STORAGE, MOBILIZATION, AND RETRIEVAL OF VERY HIGH YIELD STRENGTH SLUDGES

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ABSTRACT

The First Generation Magnox Fuel Storage Pond (FGMSP) at Sellafield is an aging facility, containing a significant quantity of Corroded Magnox Sludge (CMS) arising from the corrosion of magnesium alloy clad Magnox reactor fuel in storage. CMS, which arises from corrosion of Magnox fuel element cladding, contains primarily magnesium and uranium corrosion products, and is known to be capable of developing high yield strength over time in a settled and dewatered state.

As part of Sellafield clean-up mission a programme of work is under way to retrieve and process the sludge into a form suitable for long term storage. Approximately 1200m^3 of CMS will be retrieved from various areas of the Magnox Fuel Storage Pond (Figure 1) and hydraulically transferred into 3 Bulk Storage Vessels (BSVs). A power fluidic Pulse Jet Mixer (PJM) system has been specified to manage the sludge bed in the BSVs and assist in mobilization and transfer of the CMS from the BSVs at the end of the interim storage period. This paper discusses the design of the PJM system and the development work funded by Sellafield Ltd on behalf of the UK Nuclear Decommissioning Authority to underpin the design and operational strategy for the PJM system and the BSVs.

1 INTRODUCTION

The First Generation Magnox Fuel Storage Pond (FGMSP) at Sellafield is an ageing facility, containing a significant quantity of Corroded Magnox Sludge (CMS), arising from the corrosion of magnesium alloy clad Magnox reactor fuel in storage. As part of Sellafield clean-up mission a programme of work is under way to retrieve and process the sludge into a form suitable for long term storage. The transfer of the sludge from the pond into modern stainless steel containment, the first stage in this process, is also the subject of an UK NII instruction.

Approximately 1200 m^3 of CMS will be retrieved from various areas of the Magnox Fuel Storage Pond (Figure 1) and hydraulically transferred into 3 Bulk Storage Vessels (BSVs), approximately 30m long x 3m wide x 7m deep each in a purpose built Buffer storage facility on site.

The bed of CMS in each BSV will be up to 4.8m deep and is expected to consolidate with time and depth thereby increasing the yield strength of the sludge. The rate of consolidation in the BSV will depend on properties of the sludge such as particle size distribution and the mode of operation of the Buffer facility. The sludge contains fragments of un-corroded Magnox metal which will corrode, releasing hydrogen and creating weaknesses the sludge bed which will also influence consolidation.

Figure 1: First Generation Magnox Fuel Storage Pond

The sludge will be stored in the BSV's for several years prior to transfer into a Process and Export Plant (PEP) for immobilisation in a containerised concrete matrix product for long term storage and ultimately for geological disposal.

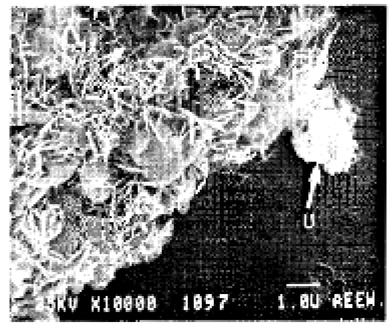
A power fluidic Pulse Jet Mixer (PJM) system has been specified to manage the sludge bed in the BSVs and assist in mobilization and transfer of the CMS from the BSVs to PEP at the end of the interim storage period. This paper discusses the design of the PJM system and the development work ongoing to underpin the design and operational strategy for the BSVs.

2 THE MAGNOX SLUDGE CHALLENGE AT SELLAFIELD

CMS contains primarily magnesium and uranium corrosion products (Figure 2). It will also contain a small percentage of un-corroded Magnox metal as particles up to 6 mm in size, fission and activation products and their corrosion products, aluminium corrosion product (0.8% Al in AL80 Magnox alloy), trace levels of fine carbon particles and traces of wind blown debris e.g. sand and organic material.

Due to its age and history CMS can vary significantly in composition, solids concentration and particle size distribution (PSD) (Figure 3).

Limited data is available on the properties of CMS in the storage pond. Predictions of the properties expected in the BSVs have therefore been generated from indirect information including characterisation work on other Magnox waste streams, desk studies and non-active development work using simulants. Further simulant settling trials, pond sludge sampling and analyses campaigns are also being carried out as part of the current work and several institutions have been engaged to challenge and to reinforce the predictions.



SMALL FUEL PARTICLE ATTACHED TO A HIGHLY CORRODED MAGNOX PARTICLE

Figure 2: Microscopic Image of CMS Particle

CMS can behave as either a rheological fluid or a soil, depending its particle size distribution and water content l. Within soil mechanics terminology the water content at the 'Liquid Limit' is used as the arbitrary transition point between a rheological fluid and a soil, typically at a Yield Stress of 2 to 3 kPa. After an initial hindered settlement period, compressive settling driven by the overburden will dewater and consolidated the CMS bed into settled solid and supernatant fractions. Soil mechanics will dominate the settled bed condition until the material is remobilised and supernate re-incorporated.

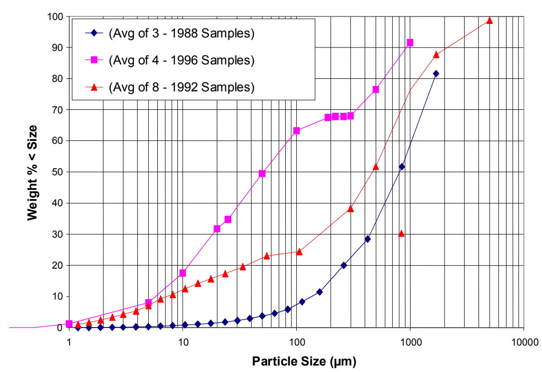


Figure 3: CMS Particle Size Distribution

For development work, the following ranges of material yield or shear strengths have been considered typical of the various zones expected in the BSVs:

- Segregated Very Fine Sludge (notionally <20µm $Mg(OH)_2$) 0 to 10 kPa
- Segregated Granular Sludge (notionally >200µm $Mg(OH)_2$) 20 to 70 kPa
- Intermediate Mixed Zones of Granular and Fine Sludge 10 to 44 kPa

3 PULSE JET MIXER TECHNOLOGY FOR THE BULK STORAGE VESSELS

3.1 Principles of Power Fluidics

Power Fluidic pumps, samplers and mixers have been operating in UK nuclear plants since 1970. The technology is proven across a range of fluidic devices and applications and is well established technology in UK nuclear facilities.

Fluidic mixing, pumping and sampling systems use a gas, generally compressed air, as the motive force for the movement of the liquid. Each system features an air piston or 'pulse tube', a fluid reservoir which is filled or discharged by the evacuation or pressurization of the void space above the liquid level. The control of the air into and out of the pulse tube is accomplished using a Jet Pump Pair (JPP), designated the fluidic system Primary Controller (Figure 4). The JPP comprises two back-to-back ejector elements. Its purpose is to:

- Supply a positive gas flow and pressure to the pulse tube during the drive phase
- Provide a vent path for this gas during the vent
- Produce a partial vacuum in the pulse tube during refill

The internal geometry of the device is specially designed to fulfil these roles.

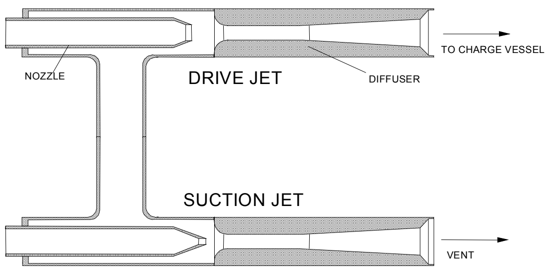


Figure 4: Section through a Jet Pump Pair

The equipment upstream of the Jet Pump Pair is designated the fluidic system Secondary Controller. Its purpose is to:

- Control the duration of the drive phase and to supply compressed air to the "drive" part of the JPP during this phase
- Control the duration of the vent phase and to switch off the air supply to the JPP during this phase
- Control the duration of the refill phase and supply compressed air to the "suction" part of the JPP

The compressed air on/off control is usually accomplished using conventional actuated valves, which only need to handle clean gas and are installed in an accessible position so that maintenance can be performed.

The phase durations are regulated electronically by the Prescon controller. The Prescon (PRESsure CONtrol) system is NuVision Engineering's proprietary method of sensing liquid levels remotely and non-intrusively and is used for the control of Power Fluidic pumping and mixing systems. The Prescon computer both analyzes the input from the process instrumentation and controls the sequencing and operation of the plant. The Prescon controller determines when the pulse tube is full and sets the datum point for the start of each cycle. It accomplishes this by analyzing the pressure signals from the "drive" and "suction" line pressure transducers and is thus totally non-intrusive.

If required the controller can compensate for variations in the system (e.g., changes in liquid level and specific gravity) through signals from in-tank instrumentation so maintaining the fluidic system operation at optimum efficiency. In addition, the Prescon software monitors process loops, checking for drift of pressure transducers, integrity of signal loops and other inputs, and provides a continuous health check on the system. Figure 5 is a schematic of a typical fluidic control system.

3.2 Fluidic Pulse Jet Mixing System Operating Principles

The following are the principal components of a power fluidic PJM system.

Pulse Tube: The Pulse Tube is a pressure vessel that acts as a reservoir to contain the process fluid during the mixing cycle.

Jet Pump Pair: The jet pumps use a compressed air supply to either produce a vacuum or pressure on the contents of the pulse tube.

The Fluidic Control System: Is the method of sensing liquid levels remotely and non-intrusively and is used for the control of Power Fluidics pumping and mixing systems.

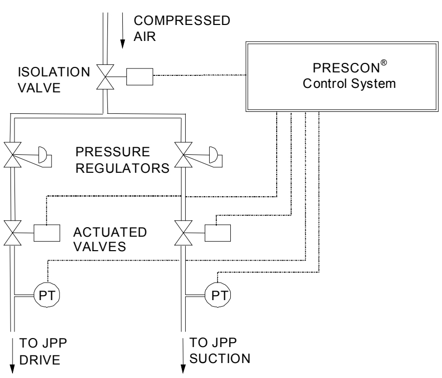


Figure 5: Fluidic Control System

Discharge Nozzle: This nozzle is incorporated into the system at the base of the pulse tube. The pulse tube is filled & discharged through this nozzle.

The pulse jet mixer system mobilizes waste via a three phase mixing process:

- Suction phase
- Drive phase
- Vent phase

Suction Phase: During the suction phase, the jet pumps are used to create a partial vacuum in the pulse tubes, which in turn draws liquid up from the vessel, through the nozzle, and into the pulse tubes (Figure 6).

The suction phase is terminated when the pulse tube is full; this is typically determined using the Prescon detection system.

The jet pumps are located at a height above the pulse jet mixers to provide 'barometric protection' such that vessel contents cannot be sucked into the jet pumps.

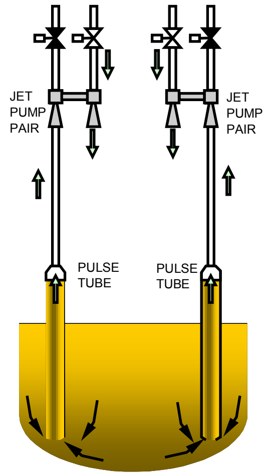


Figure 6: PJM Suction Phase

<u>Drive Phase:</u> Once the pulse tube has been filled with liquid, the jet pumps pressurize the pulse tube, which drives the liquid back into the storage vessel, agitating the contents of the vessel and re-suspending settled solid particulates into the supernatant liquid.

The duration of the drive phase is input into the Prescon controller at the beginning of operations; the value is based on data obtained during commissioning. Note, for SPP1 BSVs, varying drive times will be used to control the mixing energy input to the system (Figure 7).

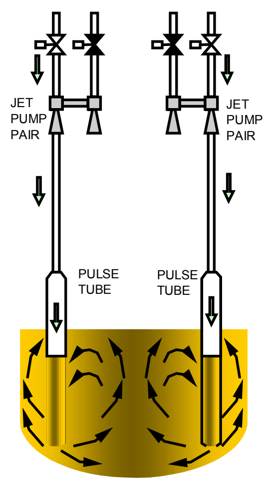


Figure 7: PJM Drive Phase

<u>Vent Phase</u>: When the liquor levels have reached the bottom of the pulse tube, the drive phase is terminated and the pulse tube is depressurized through the jet pumps in the vent phase, whilst the pulse tube partially refills under the hydrostatic head in the vessel (Figure 8).

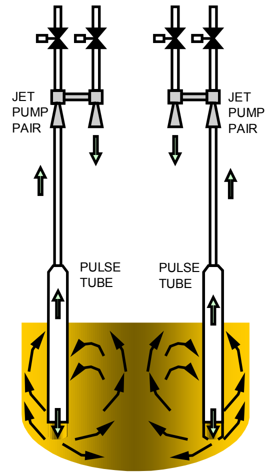


Figure 8: PJM Vent Phase

The mixing process is repeated until the sludge/liquid mixture around the pulse tube nozzle breaks through into the overlaying supernatant liquid. Once this occurs, the cycle is then repeated until the sludge and the supernatant liquid have been mixed/mobilized and/or until the required suspended solids composition is reached.

3.3 PJM Design for the Bulk Storage Vessels

The proposed system for the BSVs comprises 11 pulse tubes per vessel, each with a nominal volume of approximately $4.5m^3$. An internal diameter of 1100mm with an overall height of 5270mm has been selected. Proposed spacing of the pulse tubes is indicated in the Figure 9 below.

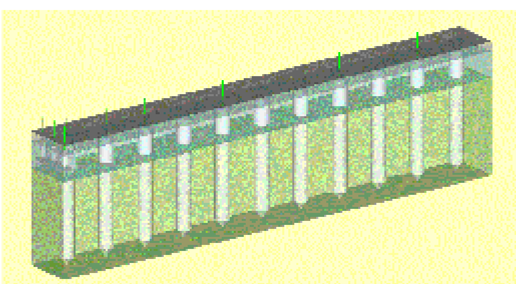


Figure 9: PJM Arrangement in a BSV

Operations in the buffer storage vessels will take place in three distinct phases;

- Filling
- Storage
- Retrieval

each of which has specific requirements relating to the PJM system. However the requirement to be able to operate the PJMs and return the sludge to a mobile condition to facilitate final sludge retrieval is paramount.

The proposed operational strategy in relation to the high yield stress sludges requires the following:

1. Capability to maximize available storage volume in the BSVs by operation of the PJMs to level the bed of sludge
2. Start-up and operation of the PJMs in a high yield stress material (should it develop)
3. Provision of contingencies and recovery options into the system to cope with un-planned circumstances

Detailed design of the PJM system for the BSVs is proceeding in parallel with technology underpinning work.

4 BUFFER STORAGE TECHNOLOGY UNDERPINNING PROJECT

The main aim of the Technology Underpinning Project (TUP) is to underpin and optimise the PJMs and other supplementary in tank sludge handling technologies to manage, retrieve and transfer the stored CMS from the BSVs to the treatment plant. Ultimately this means demonstrating that the technology performance will be robust against a range of expected conditions noting that the scope and duration of development to reduce the technology risk must be balanced against any delays to receipt of sludge from the storage pond.

The scope of the TUP project includes design and operation of scaled test rigs, together with supporting tasks to understand and mitigate the risks related to:

- Improving understanding of the range of possible CMS challenges; CMS characterisation
- Identifying how the CMS behaves and what properties are important at each stage of operation.
- Specifying appropriate test materials and simulants to cover the expected range of challenges.

The development work completed to date is building up an improving picture of the potential ranges of CMS properties and behaviours in the BSV's at different storage depths and durations. This work is also identifying the important properties that affect the ability to mobilise and retrieve the CMS (e.g. permeability and yield stress). The expected challenges range from fine cohesive type to a more granular type material challenge. The CMS condition varying from slurry to a structured soil type with strengths in the 10's of kPa as it consolidates with depth and time. A range of simulants and set ups have been chosen to best match the range of properties and CMS bed challenges expected.

Proof of Principle PJM testing is underway, and further rigs and testing are planned to define the strategy for managing the CMS and the in-tank technology to maximise the benefits and minimise any interventions needed.

Modelling of the PJM performance using CFD was considered as an alternative to, or in support of, rig trials. However the multi-phase properties together with the cyclic nature of the PJM operations, lead to complex behaviours not readily modelled. It may however be possible to develop parametric models and calibrate those models with the results from rig trials and this will be attempted later in the trials programme.

5 BSV BUFFER STORAGE PROOF OF PRINCIPLE TRIALS

5.1 Scope & Objectives

As a key part of the initial work completed under the TUP Project, a series of 'proof of principle' trials were initially undertaken to investigate performance of the PJM technology. These trials were completed on a fast track basis using readily available equipment directed toward 3 main objectives:-

1. To substantiate the design basis operating parameters (up to 2 barg drive pressure and -0.3 barg vacuum) over a range of Test Material Yield Strengths; the target range was 10kPa to 50kPa
2. To determine the conditions under which operation of contingency measures will be required.
3. To demonstrate that PJM operation is consistent and repeatable when operated under the design basis conditions.

A number of separate tests were carried out to investigate PJM performance on sludges at varying starting yield stresses from 10-70kPa. In addition to the main objectives the tests aimed to investigate the range / reach of the PJM jet to verify interaction or ' link-up' of adjacent PJMs in the BSVs. At the time this paper was written, 12 tests had been completed out of a total of 13 to be conducted under the current campaign. Data analysis and interpretation of results for trials 1 – 7 is completed and is discussed in section 6.4.

5.2 TEST RIG

5.2.1 General

The test rig was a fully functioning pulse jet mixer system, comprising a single pulse tube in a test tank assembled in NuVision Engineering's facility in Mooresville, North Carolina. The rig was not designed and built specifically for the purposes of this test programme, but was prototypical and used a mixture of new and existing components close to ½ linear scale relative to the proposed PJM system for the BSVs. The major rig components were:

5.2.2 Test Tank

This was a new polyethylene tank with a capacity of approximately 5,700 litres. The tank had an internal diameter of approximately 1600mm and was 2845mm in height. During the trials, the tank was filled with the test material and supernate to as high a level as possible, leaving only sufficient ullage to accommodate the emptying of the pulse tube during the drive phase; approximately 2.5m depth. Steel strapping bands were placed around the tank circumference in order to limit tank deflection (radial expansion) during the start-up test (Figure 10). The tank girth was measured and recorded during the test to measure any deflection of the tank during start-up. A carbon steel wear plate was installed on the base of the tank, beneath the PJM assembly to protect the base of the plastic tank from erosion. In addition, a "supernate recycling" pump was installed in the test tank to supply clear liquid from the top of the tank into the water injection or 'fluidizing' nozzle (described below).

Figure 10: Proof of Principle Test Rig

5.2.3 Pulse Tube

This was an existing ASME pressure vessel with a capacity of 288 litres. To replicate the proposed BSV design and associated tank internal obstructions, the pulse tube was installed in a frame which was positioned on the base of the test tank (Figure 11). An open 50mm NB flanged nozzle at the base of the pulse tube formed the mixing nozzle. The rig was designed such that the pulse tube nozzle velocity will be approximately 10 m/s (which equates to a drive pressure of approximately 1 barg in the pulse tube). A key feature of the test rig PJM design was a fluidizing nozzle which could be used to pump clean water or supernate directly to the nozzle at the base of the PJM to 'lubricate' the nozzle region and aid mobilization. Water was supplied to the nozzle via a15mm pipe attached to the 50mm diameter nozzle at the base. The pulse tube assembly was held in position by a restraint frame placed over the top of the assembly and anchored to the ground.

5.2.4 Jet Pump Pair

The jet pump pair (JPP) uses the compressed air supply to produce alternating vacuum and pressure on the pulse tube. The diffuser end of the drive jet pump is connected to the pulse tube; and the diffuser end of the suction jet pump was connected to a muffler vented to atmosphere. The inlets to the jet pumps are connected to a compressed air supply from a portable air compressor.

5.2.5 Control System

The control system was a standard fluidic control system with electronic Prescon controller.

Figure 11: Schematic of Pulse Tube and Restraints in Test Tank

5.2.6 Valve Skid and Jet Pump Skid

These were existing skids mainly comprising 50mm air pipework together with the associated valves and instrumentation.

5.2.7 Inspection Camera

A camera was used on the end of a long pole for observation inside the pulse tube. It is shown in the figure below. In order to allow the camera to be readily introduced into the pulse tube, a 'T' piece and ball valve were fitted to the top of the pulse tube.

5.2.8 Load Cells

Load cells were installed in the test rig for Tests #5 to #7 to measure the forces exerted by the PJM on the restraint frame. Four load cells were installed, one in each corner of the support structure. Each one had a capacity of approximately 1000kgf and a resolution of 2kgf. For Tests #5 and #6, the load cells were inserted between the PJM structure and the restraint frame). A bolt in each cell enabled a pre-load to be applied. For Test #7, the PJM support frame was extended vertically and the configuration was changed such that the PJM assembly was suspended from the 4 load cells).

5.2.9 Pump-Out System

Test tank pump-outs were conducted from tests #2 onwards. A diaphragm pump was connected to a 25mm diameter plastic suction pipe located in the test tank.

5.2.10 Supernate Replacement System

For Test #7, tests were conducted in which the slurry at the top of the tank was decanted into a separate receipt tank and clear water was then added to the test to restore the original liquid level. Decanting was accomplished via gravity flow through a 25mm transfer line installed in the test tank just above the sludge level. The slurry in the receipt tank was allowed to gravity settle. A pump installed in the top of the receipt tank was used to pump the clear water back into the test tank.

5.2.11 Water Jetting Equipment

Jetting tests were conducted prior to the commencement of mobilization Test #6 and #7. A test pipe was suspended in the test tank; the bottom of the pipe was suspended a pre-set offset distance) above the sludge surface.

Water was supplied into the test pipe via the pulse tube / Jet pump arrangement described above. The pipework was arranged in a manifold at the top of the test tank such that:

- The pulse tube could be refilled on each cycle with relatively clean water from the top of the test tank
- The manifold could easily be moved around the top of the tank such that each test could be started above an undisturbed section of sludge

The depth of the top of the sludge before and after each test was measured using a "plumb-bob".

5.2.12 Measuring Instrumentation

A Vane Shear Tester was used to direct readings of yield or shear strength in the test tank at depths up to 3 meters. Three vane sizes allow for the direct determination of undrained shear strength of soft to stiff clays. A specific gravity cup was used in conjunction with a weigh scale to measure slurry specific gravity.

6 TEST MATERIALS

6.1 Test Material Constituents

Principal test material constituents (Figure 12) were as follows:-

Versamag
(trade name) - precipitated fine white magnesium hydroxide.

Hydromag G(s)
(trade name) - magnesium hydroxide in pellet form.

Crushed Slate
Crushed slate with a particle size ranging 0-4mm.

Figure 12: Test Material Constituents

6.2 Test Material Recipe

The test material was prepared using a Sellafield Limited prescribed formulation :-

	Percentage by Weight
Versamag	55.7%
Hydromag	36.0 %
Slate	8.3%
	100.0%

Mixing the above solids with water formed the basic test material; the amount of water added to the solids determined the final Yield Strength (Figure 13).

Initially test material was prepared using all fresh constituents; however used test material was also 'recycled' by air drying to a cake form in settling beds and manually re-crushing.

6.2 Measuring Instrumentation

A Vane Shear Tester was used to direct readings of shear strength to depths up to 3 meters. Three vane sizes allow for the direct determination of undrained shear strength of soft to stiff clays. A specific gravity cup was used in conjunction with a weigh scale to measure slurry specific gravity.

6.3 TEST PROTOCOL

6.3.1 Test Material Preparation

Bench scale trials were conducted with the recycled test material several days prior to mixing a tank charge to establish the exact recipe required to achieve the target yield strength values. Batches of sludge test material were prepared using commercial mortar mixers. Approximately 40-50 batches were required for each test. The pulse tube and the test tank were filled with either sludge or slurry up to the same level. It was anticipated that when the tank was filled, the test material would not flow into the pulse tube, hence the pulse tube was filled separately through the top opening. When all of the sludge has been added to the test tank & pulse tube, a small amount (1"-2") of water was added on top to prevent dry-out. After filling, the sludge in the tank and the pulse tube was left for a period of several days for the yield strength of the test material to fully develop.

Figure 13: Mixed Test Material

6.3.2 Test Procedure

A successful start-up was defined as one in which sludge and supernate are expelled from the pulse tube during a drive phase. A failed start-up is one in which either nothing or only supernate is expelled. The effectiveness of a drive phase was determined by a combination of visual observation of movement in the tank, tank level variations and camera inspection inside the pulse tube. The steps in each trial were:

1. Apply a 1 barg (drive pressure) / -0.3 barg (vacuum) cycle for up to 50 cycles. If start-up is successful, go to step (5).
2. Apply a 2 barg (drive pressure) / -0.3 barg (vacuum) cycle for up to 50 cycles. If start-up is successful, go to step (5).
3. Apply a 1 barg (drive pressure) / -0.3 barg (vacuum) cycle with fluidizing water for up to 50 cycles. If start-up is successful, go to step (5).
4. Apply a 2 barg (drive pressure) / -0.3 barg (vacuum) cycle with fluidizing water for up to 50 cycles. If start-up is successful, go to step (5).
5. After successful start up, continuously operate the system with a 1 barg drive pressure and a -0.3 barg vacuum for a period of 10 days (24 hours per day).

If, at any time during the continuous operating period, the pulse tube did not empty during drive or fill during suction, supernate" was injected via the fluidizing nozzle until normal operations were resumed. Monitoring of the PJMs suction time was used as an indication of the need to add fluidizing water.

If either of the following conditions existed, then the vacuum level in the pulse tube was increased, i.e.

- None of the start-up trials in 1 to 4 above were successful

- During the continuous operating period, it is found that excessive fluidizing water needs to be added in order to maintain PJM operation.

6.3.3 Yield Strength Measurements

On a daily basis, the shear vane was used to measure the yield strength of the test material (Figure 14):

- At 4 circumferential positions throughout the depth of the tank
- At radial positions along the base of the tank in order to determine the range of effectiveness of the jet.

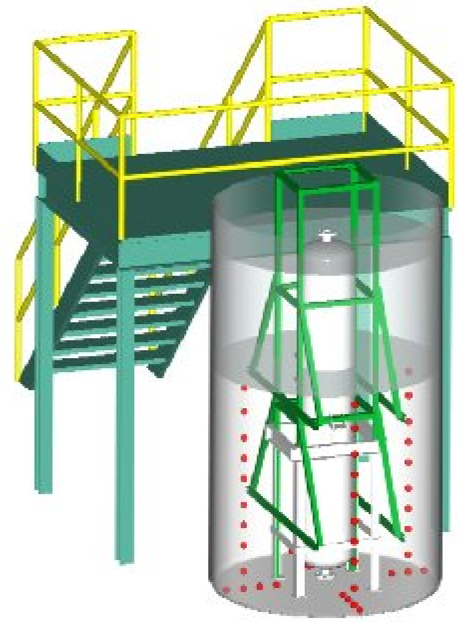


Figure 14: Yield Strength Measurement Locations in Test Tank

6.3.4 Test Measurements & Records

The following methods of measuring and recording results were employed during the trials as described below:

(a) Yield Strength measurements of the tank contents using a Shear Vane
(b) Visual observation in the test tank
(c) Manual probing in the test tank to determine sludge levels & locations etc
(d) Storage of operating parameters (pressures and cycle times) via the Prescon PC controller
(e) Tank deflection measurement during start-up
(f) Fluidizing nozzle flow rate and duration
(g) Video record of the trials

6.4 TEST RESULTS & CONCLUSIONS

At the time of preparation of this paper, data analysis and interpretation of results for trials 1 – 7 only had been completed and is discussed below.

6.4.1 Start-up Performance

The start up procedure for each of the trials was designed to progressively implement strategies of increasing the pulse tube drive pressure (up to 2 barg) followed by the application of fluidizing water. Trials #1 to #4 inclusive commenced each test with the pulse tube filled with sludge, whereas the pulse tube was initially filled with slurry (~ SG=1.2) for Trials #5 to #7.

It was found that the first two trials (20kPa & 40 kPa test materials) started immediately with 1 barg drive pressure. Some difficulty was encountered in the start-up of Test #3 (50kPa test material) however, by using 2 barg drive pressure together with the fluidizing nozzle, successful start-up was achieved. Some difficulty was encountered with start-up of Test #4 (10 kPa test material) whereby the PJM could drive successfully but would not then refill. It is believed that this was due to the sludge slumping to the PJM nozzle. However successful start up was achieved with the application of fluidizing water together with the application of -0.3 barg suction to the PJM. The system started successfully on the first drive phase in Trials #5 (50 kPa), #6 (10kPa) and #7(10kPa). It is believed that this was largely due to the presence of a slurry, rather than high yield strength (YS) sludge in the pulse tube.

6.4.2 Continuous Operation Performance

One objective of the trials was to verify the design operating parameters of up to 2 barg drive pressure and -0.3 barg vacuum. All trials successfully operated at these pressures, amassing a total of 326,745 operating cycles during 2828 operating hours. The only difficulties encountered were immediately after surface breakthrough in certain trials, when system operation was not consistent and difficulty was encountered sporadically in either emptying or refilling the pulse tube. In such cases the fluidizing nozzle was operated for approximately 100 cycles and this was successful in promoting stable and consistent operation. This result demonstrated the effectiveness of this proposed recovery strategy i.e. utilising the fluidizing nozzle to overcome any problems encountered with high yield strength material.

6.4.3 Progressive Yield Strength Reduction

During all trials the progressive reduction in test material yield strength, particularly along the base of the tank, and the implications for linkup between adjacent PJMs in the SPP1-BST vessels was closely studied. This was achieved through daily yield strength measurements at specific positions along the tank base (Figure 15). In general, interpretation of the data on a daily basis was difficult because of the variability in the yield strength throughout the sludge bed. If a particular yield strength measurement fell from one day to the next then this could mean:

a) the PJM had been successful in reducing the YS of the test material in that area

or

b) the reading was taken in a different location, i.e. it was a measurement of a different volume of test material which happened to have a lower YS

or

c) the reading was taken in exactly the same area as on the previous day and the presence of the disturbed material gave a low reading (the probability of this occurring is fairly low).

Similarly if a yield strength measurement increased from one day to the next then this could mean:

a) there had been bulk movement of test material, a batch of higher YS test material had moved into an area previously occupied by lower YS test material

or

b) the reading was taken in a different location – same as option (b) above.

It should be noted that test material settling alone is not a plausible explanation for an increase in YS measurements from day to day, as initial strength generation depends largely upon the process of hydration of the dry test material rather than settling effects.

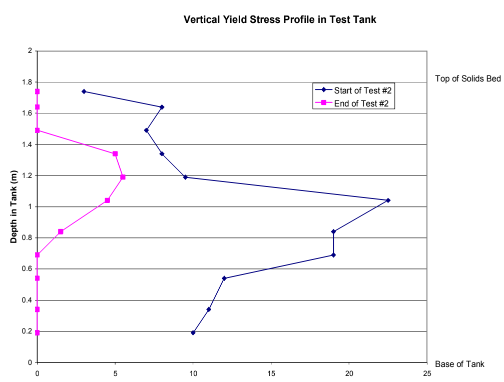


Figure 15: Progressive Yield Strength Reduction in Test Tank from PJM Operation

6.5 CONCLUSIONS OF PROOF OF PRINCIPLE TRIALS 1 THROUGH 7

Initial bench scale trials with the test material had indicated that:

- Applying shear alone to the test material will not reduce a yield strength measured in kilopascals down to the pumpable range (hundreds of Pascals)
- Dilution with water has a large, rapid impact on reducing yield strength.
- Dilution with supernate of SG=1.2 or greater has a smaller, slower impact on reducing yield strength
- Without agitation, the rate of absorption of diluent by the test material is slow and appears to be confined to the (~25mm thick) layer which is in contact with the diluent.
- Using a solvent (in this case pH 11.5 diluent) instead of tap-water had no discernable effect.

In all test rig trials, start-up occurred successfully at 1 or 2 barg drive pressure, in some cases together with the application of fluidizing water. In trials #5-#7 (10kPa and 50kPa yield strength), the pulse tube was initially filled with slurry and start-up occurred successfully, without intervention.

The PJM system successfully operated for a total of 2828 operating hours (326,745 cycles) at the design base operating pressures of 1 barg drive and -0.3 barg suction.

It was determined that the majority of yield strength reduction occurs within the first 2-3 days of pulse tube operation. After that time, the "supernate" is at (or close to) being saturated with solids and at a steady state SG so further dilution is slow.

Operating the fluidizing nozzle with fresh water had an impact on reducing test material yield strength in the tank. Operating the fluidizing nozzle with 'saturated' supernate (SG=1.2) had no apparent impact on yield strength reduction.

Increasing PJM nozzle velocity from the design basis of 10m/s to 15m/s had no apparent impact on yield strength reduction.

Operating a regime of pumping out all mobile material and replacing this with fresh water accelerated yield strength reduction in the bed and facilitated removal of approximately 97% of the original test material in each trial where this method was adopted. In essence operating to mimic the much higher volumes of supernate available for mobilisation in the actual BSVs had a significant impact on yield strength reduction.

Although data from trials 8-12 had not been processed at the time of publication of this paper, the results obtained were also consistent with the above conclusions.

7 SUMMARY AND WAY FORWARD

7.1 GENERAL

Characterisation work to better understand the likely behaviour and properties of CMS is continuing.

Rig trials and associated support work to-date to develop operating envelope and operating strategies for the PJMs has been very successful in developing confidence and needs of the system. The key conclusions from the trials conducted to date are:-

- It has been shown that addition of water injection to the nozzle of each PJM is essential to cover all possible conditions.
- A regime of PJM mobilization combined with regular pump-outs and addition of make up water successfully and repeatedly emptied the test rig.

Future work will focus on developing more representative models to better define understanding of how mobilisation will proceed in the BSVs. This will require:-

- Purpose designed and built, ¼ and ½ scaled multiple PJM rigs. Generally Scale rigs will help to underpin design, better define capacities and develop operating strategies.
- Scaling studies to increase confidence in relating the results of rig trials to actual performance in the BSVs.
- Continued operation of the basic proof of principle rig, which allows typical test material challenges to be put against PJM system and is still expected to generate valuable basic intelligence on start-up and mobilisation performance and issues.

7.2 NEW ¼ & ½ SCALE TEST RIGS

The information obtained from the proof of principle trials provided basic confidence in the fundamental performance of the PJM technology. However the TUP project identified that new, more representative scale test rigs were required to further underpin the performance of the proposed PJM system and establish guidance for scale up of observed performance to the full scale system in the BSVs. Purpose designed and built test rigs at ¼ and ½ scale are now being designed and built to Sellafield Limited specification. The rigs will possess the following advantages over the current proof of principle test rig, including:-

- More representative design features and scaling
- Multiple (3 each) PJMs
- Transfer eductors (extract pumps) working in conjunction with PJMs
- Rectangular test tank (same basic geometry as BSVs)
- Facility to increase tank depth (and sludge head)
- Comprehensive instrumentation & monitoring
- Can accommodate alternative test materials including inactive CMS

Use of two rigs at different scales will help develop scale up relationships and underpin projections of real plant capabilities at full scale. A small scale rig maximises the number of trials that can be undertaken and allows inactive CMS (which is in short supply and difficult to manufacture) to be used and compared with other chemical simulants. For the larger rig, size is limited by practical operational and schedule considerations. Half geometric scale approaches the practical limit whilst allowing sufficient trials to be done in the time available before plant commissioning.

The option of a full scale test rig has been fully evaluated and concept designs produced however is unlikely to be pursued. The logistical challenges of conducting tests at full scale and the timescales for individual tests are considerable so the data generated is likely to be of limited additional technical value in predicting plant performance and operating strategies at full scale, particularly when taking account of the variability and uncertainties in sludge properties.

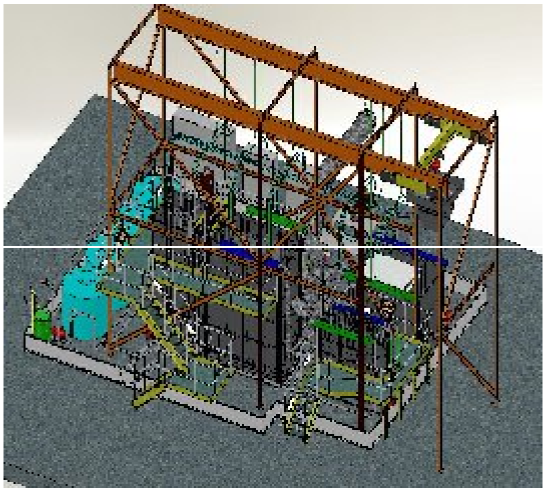


Figure 16: Schematic of Planned BSV ¼ & ½ Scale Test Rigs

Following commissioning of the new rigs it is planned to:-

- Operate ¼ scale rig with both inactive CMS and VCHG - gives a comparison of performance with different materials at the same scale.
- Operate ½ scale rig with VCHG - gives a comparison of different scales with the same test material.
- Use the scale rigs to further underpin design and develop operating strategies.
- Testing of contingencies and recovery options

The new rigs will be installed, commissioned and operated in a test facility in the UK in late 2010 (Figure 16).