mixture. If a sample is taken incorrectly or it is determined that the sample is not a valid representation of the tank waste, WTP will refuse the transfer until such a sample can be provided. It is, therefore, fundamental to the success of both the Tank Farms Contractor (TFC) and WTP that a method for reliable, representative sampling be developed and that waste transferred to the WTP be consistent with that sample.

One of the proposed solutions for ensuring that waste can be delivered in accordance with WTP waste acceptance criteria is a separate mixing and sampling facility. Such a facility would be dedicated to accepting HLW sludges from DSTs and developing conditions for reliable sampling and transfer operations immediately prior to transfer to the WTP. Currently, it is thought that uniform mixing of waste will be required to obtain a sufficiently reliable sample. While testing is currently planned to demonstrate the homogeneous mixing capability of existing jet mixer pumps in DSTs, a MSF is being considered as a contingency in the event that the demonstration proves unsuccessful. This facility would utilize an alternative mixing technology and be designed specifically to ensure proper mixing and sampling.

1.2 OBJECTIVE

This paper seeks to briefly evaluate several methods for determining speed and power requirements for agitator-style mixers proposed for use in MSF and recommend best-suited

method. Techniques, obstacles, and proposed future work will be discussed. In addition, estimates of functional requirements for the process mixing vessels including vessel geometry, agitation speed, and power consumption are provided.

1.3 OVERVIEW OF MSF REQUIREMENTS

For an initial estimation purposes, MSF will be considered to house six, 500,000 gallon tanks, each equipped with equivalent waste mixing and sampling capabilities. This estimate was arrived at by considering contingency support in the event that some batches would be unavailable for on-schedule transfer to WTP. WTP waste acceptance criteria mandates that HLW will be transferred in batches of up to 160,000 gallons (ICD-19).

1.4 AN INTRODUCTION TO MECHANICALLY AGITATED SYSTEMS

Mechanically agitated systems have long been used to facilitate mixing of innumerable sorts. Basically, a mechanically agitated vessel system consists of several key components. A vessel is needed in which the materials to be mixed can be confined. An agitator, very often some form of a propeller or paddle, is placed within the vessel to stir the material and promote dispersion. Finally, a motor or some source of rotational energy is affixed to the agitator, often by a shaft. Figure 1-1, below, shows a standard mechanically agitated mixing system.

Figure 1-1. Standard mechanically agitated vessel (from mixingsolutions.com)

The degree, or quality, of solid suspension can be measured in several ways, but is most frequently classified into three categories: on-bottom motion, off-bottom suspension, and uniform suspension. Figure 1-2, below, is provided as a visual representation of each category.

Figure 1-2. Degrees of suspension (modified from Edward et al. 2004)

On-bottom motion describes the complete motion of solids particles on the bottom of the vessel. This is often achieved at very low levels of agitation where most solids constantly remain in contact with the vessel base. Off-bottom suspension refers to a state of agitation in which all particles exhibit complete motion, with no particle resting on the vessel base for longer than 1-2 seconds. Many correlations, originating with the work of Zwietering (discussed below) are concerned with the minimum agitator speed required to achieve this state. It is referred to as the “just-suspended” speed. Uniform suspension describes the state of suspension at which particle concentrations and distributions are nearly uniform throughout the vessel. A concentration gradient of 5% is considered adequate for most applications. Uniformity of 100% is nearly impossible, and at the very least often impractical and unnecessary, due to the existence of a thin fluid layer of lower particle concentration at the top of the fluid. Therefore, the term “uniform suspension” as used in this document will refer to a suspension of approximately 95% uniformity.

2. A DISCUSSION ON COMPLEXITY

It is often easy to underestimate the complexity of determining hardware requirements for mixing applications. The following section provides a brief discussion of aspects that must be sufficiently considered when developing such requirements.

2.1 VESSEL GEOMETRY

Mixing is dominated by fluid flow characteristics, and fluid flow, in turn, is a function heavily related to tank geometry. A poorly designed tank may never mix correctly no matter how fast the impeller spins.

Liquid level height and vessel diameter are two very important quantities. The liquid height to vessel diameter ratio (Z/T) will determine the number of impellers required for various degrees of suspension. The impeller diameter to tank diameter ratio (D/T) will dictate other requirements

such as agitation speed, power, and shaft torque. How the impeller(s) enters the vessel will determine numerous other geometrical decisions. Top entering mixers on the tank centerline often create a vortex effect which must be accounted for by the installation of baffles. The number of baffles, their location, and dimensions all become key factors that will affect mixing. Slight variations in any of these geometries may be the difference between exceptionally good mixing and none at all.

There is no one configuration of these parameters that will suit all applications. As process variables change, tank geometry must change to suit them. One configuration may work exceptionally well for a particular application but may be the worst configuration for another.

2.2 IMPELLER

Impeller selection is, while less enigmatic than tank geometry, another very important suspension-defining variable. Numerous impeller styles exist to serve different purposes. Selection is made fairly easy for suspending solids in low-viscosity fluids. A hydrofoil is a specific type of axial flow impeller which lends itself particularly well to solids suspension in low-viscosity fluids. It is more efficient than a pitch-blade turbine, requiring less power for a comparable suspension quality. Once the impeller is selected, the optimal speed that can achieve the desired level of suspension can be determined. Many techniques and methods have been developed attempting to correlate impeller speed with suspension, each with different constraints and limitations.

2.3 PROCESS CONSTITUENTS AND PROCESS REQUIREMENTS

The process constituents, as related to this report, are defined as those materials which will undergo mixing. In this case, they are the liquid supernatant and solid sludge. The process requirements are criteria that must be met by the mixing system. They involve qualifications for degree of suspension, process constituent envelope, batch size, and the like. The process constituents and process requirements dictate the design of the system.

Design difficulty is closely related to the nature of the process constituents. Complexity arises when numerous constituents of varying densities, sizes, and concentrations are present. Several items that must be considered for system design are:

- Flow patterns induced by the tank geometry and impeller must be sufficient to meet process requirements
- Flow pattern changes as a result of variable process constituents must be considered
- Vessel design should be optimized to reduce motor power requirements

Numerous attempts have been made to predict mixing behavior by way of physical testing, correlations, and computational fluid dynamics. While these methods work to some capacity, the overwhelming number of variables and unknown phenomena has prevented an accurate

mathematical representation for all configurations and under all circumstances. Correlations can be found, however, that provide reliable predictions over a narrow range of conditions.

A particular difficulty facing MSF is that not all HLW has been characterized and therefore not all waste properties are known. This issue is further complicated by the fact that batch rheology and characteristics may change upon transfer from the storage tanks to MSF tanks. Therefore, consideration must be made in the design to accommodate unknown waste.

3. ANALYTICAL TECHNIQUES – THE ZWIETERING CORRELATION

Numerous studies and years of research have been devoted to developing methods for predicting mixing behavior and system requirements. Correlations, such as those presented in the following section, have been widely used to assist in the preliminary design of liquid-liquid and liquid-solid mixing systems by means of mechanical agitation. The following section is an explanation of the results and limitations of several correlations relevant to defining MSF performance requirements.

3.1 APPLICATION OF THE ZWIETERING CORRELATION

Possibly the most popular correlation for suspending insoluble solids in a liquid was one proposed by T. N. Zwietering in 1958. By performing numerous experiments suspending glass and sand in water, Zwietering observed that a relationship exists between the critical mixing speed required to keep particles in a “just suspended” state and numerous process variables. The just-suspended criterion is defined as no particle resting on the vessel bottom for more than 1-2 seconds during agitation has since been a significant characteristic of subsequent research. The Zwietering correlation was recommended as a good starting point for evaluating necessary mixing equipment requirements by numerous sources and was, therefore, employed first (Dickey D.S., 2009-5-20; Etchells, et al. 2009; Oldshue 1983; Edwards, et al. 2004)

In its dimensional form, the Zwietering correlation is presented by Etchells et al. (2009) as the following (Eq. 3.1):

$$N_{js} = s v^{0.1} \left(\frac{g \Delta \rho}{\rho_L} \right)^{0.45} X^{0.13} d_p^{0.2} D^{-0.85} \quad (\text{Eq. 3.1})$$

where

N_{js}	=	just-suspended impeller speed
s	=	Zwietering geometrical constant
v	=	liquid dynamic viscosity
$\Delta \rho$	=	solids – liquids density difference
ρ_L	=	liquids density
X	=	solids to liquids mass ratio

d_p	=	particle diameter
D	=	impeller diameter
g	=	acceleration due to gravity

Once N_{JS} is obtained, the power required to turn the impeller can be calculated by Equation 3.2 (Etchells, et al. 2009).

$$P = P_0 \rho_{slurry} N^3 D^5 \quad (\text{Eq. 3.2})$$

where

P	=	power
P_0	=	power number
ρ_{slurry}	=	slurry density
N	=	impeller speed (N_{JS} or other)

As solid particles are dispersed throughout the liquid, the mean density of the mixture will increase. To account for this increase, average slurry density (ρ_{slurry}) was used to calculate power. Regardless of suspension degree, ρ_{slurry} was calculated as if all particles were dispersed uniformly. Equation 3.3 shows the formula used for ρ_{slurry} .

$$\rho_{slurry} = \frac{100}{\frac{c_w}{\rho_s} + \frac{100-c_w}{\rho_L}} \quad (\text{Eq. 3.3})$$

where

c_w	=	solids concentration percentage by weight
ρ_s	=	solids density

Oldshue (1983) recommends a scale up factor of 1.7 to estimate the impeller speed for uniform suspension (N_U) from N_{JS} for particle free settling velocities of 16-60 ft/min. This range of free settling velocities was considered because of its conservatism.

$$N_U = 1.7 N_{JS} \quad (\text{Eq. 3.4})$$

While it is possible that uniform suspension may not be required for sufficient sampling and transfer, this has not been confirmed. Therefore, and on the basis of providing a conservative estimate, this document will consider uniform suspension as the necessary suspension requirement for sufficient sampling and transfer.

Regarding scale up, the Zwietering correlation may be applied directly to large-scale applications or a scale up factor may be used. Many scale-up factors have been proposed but literature does little to provide a best recommendation. As a result, this evaluation opted against a scale up factor and applied the correlation directly.

Despite its popularity, the Zwietering correlation is not without its limitations. It is not the exclusive solution to all solid-liquid mixing applications. Most notably, perhaps, is that the correlation begins to break down when applied to processes involving variables and parameters not accounted for in its derivation. This particular constraint has proven most cumbersome when attempting to adopt the correlation for use with Hanford tank waste. Several key boundaries limiting its operational range are particle size, particle density, liquid density, and the solid-liquid density difference, $\Delta\rho$.

The correlation is best suited for suspending two insoluble constituents of uniform properties, such as sand in liquid water. In this case, both the water and sand can be assumed to be of distinct, constant densities, viscosities, etc..., and the standard deviation of each property is relatively small. Actual results may deviate from the correlation when it is applied to substances that have variable physical properties, i.e., variable solids or liquid densities, large variations in particle size, exhibition of non-Newtonian behavior, or use parameters in great excess of the values provided in Table 3-1. After a quick analysis, it became clear that numerous process constituents facing MSF departed significantly from Zwietering's design conditions. Some of these can be observed by comparing Tables 3-1, 3-3 and 3-4.

Table 3-1. Operating conditions over which the Zwietering correlation was obtained (Etchells et al. 2009)

Parameter	Range covered
$\Delta\rho(\text{kg/m}^3)$	560 – 1800
$d_p(\mu\text{m})$	140 – 520
$X(\%)$	0.5 – 20
$T(\text{m})$	0.1 – 0.6
D/T	1/6 – 1/2
n_b	4
C/T	1/20 – 1/2
Impel. type	4
Vessel base shape	Flat, dish & conical
$\mu_i(\text{mPa s})$	0.3 - 9

3.2 COMMENTS ON APPLYING ZWIETERING'S CORRELATION

Analysis using the Zwietering correlation began by determining average values for each property of interest. The correlation was then applied and analysis made to evaluate suspension requirements facing an "average" batch. However, because tank waste is not conveniently "averaged" over all tanks, further analysis was done by attempting to model several different scenarios. This was intended to provide insight regarding how N_{JS} , N_U , and power consumption would respond to more difficult circumstances than presented by an average batch.

RPP-5346 and RPP-9805 provided best-recommendation (BR) estimates for average values based on data collected from eight HLW tanks, which are presented in Table 3-2. While WTP-

RTP-153 is generally considered the recent source for particle size and density, it is self-admittedly not conservative. Therefore, in the interest of being conservative, BR solids and liquids properties from RPP-5346 and RPP-9805 were used instead.

Table 3-2. Best-recommendation waste property parameters of average HLW

Property	HLW
Particle Size (μm)	7.5
Solids Density (kg/m^3)	2900
Liquid Density (kg/m^3)	1100, 1300
Liquid Viscosity (cP)	1.5, 1.6
Solids Loading (%vol)	$\leq 10\%$

The study summarized in RPP-5346 sought to characterize tank waste physical properties in an attempt to define a design basis for pressure drop and transfer pump requirements. Similar to the Zwietering correlation, pressure drop and related calculations for the transfer system analysis required representative values for relevant parameters. Rather than attempting to model every different type and concentration of waste that may pass through the transfer lines, one set of parameters was needed that would reliably represent all HLW. The best recommendation properties resulting from this study were developed specifically to meet this need.

Numerous cases were considered in order to develop an understanding of power requirements as a function of various waste parameters. To evaluate operational requirements under average waste loadings, best recommendation parameters were used (Table 3-2), including the 95/95 tolerance level particle size (RPP-9805). Two best-recommendation values were provided for liquid density, and therefore the average was used ($1200 \text{ kg}/\text{m}^3$). As another case, and in consideration of larger, denser particles, one solid constituent was evaluated at a time, the densest of these being PuO_2 . A 10% solids concentration (by volume) was assumed and the particle size for each solid constituent was taken to be the maximum observed by WTP-RPT-153. In addition to distinct particles, large clusters of agglomerated solids have also been found, the largest of these being 1mm in diameter. Therefore, in an attempt to understand performance requirements in the presence of such large particles, additional cases were considered wherein 0.25% by volume of the solids concentration was assumed to be comprised of particles 1mm in diameter. In the case of PuO_2 , even if all PuO_2 present at the Hanford tank farm was transferred in one batch to a 500,000 gallon tank, its solids concentration would be approximately 0.008316% by volume, well below 10%. As such, 0.008316% was used instead of 10%. Further notes on calculations are provided in Appendix A.

Because no applicable s values for a hydrofoil impeller operating under the desired process conditions could be procured, a pitched-blade turbine with four blades and a 45° blade angle (PBT4-45) was used.

3.3 ZWIETERING RESULTS

Table 3-3 shows results based on the use of a single PBT4-45 and the required impeller speeds and power to achieve both just-suspension and uniform suspension in a 500,000 gallon vessel. Table 3-4 shows results based on waste parameters identical to those from Table 3-3, but with the employment of two impellers, as is recommended for uniform dispersion in a vessel of $Z/T = 1.3$ (See Figure B-1 in Appendix B). Tank diameter was taken to be 40 ft, and the impeller diameter was taken to be 13.3 ft. For both cases power must be increased nearly five times to achieve uniform suspension from just-suspension. Use of two impellers mandates doubling the required power as used with a single impeller.

Calculations contained within this section are preliminary and served to guide the problem of sizing mechanical mixers for mixing Hanford tank HLW sludge toward a more empirical approach to determine proper mixer sizing/configuration. While the preliminary calculations contained herein do not fit the definition of "computation" per TFC-ENG-DESIGN-C-10 (thus requiring no documented calculation check), it was determined that little value would be added by performing a calculation check commensurate with an informal calculation, and therefore none was performed. Users must recognize this limitation and engage in calculation verification as per TFC-ENG-DESIGN-C-10 if results from calculations are used explicitly.

Table 3-3. Zwietering correlation results for 1 PBT4-45 impeller

Conditions ($\rho_s/\rho_L/d_p$)	μ_L (Ns/m²)	ρ_s (kg/m³)	ρ_L (kg/m³)	ρ_{slurry} (kg/m³)	solid vol %	d_p (μm)	N_{JS} (rpm)	N_{JS} Power (HP)	N_U (rpm)	N_U Power (HP)
BR/BR Mean/BR	1.60E-03	2900	1200	1370	10	7.5	15.5	44.4	26.3	218.3
BR/BR Mean/95-95 TL	1.60E-03	2900	1200	1370	10	22	19.2	84.7	32.6	416.4
BR/BR Mean/Zwietering Min	1.60E-03	2900	1200	1370	10	140	27.8	257.3	47.3	1264.0
PuO ₂ /BR Mean/Max Observed	1.60E-03	11430	1200	1201	0.008316	40	22.7	123.5	38.7	607.1
PuO ₂ /BR Mean/Max Agglom.	1.60E-03	11430	1200	1200	0.0004158	1000	29.3	265	49.9	1302
Bi ₂ O ₃ /BR Mean/Max Observed	1.60E-03	8900	1200	1970	10	10	37.4	903.8	63.7	4440
Bi ₂ O ₃ /BR Mean/Max Agglom.	1.60E-03	8900	1200	1219	0.25	1000	57.5	2020	97.7	9925
ZrO ₂ /BR Mean/Max Observed	1.60E-03	5680	1200	1648	10	50	38.2	802.3	65.0	3941
ZrO ₂ /BR Mean/Max Agglom.	1.60E-03	5680	1200	1211	0.25	1000	42.5	810.8	72.2	3983

Table 3-4. Zwietering correlation results for 2 PBT4-45 impellers

Conditions ($\rho_s/\rho_L/d_p$)	μ_L (Ns/m²)	ρ_s (kg/m³)	ρ_L (kg/m³)	ρ_{slurry} (kg/m³)	solid vol %	d_p (μm)	N_{JS} (rpm)	N_{JS} Power (HP)	N_U (rpm)	N_U Power (HP)
BR/BR Mean/BR	1.60E-03	2900	1200	1370	10	7.5	15.5	88.8	26.3	436.6
BR/BR Mean/95-95 TL	1.60E-03	2900	1200	1370	10	22	19.2	169.4	32.6	832.8
BR/BR Mean/Zwietering Min	1.60E-03	2900	1200	1370	10	140	27.8	514.6	47.3	2528.0
PuO ₂ /BR Mean/Max Observed	1.60E-03	11430	1200	1201	0.008316	40	22.7	247.0	38.7	1214.2
PuO ₂ /BR Mean/Max Agglom.	1.60E-03	11430	1200	1200	0.0004158	1000	29.3	530.0	49.9	2604.0
Bi ₂ O ₃ /BR Mean/Max Observed	1.60E-03	8900	1200	1970	10	10	37.4	1807.6	63.7	8880.0
Bi ₂ O ₃ /BR Mean/Max Agglom.	1.60E-03	8900	1200	1219	0.25	1000	57.5	4040.0	97.7	19850.0
ZrO ₂ /BR Mean/Max Observed	1.60E-03	5680	1200	1648	10	50	38.2	1604.6	65.0	7882.0
ZrO ₂ /BR Mean/Max Agglom.	1.60E-03	5680	1200	1211	0.25	1000	42.5	1621.6	72.2	7966.0

3.4 ZWIETERING CORRELATION CONCLUSION

While the Zwietering correlation is not well suited for application in this particular study due to its narrow range of acceptable parameters, it did result in at least one useful observation. It is clear that a very sizeable increase in power is necessary to achieve uniform suspension from just-suspension.

4. ANALYTICAL TECHNIQUES – THE OLDSHUE TECHNIQUE

Application of the Zwietering correlation is very limited in many regards and insufficient for developing a set of functional requirements for MSF. Therefore, pursuit of a more reliable and comprehensive techniques ensued. Several techniques were applied or considered and their results compared. The first of these techniques originates from Fluid Mixing Technology, by James Oldshue, and for lack of a better term, will be referred to as the Oldshue technique.

4.1 THE OLDSHUE TECHNIQUE

The Oldshue technique was developed as a rough guide for estimating power requirements for relatively small scale plant application stirred vessels. It involves using a series of visual graphical interpretations, rather than equations, to determine mixing equipment requirements.

One distinct benefit of the Oldshue technique over Zwietering's correlation is that it is inherently inclusive of conditions for uniform suspension. Unfortunately, however, it is not without limitations. Most notably, direct application of this method is limited to mixing vessels ranging from 1,000 to 30,000 gallons in volume. This restriction resulted in the need for some form of a scale up procedure (See Appendix A for details regarding scale up method). Oldshue notes that while the technique provides a fairly conservative power requirement estimate, laboratory scale testing may be required to fine-tune some slurry variables (Oldshue, 1983).

4.2 APPLYING THE OLDSHUE TECHNIQUE

Unlike the Zwietering correlation, which yields an impeller speed, the Oldshue technique yields an estimated power requirement for both N_{JS} and N_U . Using the power requirement for uniform suspension, Equation 3.2 can be rewritten in the following form to produce an impeller speed:

$$N_U = \left[\frac{P}{\rho_O \rho_{slurry} D^5} \right]^{1/3} \quad (\text{Eq. 4.1})$$

When two impellers are used the power number may increase by a factor of two, such that $P_O = 2P_{O_1}$.

The Oldshue technique requires settling velocity as a functional parameter, rather than density and particle size, like the Zwietering correlation. Settling velocity (V_s) was calculated by the following equation:

$$V_s = 1.73 \left[\frac{d_p g (\rho_s - \rho_L)}{\rho_L} \right]^{1/2} \quad (\text{Eq. 4.2})$$

Equation 4.2 represents a particle's free settling velocity in the turbulent regime as provided by Edwards, et al. (2004). Since mixing and particle dispersion by means of mechanical agitation take place in the presence of turbulent flow patterns, turbulent conditions were assumed and use of this expression is reasonable.

Table 4-1 shows a list of cases which the Oldshue technique was applied to. Scenario 1 represents equipment requirements based on a settling velocity corresponding to best-recommendation values for particle size and solids density, and best-recommendation average for liquid density. Scenario 2 incorporates the 95/95 tolerance limit particle size offered in RPP-9805. This is the value for which the authors of said document feel 95% confident that 95% of tank waste particles will be lower than. Scenarios 3 and 4 represent conditions of intermediate settling velocities. Scenario 5 uses Zwietering minimum recommended operational values. Scenario 6, while not included in further calculations, shows the free settling velocity of a PuO_2 agglomerate, the largest, most dense particle assumed to be in sludge waste. Because the Oldshue technique is only able to account for settling velocities up to 20 ft/min, it was included merely for the purpose of comparison to other settling velocities.

Table 4-1. Particle free-settling velocities

Scenario	Metric	d_p (μm)	ρ_s (kg/m^3)	ρ_L (kg/m^3)	V_s (ft/min)
1	Best recommended values (RPP-9805)	7.5	2900	1200	3.47
2	95/95 TL (RPP-9805)	22	2900	1200	5.95
3	Intermediate Value	-	-	-	5
4	Intermediate Value	-	-	-	8
5	Zwietering Minimum Operating Values	140	2900	1200	15.02
6	Heaviest, Most Dense Particle (PuO_2 Agglomerate)	1000	11430	1200	98.49

Table 4-2 shows the results obtained when the Oldshue correlation was applied to the cases listed in Table 4.1 (excepting Scenario 6). These calculations assumed the following parameters:

- Two impellers, PBT4-45 style with $W/D = 0.2$ and $P_O = 1.27$
- Standard 4-baffle configuration; baffles of width $T/10$ to $T/12$

- $Z/T = 1.3$; $D/T = 1/3$
- 10% by volume solids concentration
- Vessel volume of 500,000 gallons

Table 4-2. Power and impeller speed predictions

Settling Velocity (ft/min)	N_U (rpm)	Power (HP)
3.5	20.8	200.4
5	27.1	442.6
6	31.6	700
8	36.7	1195
14	44.2	1919

Further analysis was done utilizing the Oldshue technique's flexibility to represent the optimal impeller geometry. The Oldshue technique accounts only for a PBT4-45 style impeller, rather than the recommended hydrofoil style (Tatterson 2009-5-21). The method used to adapt the Oldshue technique to an alternative impeller style consisted of modifying the power number. Results are compared in Table 4-3 below. Further notes on calculations are provided in Appendix A.

Table 4-3. Power consumption based on Oldshue Technique

Settling Velocity (ft/min)	N_U (rpm)	PBT4-45 Power (HP)	A-2 Hydrofoil Power (HP)
3.5	20.8	200.4	94.7
5	27.1	442.6	209.1
6	31.6	700	330.7
8	36.7	1195	564.5
15	44.2	1919	906.5

4.3 OLDSHUE TECHNIQUE CONCLUSION

The attempt to apply the Oldshue technique as a better means of estimating agitator speed and power requirements was met with mixed success. Because its application involves numerous graphical interpretations rather than discrete equations, results may vary. Furthermore, it is not known how well the technique applies when adapted for scale up or alternate impeller styles. In its defense, the Oldshue technique was able to accommodate a much wider range of process variables than that of the Zwietering correlation.

When presented with the best recommendation average particle size and densities, application of the Oldshue technique estimated a necessary power requirement of 200.4 HP operating at 29.0 rpm with two PBT4-45 impellers. When A-2 style hydrofoils are substituted for the PBT

impellers and operated at the same speed, the power consumption is reduced by more than half, to 94.7 HP.

Calculations contained within this section are preliminary and served to guide the problem of sizing mechanical mixers for mixing Hanford tank HLW sludge toward a more empirical approach to determine proper mixer sizing/configuration. While the preliminary calculations contained herein do not fit the definition of "computation" per TFC-ENG-DESIGN-C-10 (thus requiring no documented calculation check), it was determined that little value would be added by performing a calculation check commensurate with an informal calculation, and therefore none was performed. Users must recognize this limitation and engage in calculation verification as per TFC-ENG-DESIGN-C-10 if results from calculations are used explicitly.

5. ANALYTICAL TECHNIQUES – MODIFIED FROUDE NUMBER CORRELATION

The third correlative approach considered for estimating the power and speed requirements for a mechanically agitated system was provided by Dr. Gary Tatterson, a professor of chemical engineering at the University of Arkansas. Dr. Tatterson, a recognized expert in fluid mixing, recommended a correlation based on a modified Froude number developed by C. Buurman (Buurman et al., 1986).

Limitations of the MFN correlation were very similar to those experienced by the Zwietering correlation. The parameters over which the correlation was obtained are too narrow to accommodate actual tank waste process parameters. For this reason, application of the MFN correlation was not pursued.

6. CONCLUSION ON CORRELATIVE TECHNIQUES

In short, use of the Zwietering and modified Froude number correlations is not recommended due to their severe deviations from the recommended operational range. Figure 6-1 is provided as a comparison of several design parameter ranges to the corresponding recommended range for each correlation. Of the three correlative techniques evaluated, the Oldshue technique proved most promising, as it incorporated the largest operational range. Of the three techniques evaluated, it may be the best method for quickly estimating MSF power and speed requirements. However, the Oldshue technique accounts only for use of a 4 blade 45° pitch blade turbine impeller, and numerous assumptions must be made to adapt it for use with alternate impeller styles. It should also be noted that only testing can confirm the reliability of any of these correlations and until such testing is performed one should exercise caution when applying them. Application of the Oldshue technique and related assumptions (as discussed in Section 4) yielded

a required impeller power of 95 HP at 29 rpm to suspend waste with a 3.5 ft/min average settling velocity.

Figure 6-1. Parameter range comparison

7. ALTERNATIVE METHODS

7.1 COMPUTATIONAL FLUID DYNAMICS

Computational fluid dynamics (CFD) is an analytical method that has risen in popularity as computer technology has advanced. It is a simulation method for studying fluid flow patterns that involves numerous iterations of mathematic computations. Due to its mathematically intense nature, it is carried out almost exclusively using computers. While it is widely used for many fluid flow applications, its adoption for use in the mixing industry has not gone unchallenged.

Numerous industry experts claim that CFD alone is currently insufficient for determining and guaranteeing hardware requirements to meet specific desired process results. While they acknowledge that CFD is very useful for understanding such things as fluid flow patterns and velocity fields, it may not sufficiently model solids suspension (Meyer, et al.2009). When applied in conjunction with scaled model testing, however, CFD may provide useful data and greater confidence regarding scale-up procedures.

Because CFD modeling is expensive and resources to perform the evaluation were not readily available, its implementation was not considered within the scope of this report.

7.2 SCALED MODEL TESTING

If there is one universal theme that propagates itself among mixing professionals it is that there is no substitute for scaled testing. All correlations found in literature originated from scaled testing. Quite often, their experimental procedure and process variables are intended to represent an “average” application. In the common event that a particular process cannot be described by

these correlations, scaled testing is the only failsafe means of solution. Correlations can then be made that apply specifically to one's unique process.

Scale model testing involves the development of vessels intended to represent the behavior of another, often larger, vessel. Tests are conducted with these vessels which would be too difficult, time consuming, or expensive to do at full-scale. Most tests are designed around developing correlations for vessel scale up. When done correctly, scaled model testing is the most reliable technique for determining mixing system requirements.

Many considerations must be made when attempting a scaled test program. Aspects such as simulant selection and geometric similitude play significant roles in determining the accuracy of test results and how applicable they are to the intended application. Incorrect scaling procedures will result in erroneous data. Implementation of a scaled model test program is discussed further in Section 8.

7.3 EXPERT APPEAL – PHILADELPHIA MIXING SOLUTIONS, LTD.

When it became apparent that correlations and text-book methods were likely to be insufficient for developing functional requirements for the MSF mixing system, contact was made with Philadelphia Mixing Solutions, Ltd. (PMSL). PMSL is the NQA-1 certified supplier of mechanical mixing equipment for Bechtel, the WTP contractor, and their equipment has been installed extensively and employed successfully in the nuclear industry for many years. Based on the PSDD from Table 7-1, they generated an estimation of the power and speed requirements for uniform and homogeneous suspension.

Table 7-1. PSDD as utilized by PMSL

Solid-Phase Compound	Crystal Density (g/mL)	Volume Fraction	Maximum Observed Particle Size (µm)
Al(OH) ₃ , Gibbsite	2.42	0.515	20
(NaAlSi ₃ O ₈) ₅ •(NaNO ₃) _{1.5} •2H ₂ O	2.365	0.166	8
AlOOH, Boehmite	3.01	0.106	0.05
NaAlCO ₃ (OH) ₂	2.42	0.095	4.2
Fe ₂ O ₃	5.24	0.041	1.6
Ca ₃ OH(PO ₄) ₃	3.14	0.020	0.1
Na ₂ U ₂ O ₇	5.617	0.016	15
ZrO ₂	5.68	0.011	50
B ₁₂ O ₂	8.9	0.0081	10
SiO ₂	2.6	0.0069	100
Ni(OH) ₂	4.1	0.0055	0.5
MnO ₂	5.026	0.0054	10
CaF ₂	3.18	0.0023	15
LaPO ₄ •2H ₂ O	6.51	0.0013	3
Ag ₂ CO ₃	6.077	0.000094	4
PuO ₂	11.43	0.000013	40

In order to calculate mixer design requirements, PMSL requested an estimated PSDD representative of sludge waste. Table 7-1 was a PSDD developed in WTP-RPT-153 and was provided to meet this request. The best recommendation particle size resulting from the WTP-RPT-153 study was 7.7 µm, and PMSL calculated a solids density of 2774 kg/m³ based on the PSDD given in Table 7-1. Liquids density was given as 1200 kg/m³ and solids concentration as 10% by volume.

Table 7-2 lists suspension speed and power requirements for an average particle settling velocity of 0.6577 ft/min (as calculated by PMSL). In this case, homogeneous (as opposed to uniform) is the desired degree of suspension. For homogeneous suspension based on the provided PSDD, PM recommends a 114 HP motor operating a 23 rpm.

Table 7-2. PMSL's recommended speed and power requirements

Solids Suspension Level	Just Suspended	-	Off Bottom	-	Moderate Uniformity	-	Nearly Uniform	-	Uniform	-
	Just Suspended	20% Uniformity	35% Uniformity	50% Uniformity	60% Uniformity	70% Uniformity	80% Uniformity	90% Uniformity	Uniform Sus.p.	Homogeneous
Mixer RPM	10	11	13	14	15	16	17	19	20	23
Power (Hp)	9.38	12.43	20.61	25.74	31.65	38.42	46.08	64.33	75.03	114.11
Torque (lb-in)	59112.24	71524.86	99896.36	115855.24	132996.21	151319.27	170824.42	213380.97	236432.38	312679

These values were generated by PMSL's own proprietary process. PMSL has developed a computer program that catalogs and analyzes data from past tests. These results become part of their comprehensive computer model for determining mixer specifications. This method, which is essentially based on a torque/unit volume approach, has been implemented successfully in the design of more than 40,000 mixers. The largest mixer designed by PMSL is six million gallons

in volume. Design by this procedure has been confirmed by subsequent lab testing and field testing and has resulted in no warranty claims made by customers regarding solids suspension performance (Hutchinson, T., 2009-8-7).

Despite confidence in the recommendations produced by the PMSL model, a PMSL company representative agreed that scaled testing is the only true means by which to confirm mixer performance, and recommended such an approach for the MSF application. Appendix B shows the complete spreadsheet and preliminary design sketch for recommended vessel geometry as generated by PMSL.

8. CONCLUSION AND RECOMMENDATIONS

The primary goal of this assignment was a success to the extent that it evaluated the validity of employing a correlation, such as that of Zwietering, to the MSF mixing design strategy. In short, correlations and techniques found in publicly accessible literature are largely insufficient due to the complexity of Hanford tank waste. They are developed to handle a tight range of process variables and Hanford tank waste and other application parameters fall well outside these parameters in most cases. The one exception was that of the Oldshue technique. Application, limitations, and results from this method are presented in a Section 4.1. Pending the determination of a reliable particle settling velocity (of less than 20 ft/min), approximate power and speed estimates may be made without exceeding the technique's recommended operational range. However, scale up is required for this technique and the scale up method and adaptation for different impeller styles employed in this investigation have not been experimentally verified. When compared to the results provided by Philadelphia Mixing Solutions, the Oldshue technique estimated a required power within 17% of the PMSL recommendation. Oldshue estimates a required impeller power of 94.7 HP at 29 rpm for a settling velocity of 3.5 ft/min. PMSL recommends 114 HP at 23 RPM for a much lower settling velocity of 0.6577. The observer must note that while the power and speed estimations provided by both sources are similar, the settling velocities used to calculate them are not. Regardless of the fact that the Oldshue correlation can be applied within its recommended operational range, it is in need of confirmation by physical testing before any definitive decision can be made concerning its validity.

Because no correlations were found that provided confirmed, reliable results, alternative methods were pursued. Of those considered, none proved more dependable than an appeal to industry experts at Philadelphia Mixing Solutions. Based on calculations using values provided in Table 7.1, PMSL was able to provide fairly confident recommendations for required agitator speed and power consumption for varying degrees of suspension. For homogenous suspension these recommendations were approximately 114 HP at 23 rpm.

While confident in their recommendations, PMSL agreed that scaled testing was the only failsafe way to ensure the desired mixing requirements are met. This statement concurs with similar

statements made by numerous other sources that suggest complex mixing challenges should not rely on correlations, but rather data collected from scaled tests designed for its specific application (ChemicalProcessing.com, Oldshue 1983). Therefore, the final recommendation based on research done within the scope of this report is to team with experienced mixing professionals and develop a scaled testing and development program. The consultant(s) must have notable experience developing mixing systems that process broad particle size and density distributions in large vessels, ideally in the nuclear industry. Such a program would eliminate much risk and provide a level of confidence unattainable with any generic correlation.

9. REFERENCES

- 24590-WTP-ICD-MG-01-019, 2007, *ICD-19 – Interface Control Document for Waste Feed*
Rev. 4, Bechtel National, Inc., Richland, Washington.
- Buurman, C.; Resoort, G.; Plaschkes, A. (1986). Scaling-Up Rules for Solids Suspension in Stirred Vessels. *Chemical Engineering Science*, 41, 2865-2871
- ChemicalProcessing.com, 2009-5-20, [Dickey, D.S., *Are there limitations to the Zwietering correlation for suspending solids in liquids?*],
<<http://www.chemicalprocessing.com/experts/answers/2009/069.html>>
- Dickey, D.S., 2009-5-20, :“RE: Zwietering,” (e-mail to P.W. Griffin), Washington River Protection Solutions, Richland, Washington
- Edward, Paul L.; Atiemo-Obeng, Victor A.; Kresta, Suzanne M. (2004). *Handbook of Industrial Mixing – Science and Practice*. John Wiley & Sons
- Etchells, A., Alderman, N., Heywood, N., 2009 “Solids Liquid Mixing,” in *Slurry Handling and Mixing in the Nuclear Industry*, Kennewick, Washington
- Hutchinson, T., 2009-8-7, :“RE: Thank you,” (e-mail to P.W. Griffin), Washington River Protection Solutions, Richland, Washington
- Oldshue, James Y. (1983) *Fluid Mixing Technology*. New York: Chemical Engineering McGraw-Hill Pub. Co.
- Meyer, P., Bamberger, J., Wells, B., Gauglitz, P., Fort, J., 2009 “CFD,” in *Jet Mixing Experience at PNNL*, Richland, Washington
- RPP-5346, 2002, *Waste Feed Delivery Transfer System Analysis*
Rev. 2, CH2MHill Hanford Group, Inc., Richland, Washington
- RPP-9805, 2002, *Values of Particle Size, Particle Density, and Slurry Viscosity to Use in Waste Feed Delivery Transfer System Analysis*, Rev. 1, Office of River Protection, Richland, Washington
- Tatterson, G.B., 2009-5-21, :“Solids Suspension,” (e-mail to P.W. Griffin), Washington River Protection Solutions, Richland, Washington

Tatterson, G.B., 2009-5-26, :“RE: Solids Suspension,” (e-mail to P.W. Griffin), Washington River Protection Solutions, Richland, Washington

TFC-ENG-DESIGN-C-10, “Engineering Calculations,” Washington River Protection Solutions LLC, Richland, Washington

WTP-RPT-153, *Estimate of Hanford Waste Insoluble Solid Particle Size and Density Distribution* Rev. 0, Battelle—Pacific Northwest Division, Richland, Washington

APPENDIX A

NOTES ON CALCULATIONS

A.1 ZWIETERING CORRELATION

Regarding the Zwietering correlation, values for s are dependent on impeller configuration and orientation, including blade pitch, number of blades, C/T , and T/D , where C , T , and D are impeller clearance from vessel bottom, vessel diameter, and impeller diameter, respectively. As the goal of these calculations was primarily to reflect change in shaft speed and power demands as related to likely variations in waste properties, s was held constant at 6.95 (Etchells, et al. 2009). This value corresponds to a PBT4-45 impeller with $C/T = 1/3$ and $T/D = 3$.

Equation A.1-1 shows the solids to liquids mass ratio as applied in the calculations in Section 3.

$$X = \frac{\rho_s v_s}{\rho_L(1-v_s)} \quad (\text{Eq. A.1-1})$$

It should be noted that in many instances, the actual X value used in calculations presented in Tables 3-3 and 3-4 exceeded the recommended operational range of 2-15%.

The power number, P_o , is a dimensionless drag factor, analogous to the friction factor in pipe flow. It is affected primarily by impeller geometry and flow regime. Oldshue (1983) provides numerous values for P_o for differing impeller types. P_o as used in the calculations made in Section 3 of this document is 1.27, the power number for a 4-blade, pitched blade turbine (PBT) with a blade angle of 45 degrees operating in turbulent conditions (Oldshue 1983). When properly spaced, the power approaches proportionality to the number of impellers. Therefore, if two impellers are utilized, the power required to turn them would be double that of one impeller operating at the same speed (Tatterson 2009-5-26).

A.2 OLDSHUE TECHNIQUE

As mentioned previously, the Oldshue technique may only be directly applied to vessels 1,000 to 30,000 gallons in volume. The scale up procedure used to estimate values at full scale consisted of applying the Oldshue technique to a series of small scale vessels (between 1,000 and 30,000 gallons). The N_p power to vessel volume ratio was then plotted against vessel diameter and a best-fit line was generated which allowed for an estimation of required power at full scale, for a given particle settling velocity. Figure A-1 shows the plot used for scale-up.

Figure A-1. Oldshue scale-up plot

Further analysis was done utilizing the Oldshue technique's flexibility to represent the optimal impeller geometry. The Oldshue technique accounts only for a PBT4-45 style impeller, rather than the recommended hydrofoil style (Tatterson 2009-5-21). The method used to adapt the Oldshue technique to an alternative impeller style consisted of modifying the power number. P_O for a standard 4-blade hydrofoil is 0.6 (Tatterson, 2009-5-26). Taking the ratio of $P_{O,H}/P_{O,PBT} = 0.472$. This ratio is expected to represent the power consumption of a hydrofoil to that of a PBT. By multiplying the estimated PBT power consumptions from Table 4.4 by this ratio, an estimate of power consumption with a hydrofoil operating at the same speed may be made.

APPENDIX B

INFORMATION FROM PHILADELPHIA MIXING SOLUTIONS, LTD.

Figure B-1. PMSL suspension spreadsheet

SOLIDS SUSPENSION CALCULATION

[Click here for definitions](#)

Description	Data Entry
Impeller Type	LS39 (Axial Flow)
Number of Impellers	2
Vessel Z/T	1.243
Vessel Diameter [in]	480
Impeller D/T	0.38
Solids Settling Rate [cm]	0.0706
Slurry Density [lb/g]	1.18
Slurry Viscosity [cP]	1.6
Batch Volume [gal]	600000
	<input type="button" value="Calculate"/>

Calculation Results	Data
Impeller Diameter [in]	182.4

Mixer Configuration	No of Impellers	Off Bottom	Max. Off Bottom	Spacing	Max Z/T
Constant Level	2	169	274	268	1.80
Unknown Level	2	80	80	310	1.80
	No of Impellers	Off Bottom	Min. Off Bottom	Spacing	Max Z/T
Low Level	2	46	120	329	1.60

Old Solids Sett. Level	Just Suspended	20% Uniformity	25% Uniformity	50% Uniformity	Moderate Uniformity	70% Uniformity	80% Uniformity	90% Uniformity	Uniform Suspension	Homog.
100 solids susp. Level	Just Suspended	20% Uniformity	25% Uniformity	50% Uniformity	Moderate Uniformity	70% Uniformity	80% Uniformity	90% Uniformity	Uniform Suspension	Homog.
Mixer RPM	10	11	13	14	15	16	17	18	20	22
Eq. Batch Vol. [gal]	160002	225403	300004	370785	452800	526007	601206	761010	901612	120241
Reynolds Number [-]	2830322.47	2902154.71	3425819.20	3693651.45	3957483.70	4221315.94	4485148.19	5012812.68	5276644.93	606814
Friction Number [-]	0.01	0.02	0.02	0.03	0.03	0.03	0.04	0.05	0.06	0.07
Power Number [-]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Mix Power [ft]	9.38	12.68	20.81	26.78	31.85	38.43	46.08	64.33	79.03	114.71
Unit Ht [ft/imp]	0.02	0.02	0.04	0.05	0.06	0.08	0.09	0.13	0.15	0.25
Time [hr]	58112.24	71524.85	98896.30	115005.24	132886.21	151315.27	170824.42	213280.97	256432.35	512675
Unit Ton [lb-imp]	0.12	0.14	0.20	0.22	0.27	0.30	0.34	0.43	0.47	0.83
Impeller Flow [gpm]	262099.44	280950.38	341500.27	367779.22	394049.16	420319.10	446589.05	492128.94	528398.88	604258
Slip Velocity [ft/s]	27.95	30.78	36.33	39.73	41.92	44.71	47.81	53.10	55.89	64.28
Tip Speed [ft/min]	473.52	525.27	620.76	668.93	719.38	764.03	811.79	907.29	956.04	1088.9
Turnovers [min]	0.53	0.58	0.68	0.74	0.79	0.84	0.89	1.00	1.05	1.21
Blend Time [sec]	333.82	383.47	268.79	238.44	222.55	208.64	196.97	173.70	158.91	145.14
Q-Factor [hr]	48.06	58.46	71.29	79.63	88.32	97.28	106.68	125.90	135.97	167.09

Figure B-2 PMSL recommended vessel geometry

APPENDIX C

UNPUBLISHED REFERENCE MATERIAL

Presentation

Presentation Date: January 20-22, 2009

Presenter: A. Etchells

Scope of Presentation: Solids-Liquids Mixing

2.2 Semi-empirical correlation by Zwietering

$$N_{JS} = s v^{0.1} \left(\frac{g \Delta \rho}{\rho_L} \right)^{0.45} X^{0.13} dp^{0.2} D^{-0.85}$$

No solids remain at the vessel base for more than 1-to-2 seconds

Extensive data sets can be correlated

Some theoretical justification

19

Limitations and applicability

- "s" values have to be known
 - Characteristic of geometry only - maybe
- not applicable outside the experimental conditions
- applies to free and hindered settling conditions (i.e. low to moderate X), X is weight of solids divided by weight of liquid times 100 - UGH
but may not be valid or relevant in significantly non-Newtonian systems (i.e. at high X)

20

Presentation

Continued from page C-2

Table 1. Geometrical constant, s_v values for three different impeller types in a flat base vessel.

s values at C/T		1/3	1/4	1/6	1/8
RDT	D =	4.72	4.2	3.67	3.41
	T/2				
	D =	8.37	7.43	6.50	6.03
PBT4-45	D =	4.97	4.74	4.52	4.40
	T/2				
	D =	6.95	6.64	6.32	6.16
HE-3	D =	7.14	6.82	6.50	6.35
	T/2				
	D =	10.41	9.95	9.48	9.25
	T/3				

21

Table 2. Operating conditions over which Zwietering's correlation is obtained

Parameter	Range covered
$\Delta\rho(\text{kg/m}^3)$	560 – 1800
$d_p(\mu\text{m})$	140 – 520
$X(\%)$	0.5 – 20
$T(\text{m})$	0.1 – 0.6
D/T	1/6 – 1/2
n_b	4
C/T	1/20 – 1/2
Impel. type	4
Vessel base shape	Flat, dish & conical
$\mu_t(\text{mPa s})$	0.3 - 9

22

Presentation

Continued from page C-3

Z CORRELATION

- Since has been extended to many more geometries and sizes and densities
- Not perfect but conservative and nothing better

23

Main Findings

- **Impeller Geometry**
 - Axial flow impellers (e.g. hydrofoils) pumping downwards are the most energy efficient; radial flow (e.g. 6DT) and saw tooth impellers are the least energy efficient for off-bottom suspension.
 - Low C generally more energy efficient, except at extremes (e.g. $D/T > 0.5$ $C/T < 1/6$)
 - Low liquid heights – starve impeller

24

Presentation

Presentation Date: June 2, 2009

Presenter: Perry Meyer

Scope of Presentation: Jet Mixing Experience at PNNL

Email Correspondence

Originator: P.W Griffin

Correspondent: D.S. Dickey

Griffin, Peter W

From: David Dickey [d.dickey@mixtech.com]
Sent: Wednesday, May 20, 2009 7:58 AM
To: Griffin, Peter W
Subject: Re: Zwietering

Peter,

Your starting point should be Chapter 10 Solid-Liquid Mixing in the Industrial Mixing Handbook, John Wiley & Sons 2004. I cannot remember what has been published about agitation intensity for "uniform" suspension, since "uniform" rarely happens for settling particles. The power number should not change for solids suspension, although the power should be proportional to slurry density for turbulent suspension.

The test apparatus should be as large as practical and small enough to study and modify. The most important factor is geometric similarity. Usually the tank geometry has practical limits for modeling, either the mixing device of the tank internals. For large tanks, my experience has been that less than 1 meter diameter is probably too small for good test results. Larger than 2 meters becomes more difficult to do experimental work and observe the results or change conditions easily. Multiple impellers are covered in the Handbook chapter, but the simple answer is that only the lower impeller has any significant effect on off-bottom suspension. An upper impeller may improve suspension uniformity.

Dave

David S. Dickey, Ph.D.
MixTech, Inc.
454 Ramsgate Drive
Dayton, OH 45430-2097
Phone: 937-431-1446
Fax: 937-431-1447
d.dickey@mixtech.com
www.mixtech.com

----- Original Message -----

From: Griffin, Peter W
To: 'David Dickey'
Sent: Wednesday, May 20, 2009 10:41 AM
Subject: RE: Zwietering

Dave,

Thanks for the information. Is there a text or source you would recommend regarding projected increases in agitator intensity and power number to move from just-suspended regime to uniform suspension? Or is this one of those areas where correlations can't be found? Also, if I were to do a test (which seems very likely) is there a certain volume range that I should look into for a test apparatus that will decently represent such a large tank? My goal being that I don't want to develop equipment based around a test apparatus that was too small.

Lastly, any texts or insights on predicting speed, power, etc... when multiple impellers are used?

Thanks,

Peter Griffin

Email Correspondence

Originator: P.W. Griffin

Correspondent: G.B. Tatterson

Griffin, Peter W

From: GBT [gbt@ncat.edu]
Sent: Tuesday, May 26, 2009 5:08 AM
To: Griffin, Peter W
Subject: Re: Solid Suspension

Peter,

The power number is basically a drag coefficient. Anything that affects impeller drag will affect power, e.g., baffles, liquid height near the impeller, baffle number, etc.

Power number (standard geometry) for pitched blade turbines, 4 blades 45 degree pitch, is 1.26; hydrofoils 0.6. If they are spaced apart in a reasonable fashion, the power is proportional to impeller number. If the impellers are placed upon each other, the power number would vary between that of a single impeller and that of two impellers.

You can purchase my book from Amazon.com. There you can find all sorts of information and details on power.

Baffles affect power because they affect the impeller drag. However, in a very large tank, the baffle effect may be less. When you are large scale, the process changes. The problem is: "What does it change to?"

What is the diameter of 500,000 gals? I assume you are mounting the impeller along the centerline. Correct?

Of course, you should realize that there is no connection between power and mixing. You can mix at very low power. Solid suspension is different.

If you can't reach me in my office, my home phone is 336-882-4737. You can call anytime, except I may be out cutting the grass or gardening. Evening EST might be a good time.

Good Luck,

Gary Tatterson

----- Original Message -----

From: Griffin, Peter W
To: 'GBT'
Sent: Thursday, May 21, 2009 1:33 PM
Subject: RE: Solid Suspension

Gary,

I really appreciate the information.

You assumed right- I'm planning on using impellers.

I'm afraid I missed my window of opportunity to call you today, but if time allows, I may try to reach you tomorrow.

In the mean time, perhaps you can answer another question—I was planning to use 4 baffles on the tank walls to promote mixing. I've been using the $P = \rho \omega^3 D^5$ correlation to estimate the power. It is my guess that the addition of

Email Correspondence

Continued from page C-7

baffles and multiple impellers will cause a power increase. My question is, is this power increase reflected by the power number, P_o ? In other words, are there P_o numbers that account for multiple impellers and baffles?

Thanks again,

Peter

From: GBT [mailto:gbt@ncat.edu]
Sent: Thursday, May 21, 2009 8:03 AM
To: Griffin, Peter W
Subject: Solid Suspension

Peter,

Are you using an impeller or pulse jet mixers? I guess an impeller from your question. In either case data are available to answer some of your questions.

Zwietering published his correlation in 1956 (or 1957?) --- a long time ago.

Limitations of the Zwietering correlation for suspending solids in liquids are many. His paper reduces to a constant for various impellers.

For very large tanks, say 500,000 gallons, I suspect centered mounted impellers don't suspend very well - lots of sand dunes at the walls. The tank bottom will be determined by the solids. Tanks are contoured by the process itself or are made that way. I would expect side-entering jets will help.

Most everything is controlled by geometry. If you get the geometry right, then everything goes well. If not, then you have job security because of all the problems you will experience. If you use impellers, I would recommend a down pumping hydrofoil impeller 1/3 off the bottom with another up-pumping hydrofoil mounted on the same shaft 2/3 off the bottom. The bottom impeller sweeps the bottom. The top impeller carries the material up into the top portion of the tank. Adding in supporting side-entering bottom jets pointed in the right direction, you might have a fantastic geometry. This geometry is not discussed in the literature but comes to me from a lawsuit that BHP filed against Lightning Mixing Company for a slurry tank which fed a pipeline.

"How to determine a representative mean particle diameter (and density) in a substance where it can vary dramatically." I would forget the small stuff and focus on the larger and heavier particles. If you can handle the big ones then the small stuff tags along free.

Attached some articles which can help you.

As you will find out, you can approach uniformity when Z/T is 1.0 at high modified Froude numbers.

My number is 336-334-7564 x320. You can call about 11:00AM EST if you like.

Good Luck,

Gary Tatterson

----- Original Message -----

From: Griffin, Peter W
To: 'gbt@ncat.edu'
Sent: Wednesday, May 20, 2009 1:17 PM
Subject: Zwietering Correlation Question

Email Correspondence

Continued from page C-8

Gary,

Hello, my name is Peter Griffin, with Washington River Protection Solutions. I've read numerous texts and articles but have been looking for a little more information regarding preliminary estimations of impeller speed and power requirements of mechanically agitated vessels. Most of the literature and information I've collected on the topic has referred me to the Zwietering correlation. I'm curious as to the limitations of the Zwietering correlation for suspending solids in liquids.

I'm particularly interested in how well it applies to very large tanks, say 500,000 gallons, and how to determine a representative mean particle diameter (and density) in a substance where it can vary dramatically.

Furthermore, how can I be sure of uniform suspension? If the Zwietering correlation is not a good fit for this application, can you recommend another method for determining the impeller speed and estimating the power requirement? Also, is there a text or document I can refer to regarding impeller speeds, power consumption, etc... in systems with numerous impellers? Any help you can provide is greatly appreciated.

Best Regards

Peter Griffin
WFD Projects Group
Washington River Protection Solutions
Richland, WA
Phone: 509-373-6377
Fax: 509-373-4001

Griffin, Peter W

From: Todd Hutchinson [THUTCHINSON@philadelphiamixers.com]
Sent: Friday, August 07, 2009 11:18 AM
To: Griffin, Peter W
Cc: Darrell Thatcher; Steven Barnak; John Reilly
Subject: RE: Thank you

Peter,

As a follow up to our phone conversation on Wednesday the program used to generate the different levels of solids suspension is a Philadelphia Mixing Solutions written program that is based on a Torque/unit-volume approach for suspending solids. This approach has been used to successfully design 40,000 plus mixers that perform solid suspension duties. Most applicable to your application would be the mixers we supplied to IHI's Japanese WTP, the Oak Ridge, TN site, and Savannah River as well as the (8) LAW mixers and (4) HLW mixers for the Bechtel WTP. All of these mixers were reduced scale model tested using customer specified simulate to confirm the program sizing. In some of the Savannah River applications PMSL performed full scale testing.

As you are aware the Bechtel LAW and HLW mixers have not been started up yet however the Catholic University located outside of Washington, DC has performed full scale performance work with the LAW/HLW designs. They could be consulted for acceptance.

There are various published procedures for sizing mixers for solids suspension. We have found our procedure generates very acceptable results confirmed by our lab testing and the fact that we do not have any warranty claims against solid suspension performance issues. Dr. Arthur W. Etchells III could also be contacted as a reference. He does not specifically use our procedure but he has witnessed the results of the sizing using our procedure in our laboratory.

Sincerely,

Todd M. Hutchinson
GM Advanced Solutions Engineering Division
Philadelphia Mixing Solutions, Ltd.