

Development of a Liquid Jet Sludge Re-suspension Model (used on Pulse Jets or Jet Ballasts)

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A performance prediction method has been developed for a radioactive or inactive liquid jet sludge re-suspension system and it has been applied to a jet ballast (or pulse jet) system in active nuclear waste tanks at Sellafield. British Nuclear Group has frequently used such systems, including the RPP-WTP Vitrification plant design at Hanford (Hannigan 2001). A model has been developed based on work by British Nuclear Group and previously published work at Savannah River, Hanford and others (See references). Originally, this was developed as a semi-empirical model in 2001. Later most of the semi-empirical factors have been replaced by theory and measurement based concepts, so that for simple re-suspension systems the model may possibly be generalised to apply to other jet re-suspension systems at least for relatively shallow sludge beds.

DESCRIPTION OF SYSTEM MODELLED

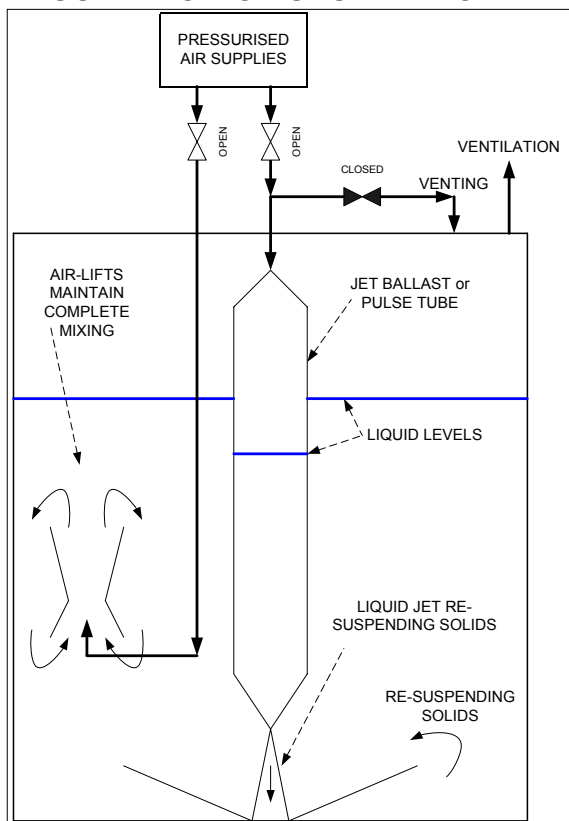


Figure 1 Schematic of Jet ballast System modelled

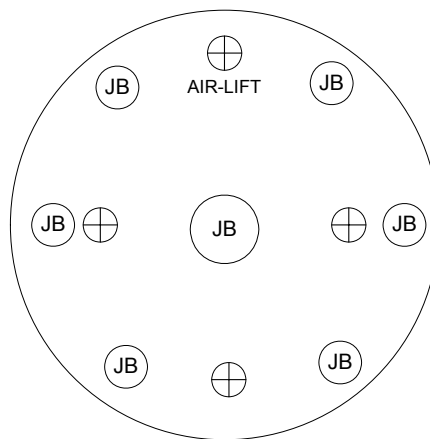


Figure 2 Layout of Jets and Air-lifts

Nuclear fuel reprocessing is a complex operation involving many stages. In the final stages of treatment for the highly active components, material is stored in tanks to allow for

cooling before final immobilisation using vitrification. At Sellafield, during this phase, solids are suspended through the use of jet ballasts (or “pulse jets”) and air-lifts (internal air driven air-lifts that circulate the liquor to stop the solids re-settling). Figure 1 shows a simplified diagram of the re-suspension and agitation system used. Any given tank contains multiple jet ballasts either positioned around the edge of the Storage tank (deflected from the wall) or centrally down-wards. Other plants with later tanks have Jet ballasts in other positions.

At the start of a cycle, the Jet ballast ullage is vented to the tank so the level in the jet ballast is the same as the general tank level. The cycle starts by pressurising the jet ballast to drive the liquor out of the base nozzle at high velocity (e.g. 10-20 m/sec). The Central Jet Ballast jet reflects off the floor re-suspending solids radially. Outer Jet Ballasts around the wall have jets reflected off the wall and floor re-suspending solids inwards from the wall. At the end of the firing period of typically 45-90 secs, using pressurised air, the jet ballast ullage is vented and the liquor flow slows and reverses to re-fill the jet ballast prior the start of the next cycle. In the tanks modelled, the jet ballasts are fired sequentially through a cycle that can typically vary from 10-30 minutes.

On later designs the liquor is vacuum lifted during the venting cycle (to high tank liquor level). This has the advantage that it maintains high re-suspension performance with tanks operating at low fill liquor levels.

Settling of solids should be avoided since this may give rise to a highly tenacious sediment bed, where the energy required to re-suspend is much greater than the energy required to keep the bed in suspension.

USING THE MODEL ON PLANT

The re-suspension model has been successfully integrated into a physical model of the radioactive plant jet re-suspension system at Sellafield discussed above.

Figure 3 A Simple Operator Input Form

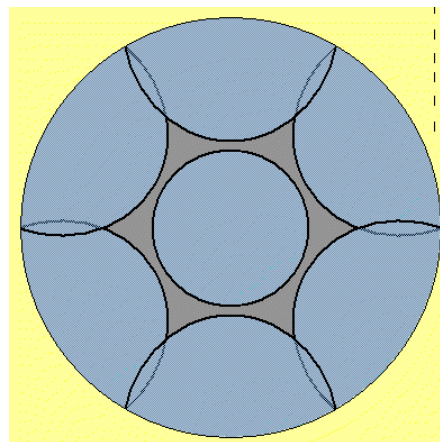


Figure 4 Simple Output Visual
(Dark Grey “ring-star” area represents sludge)

The model has been used operationally since 2001 to prevent solids accumulation. Operators use it to define optimum re-suspension conditions as the operational envelope changes and to support the plant safety case to external safety regulators. The model is important to the plant since sludge re-suspension can not be monitored visually due to the nature of the plant, although the extensive remote instrumentation on the plant can detect conditions of poor re-suspension performance. Operators can now run a simple Microsoft Excel Visual Basic form based model that allows them to input operational parameters to improve re-suspension performance if required. Figure 3 shows a typical operator input form and Figure 4 shows a typical operator output (for conditions of unsatisfactory re-suspension performance). In such a case the operator will re-adjust operating conditions to give good re-suspension conditions.

INITIATING THE RE-SUSPENSION MODEL

For the tanks modelled the Air-lift re-circulators used (seen in figure 5) are known to keep the tanks adequately agitated as long as the Jet Ballast re-suspension system can re-suspend the solids. The Air-lift system used alone does not induce sufficient tank floor velocity to re-suspend any solids.

Ideally the model would have been a CFD model but a CFD model was not possible for a number of reasons but chiefly:

- The tank internals for modelled tanks are very complex (as shown in figure 5)
- CFD modelling needs a re-suspension rate mechanism

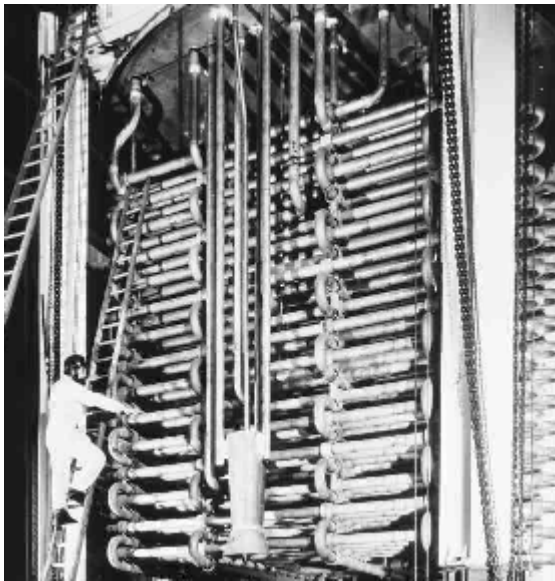


Figure 5 Active Storage Tank Internals

A further issue is that CFD program development will have to progress to allow operator usage on plant with simple easy to understand output on a normal specification PC. All an operator wants to know is how can I maintain conditions of good re-suspension?

The re-suspension rate model is not currently used in CFD modelling but the author has suggested that a Hamm et al (1989) type rate equation, as modified in this paper, could be used to describe lines of iso-momentum that define the sludge clearance at time t .

DEVELOPMENT OF THE ORIGINAL DESIGN

The Design of the Jet ballast (or Pulse Jet system) modelled was developed at British Nuclear Group (Clelland 1962, Hutson 1996) and has been used on a number of Waste Storage Tanks since that time. Originally, the plant used test rig data to set plant conditions. However, it was difficult to set conditions other than those exactly used in the tests. Also feed and operational changes could lead to operation outside the test rig data envelope so there was a need to provide a model for operational reasons.

DEVELOPING A NEW MODEL

Previous work has defined the clearance of jets operating to Ultimate Clearance point, L_{∞} or Effective Cleaning Radius, ECR (Hamm et al 1989, Ortaldo et al 1981, Poirer 2004, Powell et al 1997). This generally shows the ECR is proportional to $(\bar{u}_j d_j)$.

Much work has been published showing that fully developed jets (beyond 6-10 jet diameters) generally decay by an inverse ratio of the type (Poirer 2004, Rushton 1980, Shashidhara et al, 1975):

$$\boxed{\frac{u_{Max}}{u_j} = K \frac{d_j}{x}} \quad (1)$$

Where the constant K varies with jet configuration and also changes after the jet is reflected from a surface. For a circular "free jet" $K=6.2$ (Shashidhara et al, 1975).

Rajaratnum (1976) gives values of K for a number of different jet configurations including vertical direct-down jets as used in the center of the tanks modelled here. Using these equations, the jet velocity decay of the central down-jets can be predicted as shown in figure 6 below:

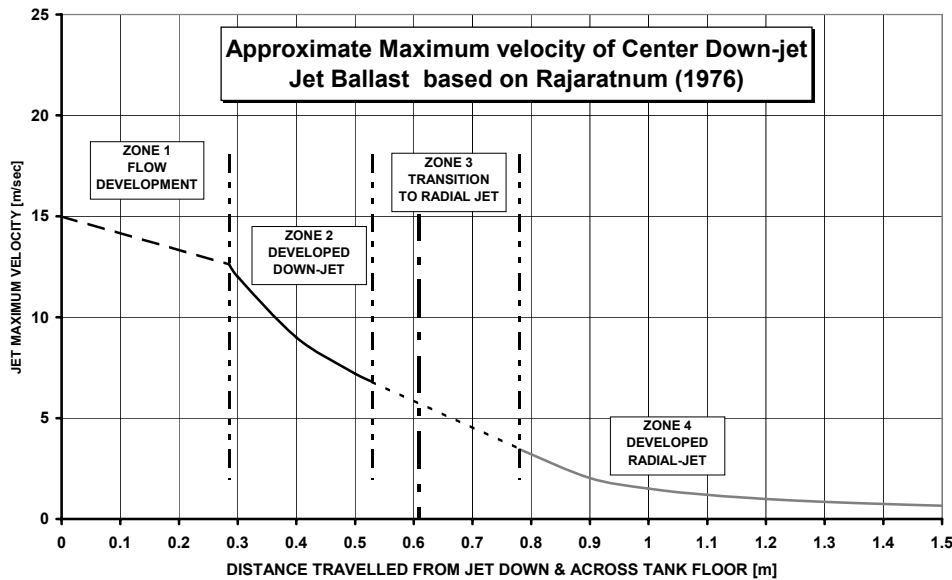


Figure 6 Typical predicted Central Down-Jet Center-line velocities

Although the full 3-D jet velocity distribution equations for the side wall jets considered, after reflection, does not exist the K values can be inferred by comparison with the performance of the center jets.

Equating the sludge yield stress force to jet momentum, as in Hamm et al (1989), leads to the clearance length of a jet as:

$$L_{\infty} = k(R_e)^{0.135} d_j \bar{u}_j \sqrt{\frac{\rho_i}{2\tau_y g_c}} \quad (2)$$

This equation, is a slight modification of that given by Hamm et al (1989) to allow for the Jet Liquor viscosity using the correction of Rushton (1980) where $k(Re)^{0.135}$ replaces constant K . The use of this correction (from Rushton on various liquid & gas jets) has been found to fit the British Nuclear Group experimental data for varying liquor viscosity very well.

The value L_{∞} in Equation (2) represents the distance a jet will clear if operated for a long period (infinite time). It represents the maximum capability of that jet (also referred to as Effective Clearance Radius, ECR). Rushton (1980) gives a value of $k = 1.41$ for a “free jet” (a theoretical jet surrounded by an infinite fluid but approximates well to many practical systems with horizontal jets above a tank floor).

Little work has been published for clearance rates with time except for Hamm et al (1989) at Savannah River. Further re-suspension rate data was obtained from the British Nuclear Group test rig data. Dividing the time-based test rig clearance data L_{Max}^{JB} by L_{∞} leads to an equation of the type shown below for the jet ballast or pulse jet system modelled:

$$L_{Max}^{JB} = k_R k_{JC} k_{AL} \phi_{CT}(T) L_{\infty} t_F^n \quad (3)$$

Where k_R , k_{JC} , k_{AL} and n are all model constants or factors.

RE-SUSPENSION RATE CONSTANT

The constant k_R is the re-suspension rate constant. This needs to be measured by jet-sludge testing but may be fairly constant at least for approximately 10-50 Pa sludges (as in the modelled tanks) but further tests are required to prove this.

JET CONFIGURATION FACTOR

The constant k_{JC} varies with jet physical configuration and merely represents the comparative performance compared to a “free jet” (it could be based on the comparison of any 2 jet configurations). The comparative performance of different jets can be either obtained practically or using known K values in equation (1). It should be noted that k_{JC} allows for any surface deflection velocity losses of the jet deflected from vessel floor or wall.

FREQUENCY FACTOR

The jet clearance varies with firing frequency, represented by the factor $\phi_{CT}(T)$. It is anticipated that this factor may be removed since it is now seen that it probably just represents the effect of settling sludge compaction on sludge yield stress. It is believed it can be replaced by measured (maximum) Yield Stress versus settling time for the sludge (over a period of hours). Figure (7) below shows a typical settling versus sludge bed compaction curve. Work is ongoing to confirm this.

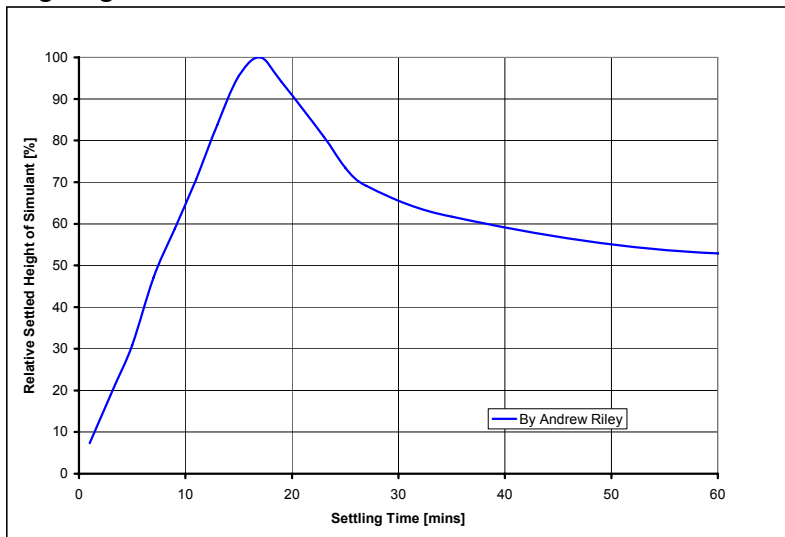


Figure 7 Affect of Settling Time on Sludge Compaction and hence Yield Stress

AGITATION FACTOR

The factor k_{AL} represents an increase in Jet ballast (pulse jet) re-suspension that increases approximately by 1/5 if the Air-lifts are on above a critical value. The Air-lifts do not re-suspend the sludge but they do increase the performance of the re-suspension system significantly when they are on. Without the air-lifts on the re-suspended sludge forms a high solids liquor layer several feet thick above the tank base. Above a critical air-flow, this improvement is constant. On the system modelled, the critical value is far below the flows normally used on plant so it has been considered as an on-off value. For other systems, if the agitation system operates below a critical value then this would need further investigation. On the system considered there is plenty of experimental data below the critical flow but it is of no practical interest to plant to operate with such very low air-lift flows. For others, this may be an area of critical interest. However Hamm et al (1989) also comment that at Savannah River “once suspended the sludges with low settling rates can be easily maintained at low agitation rates”.

This highlights the need to understand, that even if achieved with the same device, re-suspension of a sludge and agitation to maintain it in suspension are separate functional requirements. Often, as in the tanks considered in this paper, separate devices are used for the two functions.

It should be noted that below the critical air-lift flow, the re-suspension performance varied very approximately linearly with air-lift flow. It has been suggested that this effect could be simply the effect of local liquor high viscosity with the air-lift mixers off, although it could also be the effect of longer settling times as the sludge is more completely mixed throughout the liquor in the tank.

COMPARING TO OTHER DATA

Overall, it can be seen that if the mixer effect k_{AL} is ignored in equation (3) and also $\phi_{CT}(T)$ for the reasons described earlier, then $k_R k_{JC} L_\infty$ becomes analogous to the constant $(1.25/c)$ in Hamm et al (1989):

$$x = \left(\frac{1.25}{c} \right) t^{0.36} \quad (4)$$

The factor c is merely a correction of the Hamm et al (1989) data to a second time-basis. Hamm et al (1989) claim that the re-suspension performance using equation (4) is independent of sludge rheological properties. The experimental data described here gives an exponent close to the 0.35 value of Hamm et al (1989). Therefore the exponent n looks to be fairly indifferent to sludge rheology (at least for a defined yield stress range). However, it would be good to have further data to confirm this. Especially as the Sellafield sludge simulant, considered here, had a yield stress fairly close the Savannah River sludges described by

Hamm, West and Tatterson (who suggested theoretical values of $n = 0.33$ to 0.5 based on system geometry).

The other constant, $(1.25/c)$, is seen in the model to be proportional to the inverse square of the sludge yield stress $(\tau_y)^{-0.5}$. However even with a 50% change in yield stress this results in a smaller change of around 20% in horizontal clearance. Others have obtained values of -0.46 or -0.67 (Powell et al 1997). However there are some questions on the tests that gave $n = -0.67$ as to whether L_∞ (the ultimate ECR) had actually been reached with the approximately 1000 Pa sludge (Powell et al 1997).

The component value L_∞ in the equation (3) also represents the affect of other operational parameters such as air firing pressure, tank liquor depth, liquor viscosity etc on the jet velocity. Hence, it is believed that $(1.25/c)$ is affected by sludge rheology, if only somewhat weakly.

In the model, L_∞ represents physical jet configuration differences, operating envelope parameters as well as some impact from Sludge rheological properties. Hamm et al (1989) only claim the constants n and $(1.25/c)$ are independent of sludge rheology not system configuration or operating conditions.

CLEARANCE CRATER SHAPE FACTORS

If the jet velocity distribution is known (see literature for a vertical center down-jet –e.g. Rajaratnum, 1976) then the potential exists to express it as a 3-dimensional iso-momentum envelope of clearance. For the wall-reflected jets modelled the center-line decay velocity after wall reflection has been inferred from the relative performance of the center down-jet.

The program developed uses a simple 2 dimensional model that meets the plant need to know if the floor is clear of sludge.

Having estimated a jet clearance length, there is a need to specify the crater clearance width and shape. Examining the test rig data, it was found that the ratio of clearance length to clearance width was approximately constant for the wall-jets. This is not surprising if the iso-momentum envelopes for jets of known velocity distribution, clearing homogeneous sludges are examined. For jets of known velocity distribution, the clearance crater width / length ratio and clearance shape can be calculated. In some cases this will result in wider clearance away from the wall than at the wall, as typically shown below in figure 8:

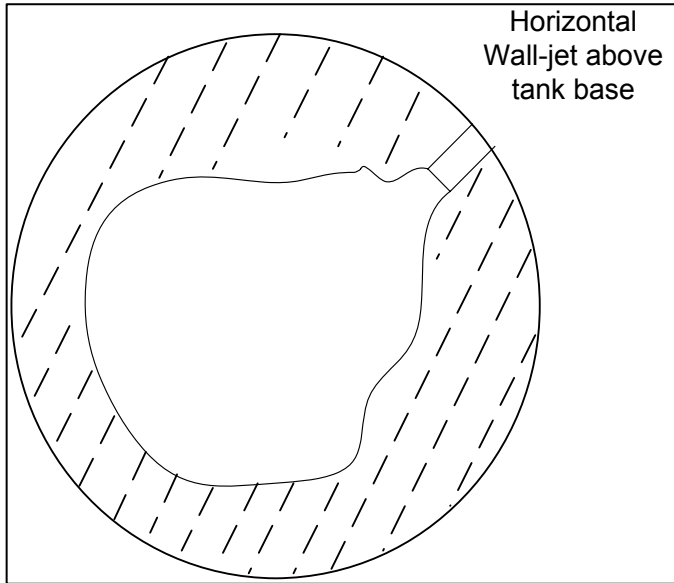


Figure 8 Typical clearance from horizontal wall-jet some distance above vessel base affected by opposite tank wall (based on Enderlin et al, 2005)

The side reflected wall-jets were approximated as elliptical craters as it fitted the test rig data well.

In reality, this assumption of uniform wall crater shapes is only approximate since the crater shape can be skewed by non-uniformity factors such as tank features or variable sludge yield stress. It is known from the test rig data that some distortion of the clearance area is caused by non-symmetrical tank features. However, distortion seen on one test crater can be the opposite on another test.

If the jet starts to clear a significant distance across the tank (e.g. more than a radius) then eventually significant effects will be seen from wall reflection both on the clearance length and crater shape. This can be seen in the photo published by Enderlin et al (2005), see figure 8 above. In the tanks modelled here, this is not an issue, since it only occurs at clearance distances beyond conditions of total clearance being attained. In other circumstances, this obviously may be more important.

THE MODEL

The model described does not represent the instantaneous floor sludge pattern for cases of poor re-suspension performance. In the tanks modelled the jets fire in sequence and no doubt to some extent floor sludge can be pushed around the tank at low re-suspension operating conditions.

Therefore, the clearance picture shown (figure 4) does not represent a single instant during operation. Rather it represents the cumulative operation of jet ballasts over a period of time

(e.g. say several hours). Since the jets fire sequentially, when a settled sludge is challenged, after one wall jet firing then only a single crater area would be cleared. Repeated firing of a single jet at a suitable frequency would keep its local crater clear, even without the air-lift mixers operating. However no single wall-jet can clear the whole tank floor alone.

As well as modelling the re-suspension system, a precursor is the physical modelling of the air driven liquor jet system to predict jet nozzle exit velocities. It was found that the nozzle Coefficients of Discharge predicted by Davies et al (1985) for tapered nozzles agreed very well with the experimental data from the British Nuclear Group test rig.

This model has shown that relatively simple concepts can be combined to predict the performance of a complex re-suspension system in a complex geometry tank extremely well. This is notwithstanding variable properties of tank sludge and tank physical geometry that probably make it an approximation of reality. The Test Rig results gave 66 sets of test data. Only some of the tests were originally used to derive the original model but it fits all the tests very well.

A word of caution about the point at which sludge is about to be re-suspended or not completely re-suspended (referred to as "Total Sludge re-suspension point"). Tests close to this point at the same operating conditions have given both total or incomplete sludge re-suspension (typically a few patches of sludge remain). Hence, it is probably unrealistic to expect a model to guarantee results close to this point. This highlights the need during design for a margin to ensure conditions of complete re-suspension close to this condition. If the model predicts re-suspension conditions well clear of this point, it is not an issue.

APPLYING THE MODEL TO OTHER SYSTEMS

Ignoring the effect of any agitation system for a different system, the designer would need system values for:

1. Sludge Yield Stress (including the effect of settling compaction over the re-suspension period of interest). On static tanks of aged sludge compaction this is no-longer a "time based variable" but Yield Stress variation in the sludge bed will probably exist due to both chemical and physical forces as well as temperature.
2. Liquor density and viscosity
3. Exponent n . A value similar to Hamm et al (1989) may be used for design estimates but for plant performance, this may be at least 20-30% in error. Therefore, a trial to confirm a value for the particular sludge would seem prudent.
4. The Re-suspension rate factor k_R . The value is based on measured simulant properties but appears valid for a range of typically 10-50Pa yield stress sludges.
5. The Jet Configuration constant k_{JC} can be estimated from either known comparative jet velocity profiles or comparative jet clearance performance. This assumes that k_{JC} is independent of any sludge properties, which although believed likely, is not proved by

experimental data. However some active tank sludges are known to have properties significantly at variance with the original Test Rig simulant but the model still applies successfully.

It is assumed that the agitation factor obtained on other systems would be similarly constant where the agitation system induced tank floor velocity was insufficient to re-suspend the sludge.

All of the above factors could probably be evaluated on a small-scale test rig, which with variable system geometry and sludge properties would also confirm the validity.

CHARACTERISATION OF SIMULANTS

The handling and analysis of liquor from the highly active waste storage plant is highly complex. In-active simulants, or surrogates, representative of plant liquors produced to simulate differing process treatment conditions and chemical compositions are used for experimental work.

To increase the flexibility and optimisation of the model and hence the process, characterisation of settling behaviour and sediments has been performed. Techniques such as gravitational and centrifugal settling allow the examination of settling profiles, sedimentation and consolidation and packing of settled beds, examples as seen in Figures 9 and 10. The study of shear yield stress, which measures the energy required to re-suspend a settled bed, generally found a weak cohesive nature, for a given range of solids concentration, characterised by low shear yield stress values indicating minimal inter-particle forces (Mason et al 2005a).



Figure 9 Gravity settling measurements of simulant over 1 hour

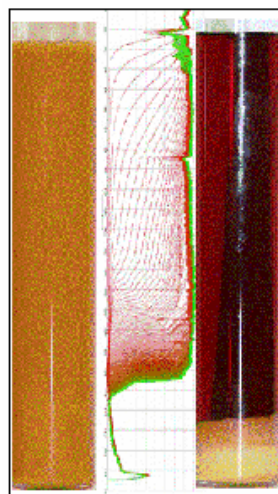


Figure 10 Centrifugal settling using LUMiFuge Stability Analyser after 112xg for 3 hours - equivalent to 2 weeks at 1xg*.

* LUMiFuge settling profile is sandwiched by photographs before and after settling.

To understand the impact of a wider operating envelope on suspended solids within potentially more complex chemical waste streams, characterisation of suspended solids is required (Mason et al 2005b). Fundamental properties such as flow curve rheology (Figure 11) and sedimentation measurements (both gravitation and centrifugal), as well as particle size (utilising a number of techniques – Figure 12a and 12b), particle shape (Figure 12c) and density are required.

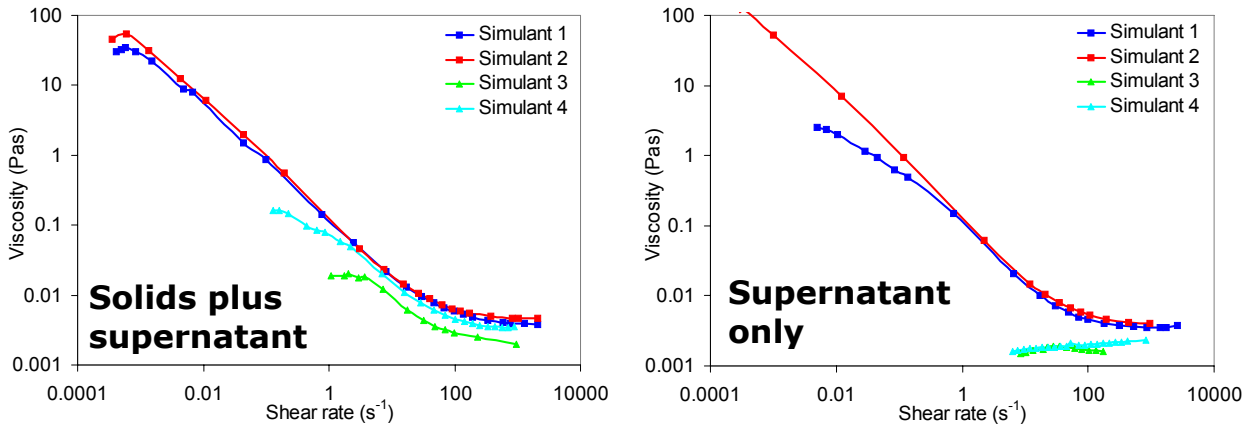


Figure 11 Rheology flow curves for in-active simulants, whole sample and supernatant only, measured using a rotational rheometer

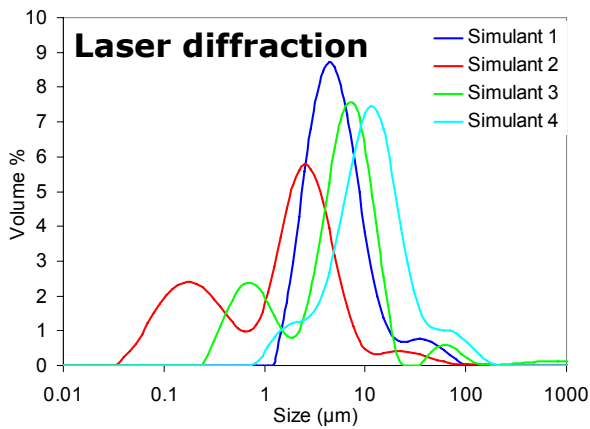


Figure 12a Particle size distribution of in-active simulants using Laser Diffraction technique

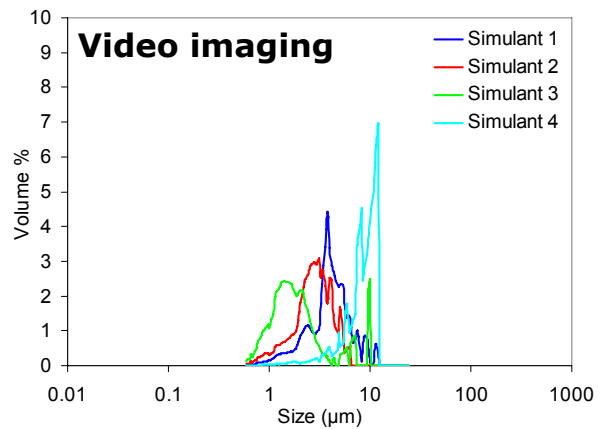


Figure 12b Particle size distribution of in-active simulants using Video Imaging technique

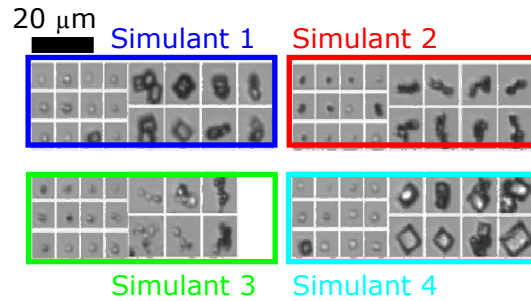


Figure 12c Particle shape images of in-active simulants using Video Imaging technique

In this paper we report the design, development and use of the model, and summarize the characterisation of a series of simulant materials through the measurement of fundamental properties.

NOMENCLATURE

ECR = Effective Cleaning Radius [m]

g_c = Gravitation constant [=1 kg_m-m/N-sec²]

k = Rushton Jet Velocity Decay constant = 1.41

K = Configuration Jet Velocity Decay constant for a jet, $K = k(\text{Re})^{0.135}$ [-]

k_{JC} = Jet Configuration Factor (comparative performance factor between different jet configurations (e.g. Vertical Down jet compared to a reflected wall jet or “free jet”).

k_{AL} = Agitation Factor that accounts for the improvement in re-suspension performance with general tank mixer device operating (e.g. Air-lifts) or not operating.

k_R = Re-suspension Rate constant [-]

L_{Max}^{JB} = Axial clearance of jet at time t [m]

L_∞ = Axial clearance of a jet operating for a long period (infinite time), also known as “ECR” [m]

Re = Reynolds Number for the Jet = $(\rho_L \bar{u}_j d_j) / (\mu g_c)$

t or t_F = Jet Firing Time [secs]

u_c = Center-line Jet Velocity [m/sec]

\bar{u}_j = Average Jet Velocity at Nozzle [m/sec]

x = Center-line distance axially out from the jet nozzle [m]

$\phi_{CT}(T)$ = Frequency factor (or cycle time factor) for relative performance at different firing frequencies (see text for explanation why expected to be replaced by Yield Stress measurements at different settling times and thence $\phi_{CT}(T)=1$)

ρ_i = Density of Fluid at Liquor / Sludge interface (usually approximated to the liquor density) [kg/m³]

ρ_L = Density of Liquor [kg/m³]

τ_y = Sludge Yield Stress [Pa]

μ = Liquor Viscosity [Pa-sec]

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