

Fuel Pond Sludge -- Lessons Learned from Initial Desludging of Sellafield's Pile Fuel Storage Pond- 12066

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ABSTRACT

INTRODUCTION

The Pile Fuel Storage Pond (PFSP) at Sellafield was built and commissioned between the late 1940s and early 1950s as a storage and cooling facility for irradiated fuel and isotopes from the two Windscale Pile reactors. The pond was linked via submerged water ducts to each reactor, where fuel and isotopes were discharged into skips for transfer along the duct to the pond. In the pond the fuel was cooled then decanned underwater prior to export for reprocessing.

The plant operated successfully until it was taken out of operation in 1962 when the First Magnox Fuel Storage Pond took over fuel storage and decanning operations on the site. The pond was then used for storage of miscellaneous Intermediate Level Waste (ILW) and fuel from the UK's Nuclear Programme for which no defined disposal route was available. By the mid 1970s the import of waste ceased and the plant, with its inventory, was placed into a passive care and maintenance regime.

By the mid 1990s, driven by the age of the facility and concern over the potential challenge to dispose of the various wastes and fuels being stored, the plant operator initiated a programme of work to remediate the facility. This programme is split into a number of key phases targeted at sustained reduction in the hazard associated with the pond, these include:

Pond Preparation

Before any remediation work could start the condition of the pond had to be transformed from a passive store to a plant capable of complex retrieval operations. This work included plant and equipment upgrades, removal of redundant structures and the provision of a effluent treatment plant for removing particulate and dissolved activity from the pond water.

Canned Fuel Retrieval

Removal of canned fuel, including oxide and carbide fuels, is the highest priority within the programme. Handling and export equipment required to remove the canned fuel from the pond has been provided and treatment routes developed utilising existing site facilities to allow the fuel to be reprocessed or conditioned for long term storage.

Sludge Retrieval

In excess of 300 m³ of sludge has accumulated in the pond over many years and is made up of debris arising from fuel and metallic corrosion, wind blown debris and bio-organic materials.

The Sludge Retrieval Project has provided the equipment necessary to retrieve the sludge, including skip washer and tipper machines for clearing sludge from the pond skips, equipment for clearing sludge from the pond floor and bays, along with an 'in pond' corral for interim storage of retrieved sludge.

Two further projects are providing new plant processing routes, which will initially store and eventually passivate the sludge.

Metal Fuel Retrieval

Metal Fuel from early Windscale Pile operations and various other sources is stored within the pond; the fuel varies considerably in both form and condition. A retrieval project is planned which will provide fuel handling, conditioning, sentencing and export equipment required to remove the metal fuel from the pond for export to on site facilities for interim storage and disposal.

Solid Waste Retrieval

A final retrieval project will provide methods for handling, retrieval, packaging and export of the remaining solid Intermediate Level Waste within the pond. This includes residual metal fuel pieces, fuel cladding (Magnox, aluminium and zircaloy), isotope cartridges, reactor furniture, and miscellaneous activated and contaminated items. Each of the waste streams requires conditioning to allow it to be and disposed of via one of the site treatment plants.

Pond Dewatering and Dismantling

Delivery of the above projects will allow operations to progressively remove the radiological inventory, thereby reducing the hazard/risk posed by the plant. This will then allow subsequent dewatering of the pond and dismantling of the structure.

A graphical illustration the programme structure is shown in figure 1.

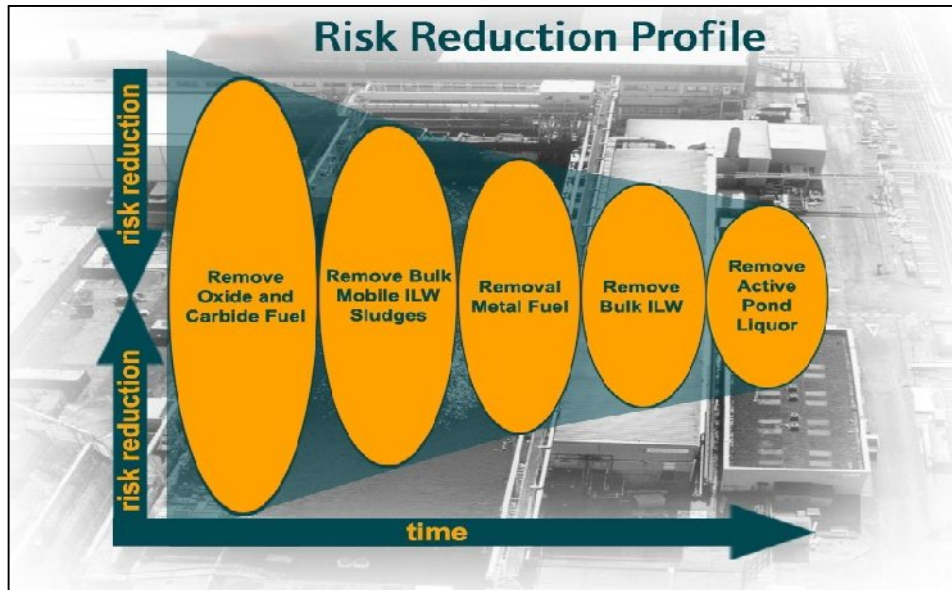


Figure 1. Graphical Representation of PFSP Remediation Strategy

SLUDGE RETRIEVAL

Operation of the pond, which is open to the environment, has led to the gradual accumulation of in excess of between 300 m³ of sludge in both the bottom of the pond and within skips. The sludge generally consists of inorganic material such as debris from fuel and metal corrosion, wind blown debris, and bio-organic materials such as algae and bird guano.

Removal of the accumulated sludge is a priority for cleaning up the Pile Fuel Storage Pond as it is a mobile waste form, and prevents effective characterisation and retrieval of the other wastes. To facilitate sludge removal, three interconnected projects have been initiated; a retrievals project to clear sludge from the pond, an interim storage facility (Local Sludge Treatment Plant), and finally, a project to provide a passivation process to packaging the sludge for long term storage.

Sludge Retrieval Project

Sludge has collected in three distinct areas; the first of these are the pond bays, where fuel was decanned and exported for reprocessing. The second area is within the pond skips used for storing inventory, this sludge has been found to have a higher concentration of corrosion product. Thirdly, sludge has accumulated on the pond floor, this is generally organic material and wind blown debris. Retrieval of sludge from each of these areas presents different challenges and required different retrieval technology to be developed and implemented.

Bay Desludging

The plant has twelve wet bays, originally used for the decanning process; the bays are very congested with redundant machinery from these operations. The bays contain

sludge which is relatively rich in corrosion products from the debris left behind from decanning operations.

A process has been deployed, which takes advantage of the hydraulic linking of pairs of bays, it creates a current within each pair of bays that will carry mobilised sludge into the main pond, from where it can be retrieved with other pond floor sludge to the corral. This is achieved by placing a pump (figure 2) at the entrance to one of the bays and drawing water from the pond through the U-shaped pair of bays and forcing it back into the pond. Once the through current is established the sludge bed is disturbed using water lances forcing the sludge into the flow and out of the bay.



Figure. 2 Bay desludging operations

The bay desludging equipment has now been deployed on six of the twelve wet bays and has removed the bulk sludge from these bays. Once the bays are desludged blanking plates are fitted on the bay doors which prevent migration of sludge back from the pond.

Pond Skip Desludging

At the start of the remediation programme the pond contained approximately 180 fuel skips. The skips are arranged in a matrix on the pond floor and contain a variety of miscellaneous ILW and fuel. Sludge has accumulated in the skips due to a combination of corrosion of the skip contents, and from organic material and wind blown debris which has settled onto the skips. The sludge has to be removed from the pond skips, not only because it forms a significant proportion of the overall inventory, but also to clean skips for export. Removing cleaned skips from the pond is a key part of the desludging strategy as it creates space on the pond floor, enabling the sludge to be retrieved more easily. The project has to date removed around 30 skips; all of which have been cleaned sufficiently for disposal as low level waste (LLW).

To enable skip desludging a skip washing machine and a skip tipping machine have been developed and installed into the pond (figure 3). Each of the skips, measuring 1.8m by 2.1m by 1.5m are transported to the skip washing machine. Sludge is then washed from the internals of the skip and pumped to the in-pond corral using a hydraulic resuspension technique where recirculated pond water is jetted onto the

sludge bed within the skip gradually entraining the sludge. The washed skip is then transferred to the skip tipping machine where any solid debris is removed and consolidated into a single skip. The externals of the skip are then washed and the skip exported. Skips not suitable for export are washed and returned to the pond without tipping, the project has washed sludge from a further 30 skips; this means 33% of the pond skips have now been desludged.

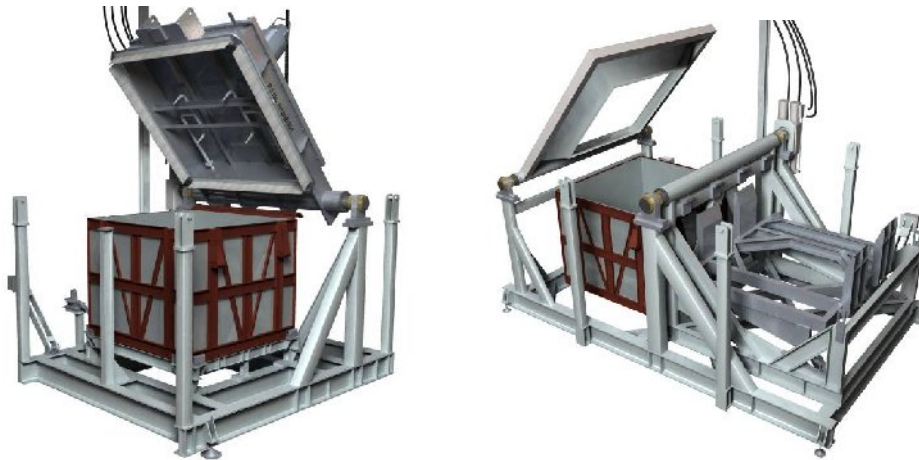


Figure 3 Skip Wash and Skip Tipping machines

Pond Floor Desludging

Pond floor desludging is again achieved mainly using a hydraulic resuspension technique. A large desludging hood (figure 4.) is placed in the area of the pond to be desludged and recovers the sludge using a similar method to that used by the skip washer. The desludging hood is transported around the pond by the skip handler machine and transfers sludge to the corral via a tensioned umbilical system which prevents the skip handler becoming entangled with the sludge transfer lines. The sludge hood has been effectively deployed to clear the first 64m² of pond floor; floor clearing performance has been very good with a single pass generally successful in clearing all material. However collecting the sludge cleared from these areas has proved problematic as described later.

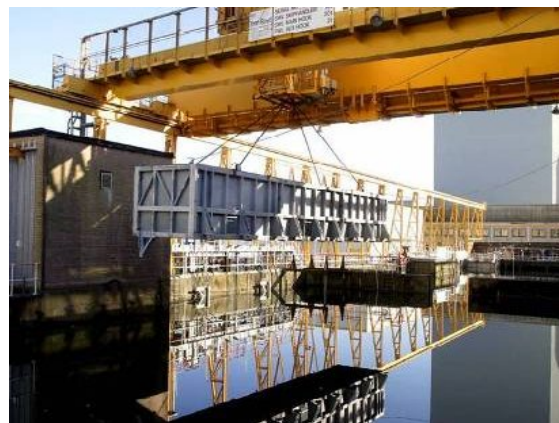


Figure 4. Installation of the sludge hood

Figure 5. Installation of corral

While the pond floor desludging hood is ideal for clearing large open areas of pond and does an extremely thorough job, a number of other devices have been provided to collect sludge from more inaccessible areas such as corners or under platforms. These include a Remote Operated Vehicle (ROV) with a plough and eductor to retrieve the sludge. Initial operation of the ROV identified that without agitation the eductor would not remove the sludge from the pond floor and the system had to be modified to include an agitation head, since this modification the system has successfully desludged half of the planned areas, with the remainder planned for completion in the next 12 months.

'In Pond' Corral

The retrievals project has provided an in pond corral to both, divorce the sludge retrieval programme from the provision of the storage plant and therefore allow an early start to desludging; the corral also reduces the size and complexity of the storage plant by concentrating sludge and allowing transfer at higher average solids content.

This initial thickening, from less than 0.01% wt from the retrieval devices to a 5%wt target from the corral, massively reduces the volumes of liquor that need to be handled by the storage plant and therefore dramatically reduce its size. The corral itself has a capacity of nearly 100m³ which allows a significant volume of sludge to be collected from the pond before transfers to the storage plant begin.

Based on characterisation data, the design of the corral was such that all of the sludge transferred it would settle in it as the residence time in the corral was much greater than the settling time required. Early operations of the skip wash machine and ROV supported this design with sludge being accumulated in the bottom of the corral. However when operation of the floor desludging hood commenced the expected accumulation of sludge in the corral was not achieved. The research and development work that was carried out to understand this issue is the subject of the main body of this paper.

Local Sludge Treatment Plant Storage and Export Projects

The Pile Fuel Storage Pond Local Sludge Treatment Plant (LSTP) provides the facilities to store, and eventually passivate the sludge by encapsulation. The plant is being delivered in two phases; the first phase provides the modern stainless steel storage tanks for containment of the sludge retrieved from the pond, the second will provide capability to condition the sludge for long term storage.

The storage plant is currently in the advanced stages of commissioning, while the project to provide the conditioning capability is reviewing options for treating the sludge. While it is highly likely that the sludge will be encapsulated in cement to generate a waste form suitable for long term storage, a number of options for providing this capability are being considered.

While these projects may well be impacted by the changes in expected sludge behaviour observed in the corral, the impacts and lessons are similar so they are not discussed further in this paper.

OPERATIONAL EXPERIENCE OF CORRAL OPERATIONS

The pond desludging campaign began with the operation of the ROV and skip washing machine, these operations appeared successful with sludge being removed from skips and pond floor and appearing to accumulate in the corral.

Direct accountability of retrieved and collected sludge is problematic for a number of reasons; firstly, the volume of sludge present in any area of the pond before retrieval is difficult to estimate as the bed is not uniform in either depth or characterisation. Secondly the volume collected in the corral is also difficult to measure as the sludge bed does not settle uniformly and will change as the retrieved sludge settles and consolidates. However, despite this lack of direct correlation of retrieved and collected sludge volumes, no indication that the corral would not hold the sludge occurred during these initial operations.

In early 2011 the plant began to operate the pond floor desludging hood to clear the pond floor; this device provides vigorous hydraulic agitation to lift sludge from the pond floor and transfer it to the corral. Pond floor clearing continued until completion of the first planned area, where the volume of sludge in the corral was expected to be around 40m³; However, during sludge hood operations the corral became extremely cloudy with suspended solids and sludge was observed passing over the corral weir and back into the pond. The corral clarified over the subsequent weeks but the sludge volume in the corral appeared to be much lower than expected; subsequent measurement indicated that only around 10m³ of sludge had been collected in the corral.

Following these observations it was decided to proceed as if each desludging operation was a specific experiment. A number of trial desludging operations using each of the desludging devices have been undertaken. Each retrieval device operates differently in terms of flow rate, wash cycle times and the type of sludge material. This data was used to develop a number of operating and process control regimes intended to mitigate any loss of sludge over the weir.

In the period up to November 2011 a further 30m³ of sludge has been transferred to the corral; however the volume of sludge in the corral remained at approximately 10m³, much less than was expected. Figure 6 shows the sludge level variability measured in the corral during the period of trial operations, and the sludge retrieval device in operation at the time of measurement. The figure shows that the behaviour is far from predictable.

The reasons for this observed variation in performance of the corral in capturing sludge are being investigated and are described below. There are a number of possible hypotheses for explaining the observed behaviour and explaining what has happened to the sludge.

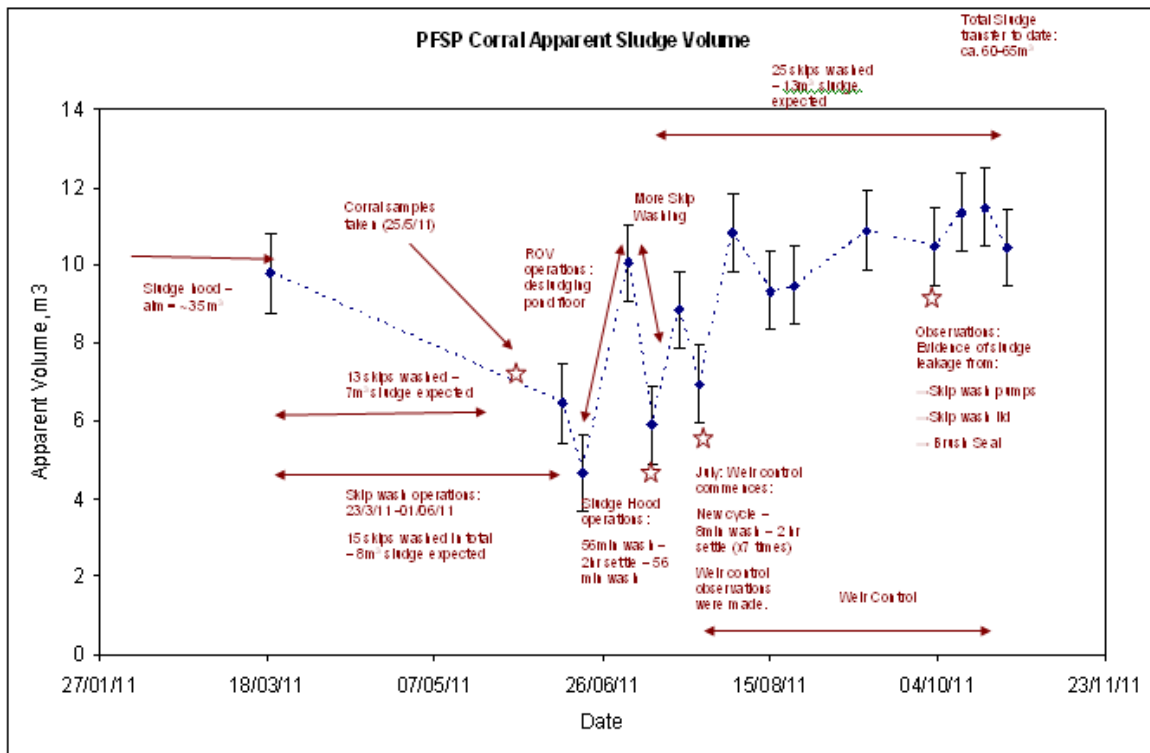


Figure 6. Sludge levels in the corral during 2011

What happened to the sludge?

It is important to note that the sludge has not been discharged into the environment, the pond discharges via a Local Effluent Treatment Plant which is carefully monitored and it is clear that the sludge has not entered this system.

A programme of technical investigation and careful plant observation was undertaken during 2011 to assess these hypotheses:

- Sludge Accountancy:
 - Corral sludge level monitoring
 - Pond sludge level monitoring and camera investigations
 - Weir control
- Corral sampling and analysis for physical, chemical and radiochemical properties
- Computational Fluid Dynamics (CFD) modelling the corral performance

Sludge Accountancy

There have been two approaches in establishing the sludge level within the corral. The first of which is to use a simple dipstick measurement. This involves a calibrated stick and CCTV camera, which enables the operator to assess the sludge level. Here measurements were taken along the length of the corral, which allowed the sludge depth profile to be trended; from this data a volume of sludge in the corral was estimated. Sonar measurement has also been used in an attempt to profile the sludge

bed. There are issues associated with both of these techniques, for example the interpretation of the sonar signal response and how this applies to PFSP sludge. The dipstick technique brings with it issues to do with deployment and measurement reliability in low visibility conditions. Ultimately, the sonar measurements were used as a comparative measure against the dip measurements, and it was found that both techniques produced similar results and confirmed that the sludge levels in the corral were much lower than expected

The sludge levels within the pond were also monitored to confirm there had been no gross underestimation of the original sludge volumes. In March 2011 approximately 40 dip measurements of the pond have been taken and compared with the original 80 measurements taken in 2005, other than areas where sludge clearance had taken place, these show no significant difference in levels before and after sludge was moved into the corral. This evidence supports the conclusion the original sludge inventory had not been overestimated but did not have a sufficient level of precision to confirm whether the missing sludge had been distributed across the remainder of the sludge bed. Observed sludge in the cleared areas was also not at sufficient depth to conclude whether or not it had returned from the corral or resulted from fresh algae growth or general redistribution of sludge in the pond.

Is the sludge being retrieved?

It is important to firstly assess whether or not the sludge was in fact retrieved and transferred to the corral then determine whether or not it is captured within the corral.

Skip wash machine

Although the skip wash machine has been cleaning the skips very well investigation into how much of the sludge that is being removed from skip is actually being transferred to the corral and how much is being lost through leak paths back into the pond was considered prudent.

The hoods are sealed using brushes to the pond floor or to the skip, and the brush seal is not designed to provide a total seal between the wash machine and the skip; its purpose is simply to provide an inflow path for pond water to replace transferred sludge and water. The inflow of pond water through the seal to replace material transferred to the corral is designed to ensure that sludge remains in the hood by creating a positive inflow. While this is generally the case, there is a relatively aggressive, violent flow in a small space in the hood with the potential to create localised back pressure and push material out of the brush seals.

Other identified leak paths include, engineered flush systems designed to protect the pump bearings and seals from dirt and debris by continuous flushing with process liquor.

If a more pessimistic estimate of the volume potentially lost from these leak paths is made this could explain about 5-10m³ of the total skip wash sludge volume, however this is not supported by a significant build up of sludge around the machine.

Sludge hood and ROV

Plant trials have been undertaken to understand the cleaning efficiency for the ROV and sludge hood. This has involved visual observations in positioning the ROV and sludge hood, observations during sludge retrieval and observations of the cleaned pond floor. This work has indicated that when properly positioned, sludge does not seem to leak from the sludge hood or ROV, and provides confidence that the sludge is transferred to the corral.

Weir Observations

As indicated previously, some sludge has been seen to overflow the weir and back into the pond to recover previously cleared areas. This indicates a mismatch between the residence time and the settling rate of the material within the corral. To mitigate these observations a process control concept of weir control was developed. In the absence of instrumentation and to enable plant trials to continue, a management control procedure was instigated requiring the operators to observe the weir and cease operations before a net flow out of sludge was observed. While the plant operators could successfully operate equipment using this method it did not result in any significant increase in corral volume, it is therefore difficult to attribute all of the loss of volume to losses over the weir.

Corral sampling and analysis

Sampling of the corral took place in May 2011 (fig.7.), from this chemical, physical and radiological analysis has taken place. The results of which have been compared with previous work which was used as the basis of design for the retrieval equipment.



Figure 7. Sampling Corral May 2011.

The following table details the results of the chemical, radiological and physical analysis:

Red	significant issue	corral sludge sample data significantly different from design basis
Orange	potential issue	corral sludge sample data different from design basis; may have an impact on corral performance
Green	OK	while there might be a difference it is small enough to have made little or no difference to corral performance

Property	Basis of Design	May 2011 Corral Samples
Physical:		
Solids content of wet sludge	10 wt %	12 wt %
Density of wet sludge	1.06 g/cm ³	1.07 g/cm ³
Density of the particulate solids in the sample	2.2 g/cm ³	2.2 g/cm ³
Particle sizes (microns)		
10% below	8	9
50% below	58	30
90% below	1000	206
Settling velocities	78 cm/hr @~4 wt%	30 cm/hr @~4wt%
Chemical Content, µg/ml wet sludge	Average for pond and skips	
Pu	14	8
U	5000	8901
Na	700	83
Ca	7650	2692
K	350	59
Mg	23500	10850
Fe	66500	8724
Al	9750	2557
Si	358	Not yet reported
C (TOC)	12500	576
Pb	500	322
Zn	3750	2354
Radiochemical Content	Alpha ~9,000 Bq/g wet for pond ~110,000 Bq/g wet for skips and bays Beta ~80,000 Bq/g wet for pond ~900,000 Bq/g wet for skips and bays	Alpha ~37,000 Bq/g wet Beta ~300,000 Bq/g wet

Figure 8. Chemical, Physical and Radiological Analysis

The analysis of the 4 corral samples is almost complete. Previous pond sludge samples would split into two phases: an organic layer and a gritty inorganic layer. The organic layer has a low density and a low solids concentration. However, it forms a large portion of the sludge by volume – around 90%. The most significant difference between the corral samples and the original basis of design feed specification is that the corral sample has a very low organic carbon content (1-2 % by mass c.f. the pond sludge which is 10-20 % organic carbon by mass). The loss of 90-95% of the organic matter by mass equates to 9-10% of the dry solids in the sludge. However, this equates to 80-90% of the sludge by volume.

Based on the operations and samples taken at the end of May, it suggests that the system as a whole (hydraulic retrieval, transport and corral settlement) is separating the light, poor settling organic material from the heavy, readily settling inorganic materials.

Whilst there is the potential for changes in other properties such as density, given the corral depths are low, the effects of deep bed consolidation may not be observed yet.

This result appears to align with plant volume observations and measurements. Up to taking the samples in May about 50 m³ was assessed to be transferred to the corral, however only about 5 m³ was measured in the corral; a loss of about 90%.

Notwithstanding the fact that retrieval operations post sampling were changed with the introduction of weir control. Extrapolating to current date, it is estimated that sludge retrieval has transferred approximately 70 m³ of sludge to the corral and approximately 10 m³ has been retained; a loss of 86%. Thus there is a question about where this organic fraction has potentially gone, for example, has it gone back to the pond or has it been destroyed, consumed or converted?

For example, it is considered that by shearing the sludge in a pump some of the material may have been physically, chemically or biologically degraded and no longer be present in the system.

It is thought that the shear in the transfer process separates the light organic material from the heavy inorganic material and that once the mixture reaches the corral they do not re-combine. Therefore the heavy, inorganic solids sink to the bottom of the corral unaccompanied by the light organic material which swirls around for a while, leaving over the weir and piling back up again in the pond.

In the initial modelling it was assumed that the particles would re-flocculate to produce relatively homogeneous material that would once again settle with only a low concentration passing over the weir.

CFD and corral performance

Some of the hypotheses related to the performance of the corral as a settling tank. A CFD model of the corral (fig.9.) was built by the specialist consultants MMI Engineering. This was used to explore the relationship between operational parameters and material properties and the degree to which solids would settle in the corral.

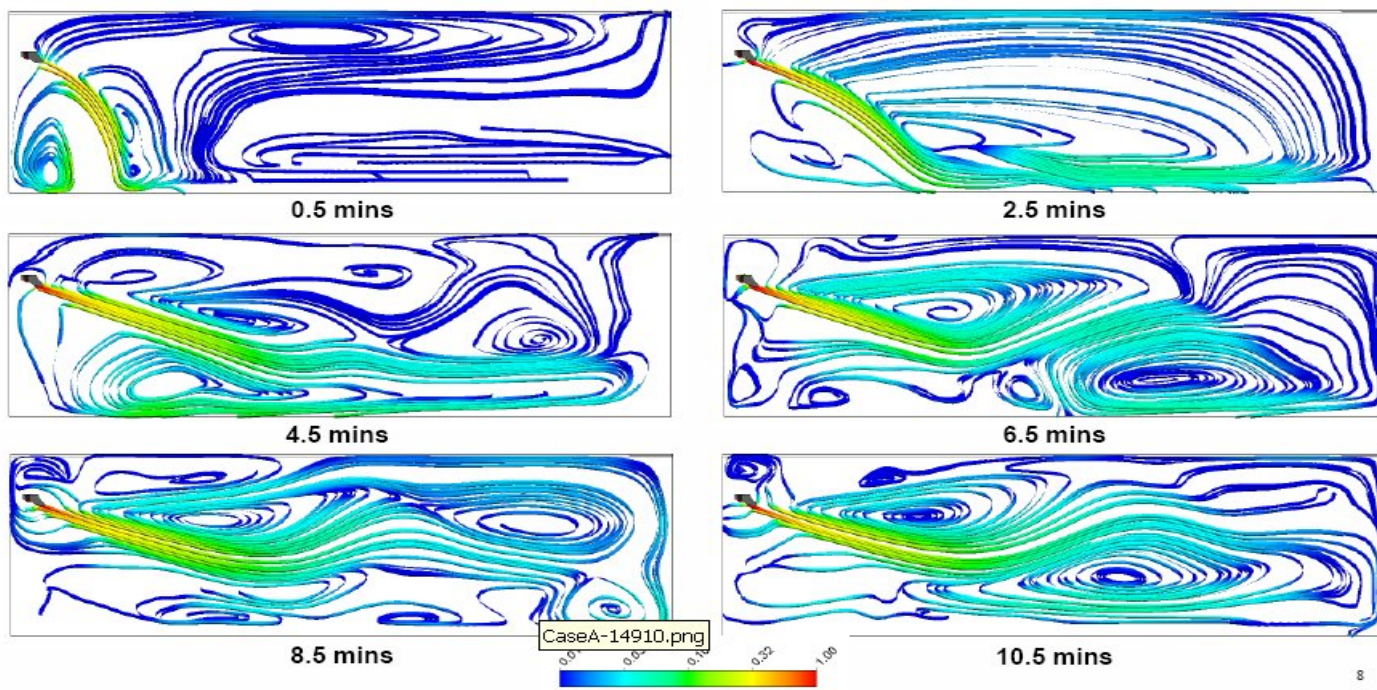


Figure 9. CFD model

The CFD work shows how complicated the fluid flow patterns in the corral are and how they evolve over time as a batch of sludge is transferred into the corral. The modelling had to assume that the solids properties were the same today as they had been measured in the 1980s and 1990s using small samples taken from the pond. The output from the model showed only a small amount of solids not settling. This does not explain where the sludge has gone.

A revised model using slower solids settling properties showed that the solids did flow into, but then out of, the corral over the weir and back to the pond. However, until some more samples are taken there is no evidence to support this.

When the model is run with the anticipated operating regime and physical properties then a small but significant portion of the solids (about 10% of that fed) will flow quickly out of the corral and over the weir. MMI have also stated that based upon their experiences the corral could be made to work as a settling tank by the addition of one or more new features and in particular a large baffle plate near to the diffuser which will create a stilling and mixing zone which slows and controls the flow of the fluid across the corral and allows time for the solids to recombine and become better at settling.

Preliminary Conclusions

It was hoped that there would be good evidence of a clear cause that aligned with one of the hypotheses. This did not occur. There are known leaks associated with the skipwash but we are not sure how much. The CFD indicates that the corral is a less than ideal settling tank but, based on the sludge properties as we understood them, solids accumulation should have been better.

What Next?

The following additional work is planned based on the above:

- Underpin CFD model by monitoring the fluid dynamics of the corral, using Acoustic Doppler Velocimeters (ADV's).
- Improve the accountancy through additional sampling and in situ measurements of the influent to the corral, the solids on the corral floor and the overflow from the weir.
- Investigate improving the settling performance of the corral through baffle plates and settling aids such as polyelectrolytes.
- Continue with plant trials and trend the data.

LEARNING AND FORWARD PROGRAMME

The work carried out to underpin the observed behaviour of the sludge has yet to conclude, however what is already obvious is that the performance of the sludge in the corral is not as expected and that some of the characterisation data for the sludge has turned out not to match that found when retrieved sludge was sampled from the corral. One apparently obvious lesson learned would be to spend more time characterising inventory before implementing projects. However, it is worth reviewing this; PSFP sludge, like many other legacy nuclear wastes is extremely difficult to characterise, the act of sampling and analysis in itself may be as difficult as the retrievals project due to the radiological hazards of removing and analysing the sample. In addition to this the sludge bed is not homogenous; therefore many samples may have to be taken to gain an accurate characterisation of the retrieved sludge. Finally there is the potential that the very act of retrieving the waste can change the characterisation through either physical changes in properties such as shearing or through separation of the various sludge constituents by the retrieval equipment.

It could therefore be argued that, to gain a comprehensive characterisation of the material you would almost have complete the project first to create a homogenous bed of material which has been subject to the correct physical processes; this being the case recommending detailed characterisation is too simple. Projects have to find the correct balance between investing time and money on characterisation against investing those resources into building flexibility into equipment and strategies to cope with changes in sludge behaviour.

Flexibility can be achieved at an equipment level by designing equipment to operate over a wide range of material characteristics for example the PSFP storage systems have been designed to recirculate sludge that is either fully homogenous or where the inorganic and organic fractions have fully separated. Equipment design should also include as many variable parameters as possible to allow the operator as much flexibility as practical to tune the equipment to to match observed performance.

Flexibility can also be achieved by managing the correct programme level strategy, for example a strategy which keeps the capital cost of equipment low and employs a buy and try philosophy to the retrieval technique, however in this case the programme must ensure that sufficient time is allowed for failure and recovery, this can be done by

having multiple work faces for plant operators and if possible keeping activities with high levels of uncertainty off the critical path.

PFSP has adjusted its programme to shift focus from skip desludging to floor desludging to allow further characterisation of sludge behaviour and if necessary modification of equipment to cope with the change in observed behaviour and has improved corral monitoring to enhance the understanding of what happening during the next phase of works

CONCLUSIONS

The programme to desludge the PFSP has made excellent inroads into providing and operating equipment capable of removing the sludge from all areas of the pond. However, collecting sludge in the 'in-pond' corral has proved more problematic, with much less sludge being collected than the volume thought to have been retrieved from the pond. While the technical programme initiated to understand the observed collection issues is yet to finally conclude, it is clear that some of the fundamental characteristics of the sludge and collection systems assumed in the design have changed

While, further characterisation and development work during the design process may have predicted these changes, limitations in being able to take and work with active samples and the difficulty in generating effective simulants for the complex, aged materials limit the amount of work that can be done. It is therefore essential that the equipment provided is not only robust to changes in sludge behaviour but also that both the equipment and operational strategy has sufficient flexibility to allow changes to be implemented.

The PFSP programme has been reviewed and changes made to allow further study of sludge behaviour while continuing to remove sludge from the pond and equipment to support other sections of the programme.

GLOSSARY

CFD	Computational Fluid Dynamics
ILW	Intermediate Level Waste
LETP	Local Effluent Treatment Plant
LLW	Low Level Waste
LSTP	Local Sludge Treatment Project
PFSP	Pile Fuel Storage Pond
ROV	Remotely Operated Vehicle
ADV	Acoustic Doppler Velocimeters