

**Utilizing a Novel Acoustic Backscatter Array to Characterize Waste Consolidation and Settling in a Horizontal Flow Clarifier – 16051**

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**ABSTRACT**

As part of a collaboration between the University of Leeds, Sellafield Ltd and MMI Engineering Ltd, bespoke acoustic instrumentation and numerical simulation methods have been established to optimize nuclear legacy waste transfers. Specifically, a new ultrasonic measurement system has been developed, allowing suspended particle concentration and consolidation to be measured remotely. This technology has been combined with computational fluid dynamics (CFD) modelling of settling particulate systems, permitting full characterization, simulation and prediction of sludge separation processes.

Presented here are experimental and numerical results on the transport and settling behavior of non-active nuclear-analogue suspensions in two flow geometries: gravitational settling of glass dispersions in a 250-liter column; and transport and sedimentation of flocculated calcite in a close-to-full-scale clarifier (9 m<sup>3</sup> total volume and 4.8 m<sup>2</sup> length). In addition, details of the design, construction and calibration of a custom-built Ultrasonic Array Research Platform (UARP) are described. Settling column results suggested that particle concentration changes could be simulated with good accuracy by a CFD model (developed using the open source OpenFOAM framework) when compared to measured samples. Large-scale clarifier trials were used to assess the effectiveness of the UARP controller with an attached *in situ* acoustic backscatter array (ABA). The ABA consisted of 8 transducers angled down at 20° to the vertical, pulsing at 2-2.5 MHz in cycles (covering 1.8 m total depth). In comparison to a range of sampled concentrations across the length of the clarifier, results confirmed that the UARP-ABA system was highly successful at characterizing these complex flows over several hours of operation, allowing visualization of depth-wise bulk density changes and bed build-up over time. Collectively, this work highlights the capability of these tools to monitor and optimize a number of current waste transfer operations at Sellafield, with further potential applications for solid-liquid separations across waste, water treatment and minerals engineering industries.

## INTRODUCTION

Within the UK nuclear industry, there is a considerable accumulation of legacy wastes in the form of particulate-in-liquid suspensions, contained in ponds, silos and tank storage areas. Many of these holding deposits were originally only intended to be temporary facilities and are far beyond their design life; and collectively, they represent the UK's highest radiological hazard. The largest of these sites is at Sellafield, where the bulk of hazardous high-priority sludges are designated for separation, transfer and interim storage within the next 5–10 years. Overall, the projected lifetime cost of decommissioning at Sellafield is estimated at approximately £67.5bn according to a UK National Audit Office report of 2012 [1], of which the treatment of intermediate-level wastes (ILW) and high-level wastes (HLW) are expected to comprise over 50% of short to medium term costs. The economic burden of this legacy influences public opinion and affects the government's ability to argue for future investment in nuclear power. Additionally, there are many similar deposits across Nuclear Decommissioning Authority (NDA) licensed sites, as well as internationally (e.g. Savannah River and Hanford in the USA).

There are significant challenges associated with safe and efficient waste processing, due to their complex compositions, poor current containment facilities and, most importantly, a lack of available characterization data. Radioactivity and toxicity means that physical sampling can be difficult and costly. The sludges are often highly heterogeneous and/or flocculated due to either historical treatment or the action of algal growth in open areas [1, 2], while their composition and material properties can change as a result of agitation during transfer, in particular, with high-shear pumping. Specifically, there is a strong engineering and scientific need to understand the settling behavior of these wastes, especially the evolution of particle concentration, stratification and compression, during mixing, transfer, and containment operations. Additionally, water, wastewater, fossil fuel and minerals industries all experience similar difficulties with respect to multiphase flows and particulate waste management [3], highlighting the broad application of research in this area.

In response to these challenges, a joint industrial-academic collaboration between the University of Leeds, Sellafield Ltd and MMI Engineering Ltd has been established to investigate how legacy waste processing can be improved, through advancement of novel instrument and modelling capabilities. The fundamental aim of the project is to reduce costs associated with sludge separation by increasing efficiency and reducing operation times, through two integrated characterization tools: 1) An innovative and versatile *in situ* acoustic measurement platform; and 2) A predictive numerical modelling framework.

Specifically, a new Ultrasonic Array Research Platform (UARP) has been developed that acts as a high frequency echo sounder, allowing particulate concentrations and consolidation to be visualized using backscattered sound, *in situ*. The device is intended to be robust and simple to operate, providing bulk density profiles at up to sixteen locations, as well as bed depth measurements, rapidly and remotely; capabilities that are not provided by existing instruments used for nuclear

applications. Importantly, it utilizes a mobile measurement array consisting of comparatively cheap and disposable transducers, allowing the instrument controller itself to be separated from radiological and toxic hazards when necessary [4-7].

Acoustic analysis has been combined with a computational fluid dynamics (CFD) modelling framework, based on existing open-source codes that are currently used to predict the behavior of clarifiers and thickeners in water treatment [8]. However, the CFD solver that has been developed contains significant extensions to account for particle aggregation and break-up, to better mimic real nuclear legacy wastes. Linking both measurement and modelling systems will enable verification of the CFD environment, ultimately allowing for full prediction of sludge separation operations. Results are presented for CFD validation experiments in a 250 L vertical settling column, using non-aggregated glass suspensions.

The main results presented in this paper are from sludge settling trials conducted at NSG Environmental in Chorley, UK, utilizing a close-to-full-scale horizontal flow clarifier (4.5 m long, 9 m<sup>3</sup> total capacity). Calcite flocculated with 6 ppm of high-molecular-weight anionic polymer (injected into the feed-line) was used as a model for non-active aggregated legacy waste. The in-house designed and built UARP controller was firstly calibrated using small-scale flocculated calcite suspensions, before being installed in the clarifier with an *in situ* mounted acoustic array. Here, transducers were set with variable pulse frequencies, and were positioned in series to cover the whole depth of the clarifier, with the strength of the backscattered return echo used to estimate particle levels and compared to extracted samples.

## METHODOLOGY AND MATERIALS SELECTION

### 1. Materials selection

The test material selection process was described in detail in a preceding paper [9], and properties of the solid species are summarized in Table 1. The glass species were utilized for column settling tests, as their highly spherical shape meant that settling behavior was simpler to predict by numerical modelling, allowing for CFD code validation. For more realistic test materials, flocculated calcium carbonate was used as a non-active legacy sludge analogue in clarifier settling trials. It is noted that as this system is also a common reference material for minerals processing suspensions, results could be correlated to previous research [10-12].

**Table 1: Properties of solid particulate test materials**

Particle Type	Trade name (supplier)	Size, d <sub>50</sub> (μm)
Spherical glass	Honite-22 (Guyson International)	41
Spherical glass	Honite-16 (Guyson International)	77
Calcium carbonate (calcite)	Omyacarb 2 (Omya Industries)	4.5

Several large polymeric flocculants, supplied by SNF Ltd, were initially tested for efficacy with the calcite. Due to its high performance in benchtop flocculation settling

experiments, and previous laboratory-scale thicker studies [11], *AN 934SH* (a medium charge density, high-molecular-weight anionic polymer) was used in all trials, at 4 – 10 ppm concentrations.

## 2. Ultrasonic Array Research Platform (UARP) acoustic controller and acoustic calibration

The UARP has been described in detail in an earlier paper [13] and is summarized briefly here. It was designed to allow for full configurability of the transmitted waveform and frequency, and complete access to the raw received signal, capabilities that are not available in most commercial instruments. The UARP allows up to 16 *transmitting and receiving channels* for connection to many standard market transducers. The transmit circuitry of each channel is based on the Maxim Integrated MAX14808 integrated circuit (IC) configured for five level switched mode excitation at up to  $\pm 100$  volts at 2 amps with integrated T/R switch. Excitation waveform characteristics allow cancellation of harmonics, precise amplitude control and synthesis of arbitrary waveforms [14-16]. An image of the UARP is shown in Figure 1 highlighting the internal circuitry.

For the conducted trials, 8 channels on the UARP were employed, connected by 7 m long cables to a vertical acoustic backscatter array (ABA). The ABA was constructed of aluminum 1 inch frame, with probes being positioned at  $20^\circ$  to the vertical in specially designed holders, 20 cm apart. (It is noted that the ABA designed allows probe mounting at any position and angle, depending on application). The utilized transducers were standard 10 mm pencil-type supplied by Olympus, with a central frequency of 2.25 MHz, variable by up to 15%. This flexibility allowed data at multiple frequencies to be obtained from a single probe.



Figure 1: Ultrasonic Array Research Platform (UARP) with cover removed.

Before large-scale settling trials were conducted, the acoustic properties of the tested particles were measured – specifically the backscatter and attenuation coefficients – according to a method described by the authors [7] in a homogeneously mixed 6 L

stirred mixing vessel. Here, different particle concentrations of pre-flocculated calcite (using 4 ppm polymer) were prepared and the acoustic backscatter response from all 8 probes was averaged over 3 minutes (to determine any variation). This analysis was used to establish a concentration calibration for conversion of trial data. In the calibration, as in the large-scale trials, the transducer frequencies were cycled between 2, 2.25 and 2.5 MHz continuously, and echo data gained over 0 - 0.3 m depths.

### **3. CFD validation in settling column studies**

A large 1.5 m by 0.5 m diameter baffled mixing-settling column was utilized for initial validation of the CFD solver. Here, mixed suspensions of glass at 30 g/L were prepared through combination of an impeller mixer and pump recycle. After achieving as close to homogenous mixing as possible, the impeller and pump were switched off and suspensions left to settle for 25 minutes. Concentration samples were taken from a four head peristaltic pump set to extract at different depths and times, and results compared to simulation. Dispersions of both Honite-22 and a 50:50 mix of Honite-22:Honite-16 were compared in this way. Additionally, particle size distributions of sub-samples were measured with a Malvern Mastersizer 2000.

A 2D axisymmetric model of the settling column was generated using Ansys ICEM Hexa v16.1. The computational mesh comprised approximately 2300 elements. The CFD calculation was undertaken using a custom solver developed in OpenFOAM v2.2.x. The solver was extended for calculating the transport of up to 10 discrete, non-interacting particles, using the mixture model [17].

The side and bottom boundaries were set to no slip and for the top water surface a free slip boundary was defined i.e. a boundary with zero shear stress. The properties of water (density and viscosity) were set based on the measured temperature taken during the experiments. The density of Honite was set in the range 2450 to 2460 kg/m<sup>3</sup> depending on the specific type. The particle sizes were determined from measured Particle Size Distributions, which were discretized in to a total of 10 particle size groups. The particle slip velocity was prescribed directly and was calculated using the drag law by Schiller and Naumann [18] for spherical particles.

It was assumed at the start of the calculation that the particulates were perfectly mixed so that a uniform mass fraction was specified over the extent of the column. Where the initial total particle concentration did not compare to the measurements, possibly due to poor mixing, the initial concentration was scaled to match the measured concentration. The effect of the impeller was not included and it was therefore assumed that the energy imparted to the fluid by the impeller decayed rapidly. As such, the initial fluid velocity was assumed to be 0 m/s.

### **4. Large-scale clarifier trials**

Large-scale non-active sludge settling trials were conducted at NSG Environmental in Chorley, UK. A bespoke 9 m<sup>3</sup> settling corral was built, approximately 4.8 m in length, 2.5 m liquid depth and 0.75 m wide. A baffle approximately 2.2m in length was offset

from the inlet end by 0.5 m to create a separate mixing zone with an installed propeller, ensuring a homogenous feed. A 0.3 m deep weir allowed suspensions to propagate into the settling section of the clarifier (being the remaining 4.3 m in length). Three large feed tanks (also of 9 m<sup>3</sup>) homogeneously mixed non-flocculated calcite at a concentration of approximately 30 g/L, and were connected with a monopump and a 1 inch line to the inlet of the mixer-settler tank. The tank inlet point was positioned at the depth of the mixer impeller (approximately 1.5 m from base of clarifier) to aid particle dispersion. The feed pump rate was set at 80 l/min, which approximately allowed for 3 tank volumes to be exchanged over the testing period of 4 hours (the settling tank was initially filled with mains water). A line injection port was positioned 5 m from the tank inlet, where polymer was introduced from a 2000 ppm stock (using a small peristaltic pump) at such a rate to give a diluted feed concentration of 6 ppm. It was assumed that the 5 meter lead-in section would be sufficient to allow for high levels of flocculation without over-shearing, which may secondarily reduce aggregate size. An image of the corral and feed tanks is shown in Figure 2.

Five evenly spaced locations along the settling section of the corral were chosen to measure concentration, both by sampling and through the mounted ABA connected to the UARP. For sampling, extractions were made at five depths (of 27, 47, 67, 107 and 177 cm from the tank base) again using a 5 head peristaltic pump. These depths were also correlated to positions of five of the acoustic transducers. A further probe was positioned vertically down at the end of the ABA to monitor bed build-up, while two additional probes (giving 8 in total) were positioned between 100 and 150 cm from the base to enable full depth coverage. The ABA and sampling pole were mounted at a 10 cm separation around the centerline of the corral (and thus assumed to both represent profiles from the center).



**Figure 2: Image of large-scale settling clarifier at NSG Ltd, Chorley.**

Concentration measurements were made at five distinct time regimes (from trial initiation as the feed pump was switched on) beginning at 30 minutes from the start and then at 50 minute intervals. It is noted however that due to the requirement to

move the ABA and sampling mounts along the corral to each lateral location, every time regime took approximately 25 minutes to complete. Hence, density profiles at the lateral positions were not strictly co-located in time. Profiling was started at the location closest to the inlet, then proceeding down the corral for each run. 3 minutes of acoustic data was averaged for each location, with samples being taken immediately preceding to running the UARP.

## RESULTS AND DISCUSSION

### 1. Calibration of acoustic system

The acoustic backscatter response of flocculated calcite in the 6 L calibration column is presented in Figure 3, for various concentrations between 3.125 – 50 kg/m<sup>3</sup> from one particular probe (very little variation was observed between transducers). In Figure 3(a), the range-corrected echo amplitude,  $G$ , is seen to vary in a linear profile with distance from the transducer,  $r$ , as expected by theory [7] (with some deviation at 0-0.05 m distances due to near-field interference). Here,  $G = \ln(rV)$  where ' $V$ ' is the average measured rms voltage. The mean gradient of  $G$  with respect to  $r$  was calculated (between 0.05-0.1 m) and is compared for all concentrations in Figure 3, b. From this linear slope, the acoustic attenuation coefficient,  $\xi$  (which depends on particle size distribution, density, shape and aggregation state) can be measured directly for each frequency.

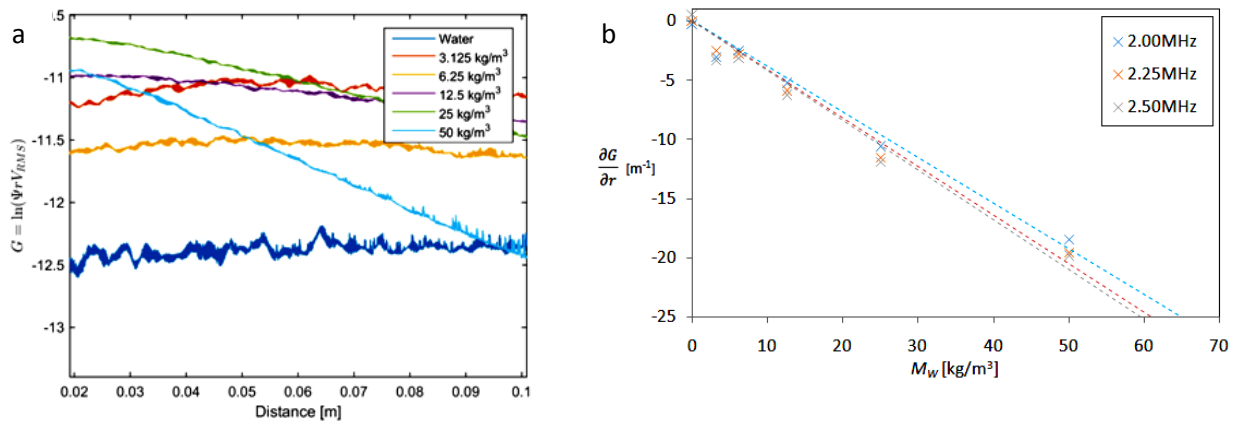


Figure 3: (a) Range-corrected echo amplitude,  $G$ , vs. distance from transducer,  $r$ ; (b) gradient with respect to distance of  $G$  vs. nominal particle concentration,  $M_w$ . Both for flocculated calcite.

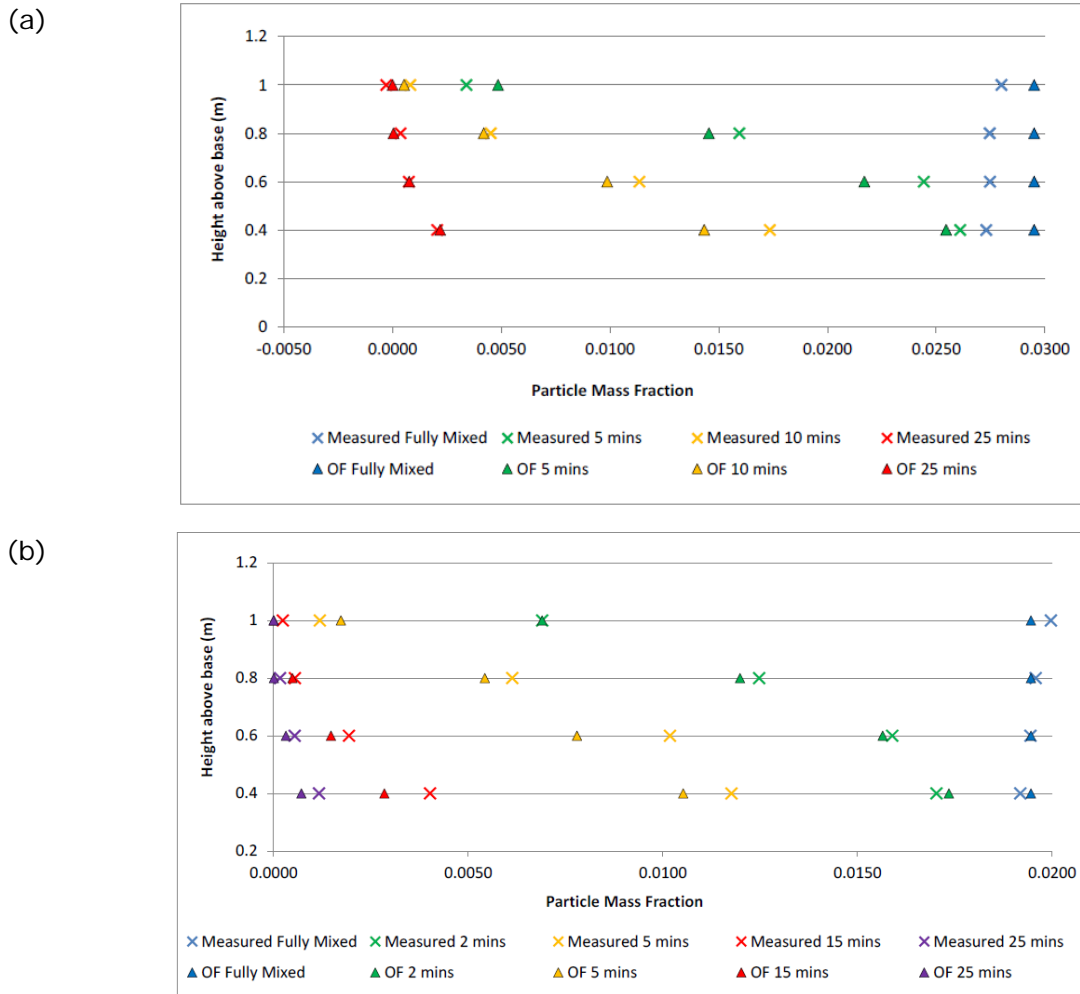
As observed from Figure 3, b, the value of the attenuation coefficient (directly proportional to the gradient of  $-\partial G/\partial r$ ) increases with frequency, again as expected from theory [7]; although, the differences overall are not significant. It is assumed that as the flocculated calcite is highly attenuating, the relatively small change in frequency (2-2.5 MHz) is not great enough to clearly resolve the frequency dependence, and an additional higher transducer would be recommended in future. However, importantly, the  $-\partial G/\partial r \propto M_w$  relationship gives a clear linear concentration correlation to be used for trial calibration. By measuring the average slope of the  $G$  parameterization for each probe in the large-scale trials, concentrations can simply be

back calculated from this relationship without any further knowledge of the system. Additionally, measured attenuation coefficients can also be used in the '*dual-frequency concentration inversion method*' [7] to compute the particle concentrations in a more theoretically rigorous procedure.

## **2. Settling column comparison of experimental & CFD numerical results**

Particle concentration results for 100% Honite-22 and 50% mixed Honite-22: Honite-16 suspensions are shown in Figure 4 (a) and (b), respectively. Here, samples at four locations between 40 – 100 cm from the column base were extracted over time, and are shown in comparison to the CFD simulation in OpenFoam (OF) for the same locations.





**Figure 4: Particle mass fraction changes of (a) Honite-22 glass spheres and (b) Honite-22/Honite-16 mixtures (each 50% by mass) over time in a 1.5 m column after fully mixed suspensions were allowed to settle; experimental ("measured", via pumped sampling) vs. numerical ("OF", i.e. OpenFOAM) results.**

It is clear from Figure 4 that the measured and predicted profiles correlate closely, highlighting the validity of the simulation code, where both suggest concentrations reduce due to gradual settling and deposition under the influence of gravity (as particle concentrations are not high enough to cause a strongly hindered settling regime). There were some slight discrepancies in terms of initial concentration estimates however (for example, shown in Fig. 4, a), which occurs from experimental rather than simulation limitations. These differences are thought to be due to some inefficiency with the pump recycle system, and there was some evidence of particle drop-out during the initial homogenization mixing, which resulted in the actual initial particle concentration being slightly lower than the added weighed amounts. This was corrected for in the 50% data (as shown in Fig. 4, b) by simply using the initial measured concentration profile as the simulation input.

Median particle size,  $d_{50}$ , of extracted samples versus model predictions are

presented in Figure 5, for the 50% Honite-22/Honite-16 mixture after 2, 5 and 15 minutes in frames (a), (b) and (c), respectively, for each of the four depth locations. Again, measured and simulation results correlate closely, and trends are consistent with that expected from diffuse gravitational settling rather than hindered sedimentation. Particle sizes decrease for each time-step further up the column, while collectively, averages reduce over time. (There were no particles collected at the upper height point after 15 minutes, and thus size  $d_{50}$  sizes were only gained for the lower three locations).

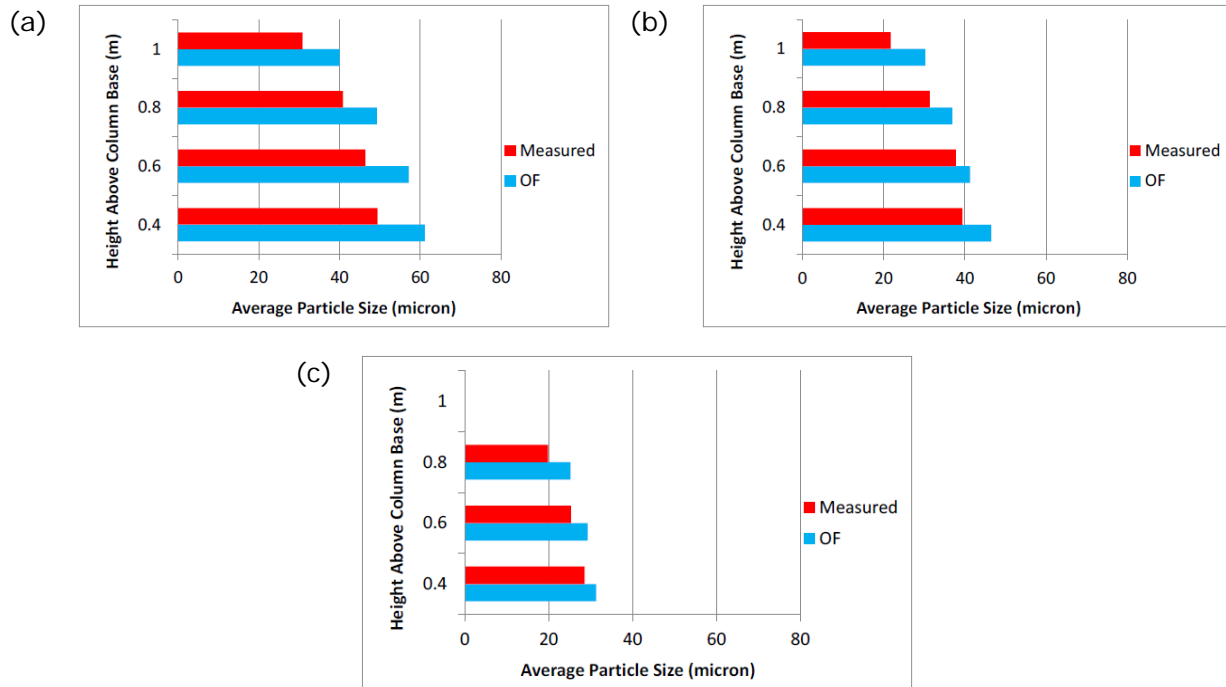


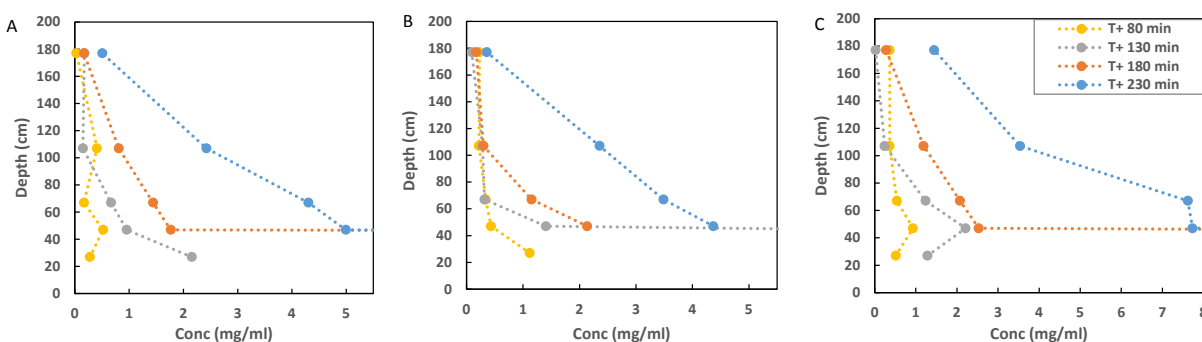
Figure 5: Median particle diameter ( $d_{50}$ ) of Honite 22-Honite 16 mixture (50% by mass) in a 1.5 m settling column at (a) 2 minutes, (b) 5 minutes and (c) 15 minutes after fully mixed suspension is allowed to settle; experimental ("measured", via pumped sampling) vs. numerical ("OF", i.e. OpenFOAM) results.

Overall the *OpenFOAM* results did lead to a consistent slight overestimation of  $d_{50}$  sizes, which is attributed again to particle drop-out in the mixer, before the suspension was allowed to settle. As the Honite-16 particles are almost twice as large as the Honite-22, they would likely deposit in preference, resulting in a reduced  $d_{50}$ , as measured. While initial deviations in concentration were corrected for in the model, there was no attempt to correct for the particle size distribution in this way, as no consistent initial PSD was measured.

### 3. Large-scale clarifier: sampled and acoustic results

Sampled particle concentrations across the length of the corral were taken to aid assessment of the performance of the UARP and connected acoustic array. Displayed

in Figure 6 are results from the extracted samples at the five heights of 27 – 177 cm (in relation to the tank base) over the last four time regimes (T+ 80, 130, 180, 230 min) for three lateral positions. The locations shown represent 1 m from the inlet weir of the clarifier (A) near the middle (B) and approximately 1 m from the outlet weir (C).



**Figure 6: Sampled concentration results from the large-scale sludge settling trial at three locations along corral; A) near settler inlet weir, B) middle of corral and c) near outlet weir. Sample times at T+ 80, 130, 180 and 230 mins.**

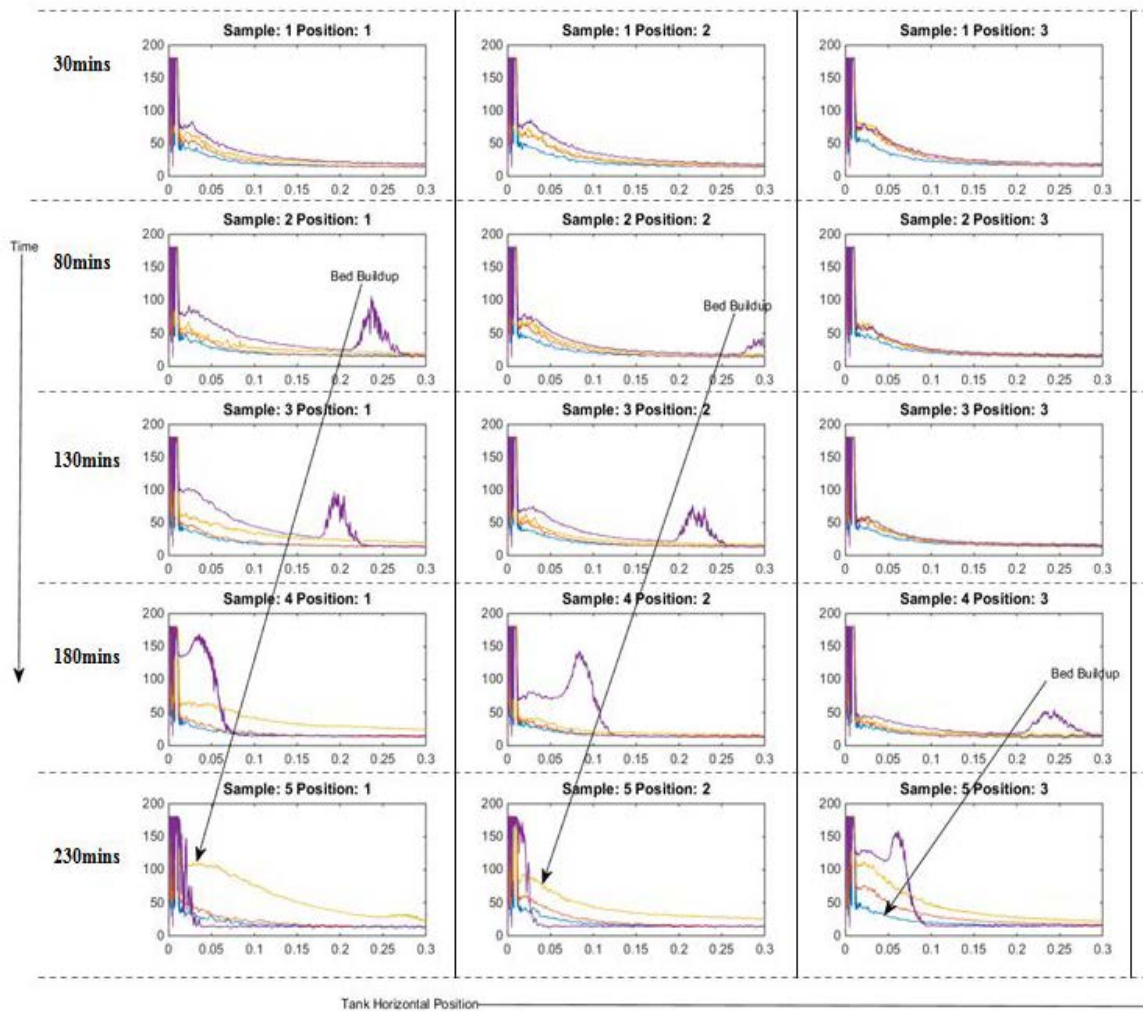
A number of features are evident from the sampled data presented in Figure 6. In particular, all locations show a distinct increase in particle concentrations between all times, suggesting that the clarifier is far from equilibrium (as would be expected, as only three exchanges of tank volume were completed within testing). It is noted also that the lowermost sampled positions (at 27 cm from tank base) were covered by the consolidated sludge layer between sample times of T+130 min to T+ 180 min, depending on lateral position. The onset of this behavior is shown in the figures by the horizontal dashed lines extending out of the figure ranges. Consolidated bed density levels are not shown, but were measured generally between 10-15 wt%.

It is also interesting that there is not a larger distinction in concentrations between lateral locations; although, it appears that particle levels in the middle section are overall lower than either the inlet or the outlet. It may have been expected that concentrations would drop towards the outlet section; however, it is assumed that in this case, a large recirculation current was produced leading to an upflow at the end of the clarifier, potentially re-suspending some particles. While no flow measurements were taken to confirm this trend, it was evident visually from the flow of particles (especially in the beginning of trials) that recirculation currents were forming within the clarifier. It is hoped that ongoing CFD modelling of the same system will be able to confirm some of these trends.

Despite evidence of flow recirculation within the clarifier, overall separation performance was very high. Samples taken from the outlet weir itself showed consistent particle levels of approximately 0.12 mg/ml (or around 45 ppm, v) which is well within design limits for most nuclear waste on-processing operations. Such high performance indicates the potential use of polymers to enhance separation in legacy

systems, despite the fact that, to date, there has been very little uptake of flocculants within the UK nuclear industry.

Data from the UARP-ABA for the same clarifier trial runs were analyzed for comparison to extracted samples. Figure 7 gives the raw rms output from five of the operating transducers (correlating to the sample locations) for all five time regimes. Voltage rms is taken in reference to the distance from each probe (0 to 0.3 m). Here, data for three lateral positions are shown representing locations between the inlet weir and the middle of the clarifier.



**Figure 7: Acoustic backscatter analysis from the large-scale clarifier trial, showing raw rms voltage versus distance from probe, from five transducers correlating to sampling depths, for five time regimes of T+30, 80, 130, 180, 230.**

Acoustical data from Figure 7 qualitatively correlates with the sampling data presented in Figure 6, where the strength of the signal return is shown to increase for

each probe over time, and also increases between probes at greater depths (shown by the colors blue to purple going top to bottom in position for each figure). Also generally, while it is difficult to derive significant difference in average signal intensity between lateral positions, again the data from position 3 (representing the middle of the tank) is generally lower. Obviously however, there is a number of limitations with any attempts to correlate particle levels from the raw voltage values, and work, currently ongoing, will fully analyze this data by converting the rms according to the  $G$  parameterization (as discussed in Results Section 1) to produce quantitative concentrations from the calibration in Figure 3.

What is additionally evident from Figure 7 is the formation of a secondary peak in the data taken from the lowermost probes (purple lines). This peak is representative of the development of the consolidated sludge bed (which gives a strong backscatter response) and can be seen for each location increasing towards the higher probes over time. The distance of this peak was inverted to be in terms of the base of the clarifier, and was used to track bed build-up, with results being displayed for the last four time periods in Figure 8. The trends show a clear growth throughout the clarifier in the consolidated bed over time, firstly towards the inlet zone, but eventually covering the entire length of the corral at later times.

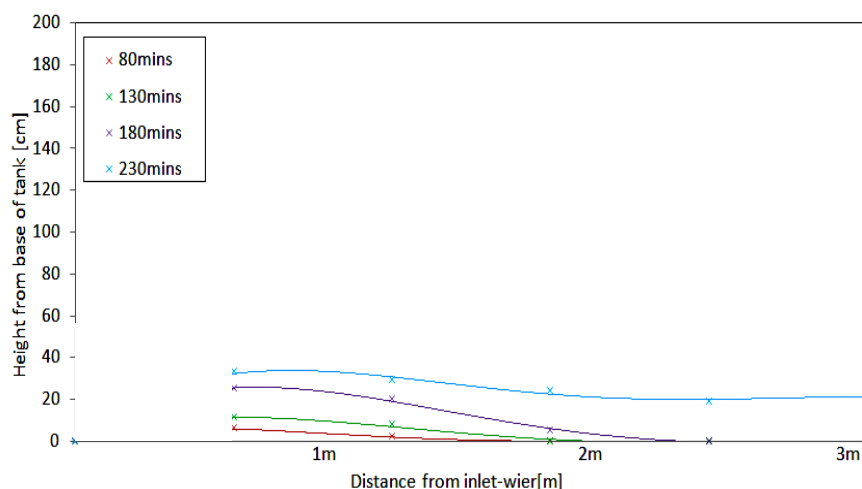


Figure 8: Build-up of consolidated sludge bed over time for the five lateral locations along corral, as measured with the acoustic backscatter array.

## CONCLUSIONS

Results confirmed that the UARP-ABA system was highly successful at characterizing these complex flows, allowing visualization of depth-wise concentration changes and bed build-up overtime, proving its capabilities for a number of future waste transfer operations at Sellafield. Further, this important experimental information was supported with a CFD drift-flux model of vertical column systems establishing the predictive power of sludge settling simulations. Combined, this work is of importance

not only for the understanding of nuclear legacy systems, but for solid-liquid separations across waste industries as well as water treatment and minerals engineering.

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## **REFERENCES**

- [1] NDA, Managing risk reduction at Sellafield, National Audit Office Report Nov. 7th 2012.
- [2] J.J. Hastings, D. Rhodes, A.S. Fellerman, D. McKendrick, C. Dixon, New Approaches for Sludge Management in the Nuclear Industry, *Powder Technology*, 174 (2007) 18-24.
- [3] G. Olsson, ICA and me - A subjective review, *Water Research*, 46 (2012) 1585-1624.
- [4] T.N. Hunter, L. Darlison, J. Peakall, S. Biggs, Using a multi-frequency acoustic backscatter system as an in situ high concentration dispersion monitor, *Chemical Engineering Science*, 80 (2012) 409-418.
- [5] T.N. Hunter, J. Peakall, S. Biggs, An acoustic backscatter system for *in situ* concentration profiling of settling flocculated dispersions, *Minerals Engineering*, 27-28 (2012) 20-27.
- [6] T.N. Hunter, J. Peakall, T.J. Unsworth, M.H. Acun, G. Keevil, H. Rice, S. Biggs, The influence of system scale on impinging jet sediment erosion: Observed using novel and standard measurement techniques, *Chemical Engineering Research and Design*, 91 (2013) 722-734.
- [7] H.P. Rice, M. Fairweather, T.N. Hunter, B. Mahmoud, S. Biggs, J. Peakall, Measuring particle concentration in multiphase pipe flow using acoustic backscatter: Generalization of the dual-frequency inversion method, *The Journal of the Acoustical Society of America*, 136 (2014) 156-169.
- [8] D.J. Burt, M. Gilbertson, Extended drift flux models for waste water sludges, *Particulate Systems Analysis* Stratford-Upon-Avon, 2005.
- [9] T.N. Hunter, G. Randall, D.J. Burt, M. Fairweather, D. Cowell, H. Rice, S. Freear, J. Peakall, S. Biggs, Measurement and Modelling of Legacy Sludge Separation and Transport Processes - 14250, *Waste Management Conference* Phoenix, Arizona, USA, 2014.
- [10] A.F. Grabsch, P.D. Fawell, S.J. Adkins, A. Beveridge, The impact of achieving a higher aggregate density on polymer-bridging flocculation, *International Journal of Mineral Processing*, 124 (2013) 83-94.
- [11] T.N. Hunter, S.P. Usher, S. Biggs, P.J. Scales, A.D. Stickland, G.V. Franks, Characterization of Bed Densification in a Laboratory Scale Thickener, by Novel Application of an Acoustic Backscatter System, *Procedia Engineering*, 102 (2015) 858-866.
- [12] B.B.G. van Deventer, S.P. Usher, A. Kumar, M. Rudman, P.J. Scales, Aggregate densification and batch settling, *Chemical Engineering Journal*, 171 (2011) 141-151.

- [13] D.M.J. Cowell, S. Freear, T.N. Hunter, I. Smith, H. Rice, M. Fairweather, D. Njobuenwu, J. Peakall, M. Barnes, G. Randall, Development of a real-time acoustic backscatter system for solids concentration measurement during nuclear waste cleanup, Ultrasonics Symposium (IUS) IEEE International, 2015.
- [14] D. Cowell, P. Smith, S. Harput, J. McLaughlan, S. Freear, Non-linear harmonic reduction pulse width modulation (HRPWM) for the arbitrary control of transducer-integrated switched excitation electronics, Ultrasonics Symposium (IUS), 2014 IEEE International, 2014, pp. 807-810.
- [15] D.M.J. Cowell, P.R. Smith, S. Freear, Harmonic cancellation in switched mode Linear Frequency Modulated (LFM) excitation of ultrasound arrays, Ultrasonics Symposium (IUS), 2011 IEEE International, 2011, pp. 454-457.
- [16] D.M.J. Cowell, P.R. Smith, S. Freear, Phase-inversion-based selective harmonic elimination (PI-SHE) in multi-level switched-mode tone- and frequency- modulated excitation, Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on, 60 (2013) 1084-1097.
- [17] M. Manninen, V. Tavassalo, On the mixture models for multiphase flow, VTT Publications, 1996.
- [18] L. Schiller, A. Naumann, VDI Zeits, 1933 M.