Demonstration of a Consolidated Tank Closure System

J.A. Faldowski
AEA Technology Engineering Services, Inc.
184B Rolling Hill Road, Mooresville, NC 28117
USA

ABSTRACT

In 2004, AEA Technology (AEAT) developed and demonstrated a strategy for employing a single Power Fluidic Pulse Jet Mixing System to both retrieve the bulk and heel waste from a tank and intimately mix the residuals with specially formulated grout. The strategy involved a multi-phased approach to understanding the specific problems associated with the tank and waste material, developing a suitable grout formulation, designing a single set of purpose-built equipment, mixing the grout and heel, and monitoring the grouted product as it cured. The result of the demonstration was a stable simulated waste form which met Nuclear Regulatory Commission (NRC) requirements for grouted Low Level Waste (LLW). This approach enables subsequent disposal of the tank in place via filling the void space with additional grout or removal of the tank for alternative disposal.

In 2005, AEAT expanded the earlier work by demonstrating that a single system could be used to mix and retrieve a simulated, non-Newtonian bulk waste and heel from a large, flat-bottomed, cylindrical tank with internal obstructions. Retrieval of the simulated waste left only 13mm of residuals behind. Following retrieval, the same Power Fluidic Pulse Jet Mixing Equipment was used to mix the residuals with a specially formulated grout, resulting in a stable, uniform product which met the NRC requirements for grouted LLW.

INTRODUCTION

Retrieval of an estimated 380 million liters of liquid and solid radioactive waste stored in tanks of various geometries around the Department of Energy (DOE) complex has been underway for many years. For several reasons, retrieval efforts have proven more difficult, more time intensive, and more costly than originally anticipated [1]. In many cases, the waste has several phases of very different physical properties. For instance, a single tank may contain a large volume of supernatant liquid over a relatively mobile or flocculent sludge with a hard-packed layer of waste material covering the bottom of the tank. Other tanks may have alternating layers of hardened material between layers of relatively more mobile material. More often than not, the precise nature of the waste in a given tank is not known before retrieval efforts are begun. Obstructions such as unanticipated debris or tank internals (e.g. cooling coils, thermocouple trees, etc.) have further complicated retrieval efforts. An increasingly strict regulatory environment has necessitated the development of better and better technologies to remove the maximum amount of waste material from a tank prior to closure.

Past tank retrieval efforts were primarily focused on past practice sluicing to mobilize and pump tank waste to a downstream receipt facility. Several major drawbacks to this approach were recognized early on. These included the addition of large volumes of clean water (up to 20 times the original waste volume or more in some cases), failure of mechanical pumps after as little as 1000 hours of operation, clogging of pump inlets by debris, erosion of sluicing system nozzles and components, and the need for secondary technologies to remove relatively large waste heels left behind following bulk retrieval. The water addition problem was solved, where practical, by recirculation of retrieved supernatant liquid to the waste tank through the sluicing system, but the other problems persist leading to higher than expected maintenance requirements which in turn lead to longer schedules, increased costs, and increased exposure of workers to radiological and industrial hazards.

AEAT has previously developed and demonstrated an effective means of mobilizing and retrieving tank waste contents using its Power Fluidic equipment [2, 3, 4, 5, 7]. To date, this equipment has been deployed successfully in tank projects at several DOE sites where the waste mobilization and retrieval has been accomplished below the proposed cost and schedule baselines. Adapting this safe, proven and effective technology for complete tank closure, including bulk waste retrieval, heel retrieval, and residuals stabilization, represents a considerable improvement to current technology employed in tank closure operations. Applying such a unified approach would save capital equipment costs, consolidate safety documentation, reduce field deployment schedule/costs, reduce secondary waste generation, and reduce worker exposure to radiation and industrial hazards.

This report documents the method of accomplishment and results of the scope of work carried out under International Agreement Number DE-GI01-00EW56054; Project Technical Plan INEEL/Sodium/01/v1 [6]. The principles of Power Fluidic mixing and retrieval and the technical issues to be addressed in using Power Fluidic equipment to grout tank heels are presented. The inactive bulk waste retrieval, heel retrieval, and jet grouting test program is described. The data, results, and conclusions of the work are presented along with considerations for future work and field deployment of the equipment into a radioactive waste tank.

BACKGROUND

In 2004, AEAT developed and demonstrated a strategy for employing its Power Fluidic mixing and retrieval equipment to intimately mix tank waste heels with a specially formulated grout [8]. This mixture results in a stable waste form which subsequently enables disposal of the tank in place via filling the void space with additional grout or removal of the tank for alternative disposal. This approach is in compliance with the NRC Draft Interim Concentration Averaging Guidance for Waste Determinations [9] which states in part "Mixtures of residual waste and materials can use a volume or mass based average concentration if it can be demonstrated that the mixture is reasonably well-mixed." Further, the guidance states, "Credit can be taken for stabilizing materials added for the purpose of immobilizing the waste…"

The 2004 work conducted by AEAT successfully demonstrated that a waste heel in a horizontal tank could be mixed intimately with grout using a Power Fluidic Pulse Jet Mixing System. In FY2005, AEAT combined the concepts of mixing and retrieval of non-Newtonian fluids with jet grouting of the residual materials to effect tank closure in a large, flat-bottomed tank with internal obstructions.

The objective of the work was threefold; to demonstrate that a single Power Fluidic System can be used to:

1. Retrieve Bulk Waste – Demonstrate efficient retrieval of non-Newtonian bulk waste from a large, flat-bottomed tank with horizontal cooling coils without water addition.
2. Retrieve Waste Heels – Demonstrate use of the same equipment to remove the heel left behind after bulk retrieval with minimal water addition.
3. Stabilize Residuals– Demonstrate use of the same equipment to intimately mix any residual material left in the tank after heel recovery with a suitable grout material.

EQUIPMENT DESCRIPTION AND CONFIGURATION

Power Fluidic equipment has been operating in UK nuclear plants since 1970. The technology is proven across a range of applications and is standard technology in UK nuclear facilities. In the US, Power Fluidic technology has been adapted for mixing and retrieval of legacy wastes stored in tanks around the DOE complex. In these applications, the technology has proven effective and robust in dealing with varied tank configurations, in-tank obstructions, and debris. The fundamental principles of Power Fluidic pumps and mixers have been well documented in the literature [10, 11, 12].

Power Fluidic mixing and retrieval systems are custom designed for the application they will serve. Systems have been designed and built in the past for tanks ranging from a few thousand liters to 3.8 million liters. These systems have been designed to cope with many different tank geometries (including vertical and horizontal, with and without tank internal obstructions), various tank waste characteristics, and a wide range of debris items. The system demonstrated in the current scope of work was configured in the arrangement depicted in Figure 1 below. This arrangement (i.e. number of mixers and pumps, arrangement in the tank, equipment sizes, etc.) was designed as prototypical of a tank waste retrieval system; however, each deployed system design is customized to address the specifics of the application in the field (i.e. riser configuration, waste composition, duty, etc.). Included in the system were three independent Power Fluidic systems, two Pulse Jet Mixers (PJM's) and one Fluidic Pump. A standard, PC based "PRESCON™" controller was connected to control the air flow to the Charge Vessel and the sequencing of the mixing and pumping phases.

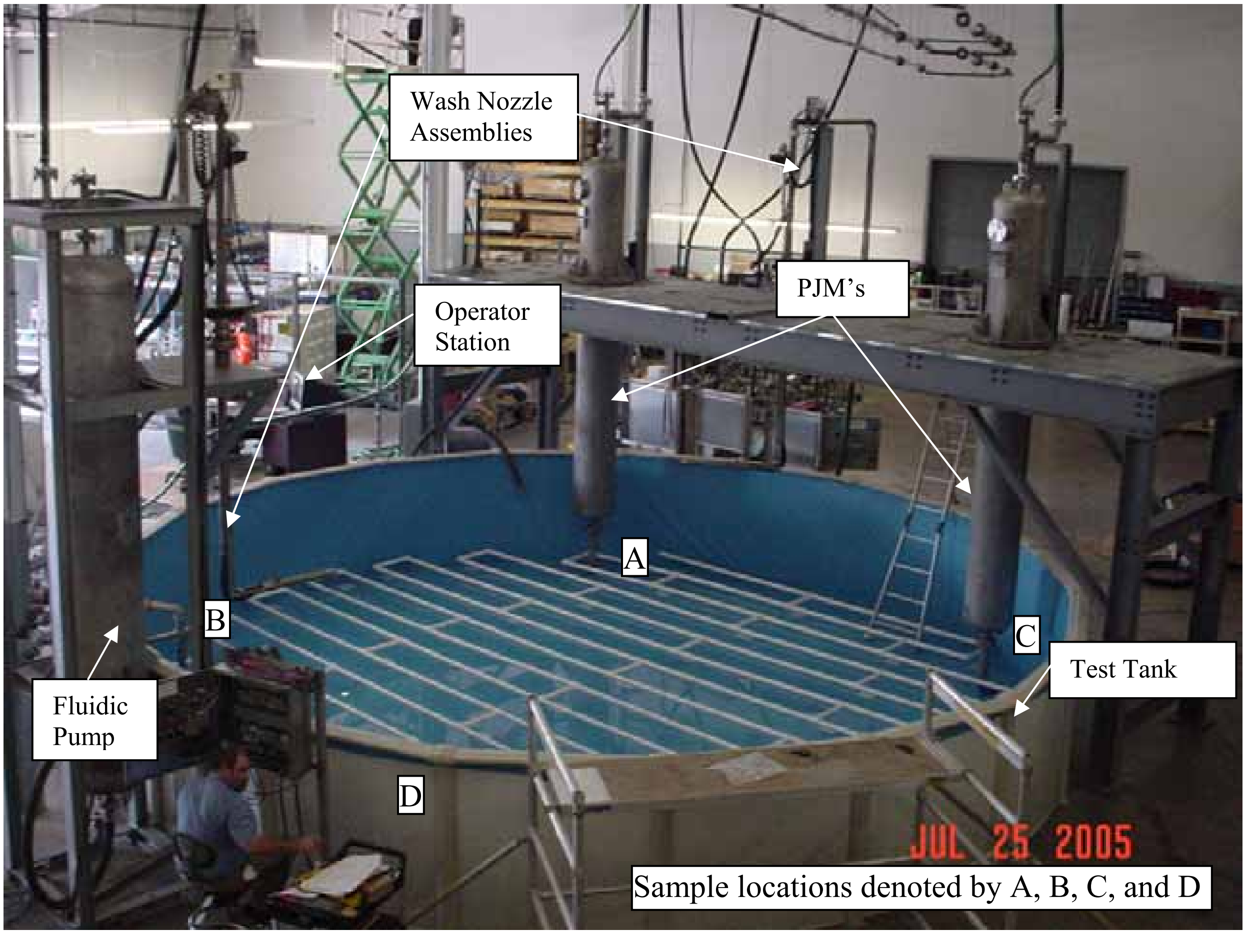

Figure 1: Photograph of the test rig.

Test Tank

In order to simulate a large section of a full–size horizontal, flat-bottomed tank, an 8.2m diameter, 1.3m high above-ground swimming pool was used. The demonstrated configuration was modeled after the 15.2m diameter Sodium Bearing Waste Tanks at the INL and was designed to represent a full-scale section of the tank rather than a scaled down model of the entire tank. A set of simulated cooling coils constructed of 3.8cm PVC pipe mounted on carbon steel supports were installed 15cm from the tank bottom (See Figure 1). The spacing between the simulated cooling coils was 41cm.

Pulse Jet Mixer Configuration

Mixing of the bulk waste simulant was performed using two rotating PJM's. These were located on one side of the tank, as shown in Figure 1.

Operation of the two mixers was independent from each other and from the pump. To facilitate this, a separate jet pump pair was used along with the associated valves and instrumentation to operate each mixer and pump independently. A PC-based control system was employed to give maximum flexibility in the operating modes available for simulant waste retrieval.

The PJM's were installed in a custom manufactured support frame, on one side of the tank opposite the Fluidic Pump element. The PJM suction nozzles were mounted so that the centerline of the inlet/discharge was 5cm above the tank bottom. The PJM charge vessels were 568 liter, stainless steel, ASME, "U" stamped pressure vessels built specifically for the demonstration. During operation, material is drawn up into the charge vessel before being discharged back to the tank to effect mixing. Conductivity probe level switches were used to detect when the charge vessel was full, initiating the change from the suction to drive phases of the mixers. The tops of the Charge Vessels were approximately 4.6m above the base of the waste tank. This height was chosen to ensure the maximum depression in the vessel (~0.9 barg depression) could draw material with a maximum specific gravity of 2.0 high enough to fill the vessel and also to facilitate gravity draining of the lines back into the tank.

Fluidic Pump Configuration

The Fluidic Pump was configured to serve two purposes:

1. retrieve material from the tank and deliver it to the tank farm (i.e. downstream facility) or,
2. retrieve material from the tank and deliver it back to the tank through one of two "wash" nozzles to facilitate mixing and retrieval of the waste heel.

To achieve this, the pump element was installed in the tank opposite the PJM's. The inlet to the element was positioned 13mm from the tank bottom. The outlet of the pump was directed through a valve skid to enable routing of the flow either to the tank farm or to the in-tank wash nozzles.

The two wash nozzles were mounted one at each side of the tank to enable delivery of material to all areas of the tank. The nozzles were custom designed by AEA Technology to be installed through 102mm risers and to provide both horizontal and vertical axis articulation. The nozzle outlet diameter was 25mm. In operation, the pressure at the nozzle tip is approximately 3.4 Bar at a maximum flow velocity of 18 mps.

DEMONSTRATION SETUP AND EXECUTION

Materials Selection

Based on past trials [13], Kaolin clay in water was identified as a potential material which could be used to produce a "universally representative" sludge. Two brands of kaolin clay were procured and mixed with water at various weight percents. The rheology of the mixtures were measured using a Viscolite 700 Portable Viscometer. This resulted in the selection of Paragon, air floated Kaolin Clay in water at 30 being selected as an appropriate simulant. At this composition, the kaolin clay mixture exhibited Non-Newtonian.

The grout formulation chosen for residuals stabilization was a 3:1 Pulverized Fly Ash (PFA)/Ordinary Portland Cement (OPC) mixture developed previously for encapsulation of kaolin clay simulant [8]. Although the lower waste loading in the current trial was expected to cause some bleed water formation on the set product, this was not regarded as a critical parameter with respect to the pre-defined test objectives.

Sampling and Analysis

Samples were collected and analyzed either in-house or by a commercial analysis laboratory in accordance with a predefined sampling plan. During mixing, retrieval, and jet grouting trials, samples were taken from any of eight locations in the tank or from the end of the transfer line, as applicable. All test tank samples (except for initial tank samples) were taken at the end of a drive phase. For samples from the tank, 500ml grab samples were taken using a ‘sludge nabber’ type sampler. The sampling bottle was plugged with a rubber stopper attached to a string before being lifted out of the liquid. The sample was then transferred to a sample storage bottle and labeled. For samples from the transfer line, a sample bottle was held directly under the outlet.

Density measurements were made using 100ml Gay-Lussac density bottles. Rheograms of each sample were produced using a Brookfield R/S Rheometer equipped with a CC-45 DIN spindle. The shear rate was ramped from 10-1000s^{-1} over 60 seconds. A total of 20 readings were made. Viscosity (η) measured in Pas and Shear Stress (τ) measured in Pa was plotted versus Shear Rate (D) measured in s^{-1}.

During the jet grouting trials, samples of the final product after at least 3 hours of mixing were collected and cast by a commercial grout testing company. These samples were stored at the test laboratory in an environmentally uncontrolled area until the test date, at which time compressive strength was measured. In addition to the cast samples, core samples were drilled from the set product at 26 days cure time. These were also stored at the test laboratory in an environmentally uncontrolled area until the test date.

Preparation of Simulant in The Test Tank

Kaolin clay (Paragon, air floated) and water were added to the test tank in the proper proportions to create a 30 $^{w}/_{o}$ mixture when well mixed. A total volume of 24,321 liters (46cm depth) of simulant was placed in the tank. Following addition of the clay, the simulant was allowed to settle for 6 days prior to beginning retrieval trials to achieve the densest possible sludge layer. Over this time, the clay settled in the tank to an average depth of 30cm (creating a 41 $^{w}/_{o}$ sludge), leaving 15cm of clear supernatant liquid above it.

Bulk Simulant Mixing Trials

The bulk retrieval test was conducted by first operating the pulse jet mixers to achieve a well mixed slurry throughout the tank. During the first drive of material back into the tank, it was clearly observed that the jet from the mixer nozzle was traveling under the cooling coils and cutting a channel through the sludge on the tank bottom. After the first drive cycle, the supernatant was too clouded to observe the jet in the sludge. The mixers were operated for 5.5 hours in various configurations over which time the specific gravity of the mixed simulant was measured as an indication of the mixing progress. That is, the higher the specific gravity of the simulant, the more solids that have been suspended by the mixers. The specific gravity of the mixed simulant was measured at four locations in the tank.

At the start of mixing, a sample of the sludge could not be obtained with the sampler being used because it was not flowable. Following 31 mixing cycles, the specific gravity at location A was measured as 1.12. After 85 cycles, the specific gravity had increased to 1.15 and after 193 cycles the specific gravity was 1.17. A summary of the specific gravity measurements taken during mixing, before any transfers were made is in Table I below.

Table I: Summary of specific gravity measurements during bulk waste mixing

Mixing Time (min)	No. of Mixer Cycles	Specific Gravity at Location:			
		A	B	C	D
0	0	1.28	- -	- -	- -
52	31	1.12	- -	- -	- -
90	54	- -	1.14	- -	- -
144	85	1.15	1.15	1.15	1.15
325	193	1.17	1.20	1.18	1.18

During the mixing campaign, it was noted that there was supernatant liquid floating on the surface of the sludge for at least 20 mixer cycles. However, after 54 cycles, the simulant surface appeared uniform across the tank with no supernatant left. After 85 cycles, the specific gravity of the simulant was measured at the four sample locations and was found to be uniform around the tank. At the same time, the tank bottom was probed and accumulations of sludge were noted near the tank walls in the areas of the tank farthest from the mixer nozzles. There was no sludge accumulation in other areas of the tank. At the conclusion of mixing, the sludge accumulations remained in these locations.

Bulk Simulant Retrieval Trials

Following the mixing trials, the simulant was allowed to settle overnight before beginning the bulk simulant transfer trials. At the start of the campaign, the sludge had settled to a 43cm depth with 25mm of supernatant liquid. The transfer campaign started with operation of the mixers for 74 cycles which resulted in a slurry of average specific gravity of 1.18, measured at the four locations in Table I. During the transfer campaign, the specific gravity of the transferred slurry was measured at the outlet of the transfer line and found to vary between 1.18 and 1.25. Table II below contains a sequential summary of the transfer campaign. By the end of the campaign, 73% of the bulk material (17,837 liters) had been transferred out of the tank without adding water for mobilization. The condition of the tank following bulk simulant retrieval is shown in Figure 2.

Table II: Sequential summary of bulk transfer campaign

Time (min)	Observation
0	Operation of Fluidic Pump begins transfer
22	Two transfer cycles are complete. Specific gravity of transferred material is measured at 1.19 after cycle 2.
52	Eight transfer cycles are complete. Specific gravity of transferred material is measured at 1.18 after cycle 8. Tank level has dropped 13cm; 6757 liters transferred.
82	Fourteen transfer cycles are complete. Specific gravity of transferred material is measured at 1.19 after cycle 14.
95	Operator notes the appearance of a sludge bank in front of the Fluidic Pump Element, limiting flow of material to the pump inlet. Control software detects aspiration at pump inlet and shuts down the system.

97	System restarted with mixers only and nozzles aimed at sludge bank in front of pump inlet to break up the accumulated sludge. This continues for 20 mixer cycles at which time the mixers are stopped.
170	Fluidic pump operation is started with outlet of pump directed through the wash nozzle to continue breaking up the accumulated sludge in front of the inlet. Mixers are operated simultaneously
235	Transfer operations resume. Specific gravity of the transferred material is measured at 1.20. After 3 cycles, the outline of the cooling coils is visible and the low tank level begins affecting the effectiveness of the mixers.
303	Sludge level is 25mm below the cooling coils. Two banks of accumulated sludge remain in the tank directly across from the mixer nozzles. Outlet of pump is directed through the wash nozzle to push sludge to the inlet.
315	Final two transfer cycles are initiated. Specific gravity of transferred material is measured at 1.25.
Following Day	Material has settled so 25mm of supernatant liquid is near the mixer nozzles. There is no supernatant liquid near the pump inlet. Mixer operation is started to mobilize additional material to the pump inlet. 10 additional transfers of material with a measured specific gravity of 1.25 run.
Conclusion	Bulk simulant transfer operations are complete. Material in tank is not flowable, therefore, the inlet of the pump is being starved and aspirating. The final average tank level is 12cm. 17,837 liters of bulk material (73%) is retrieved without water addition.

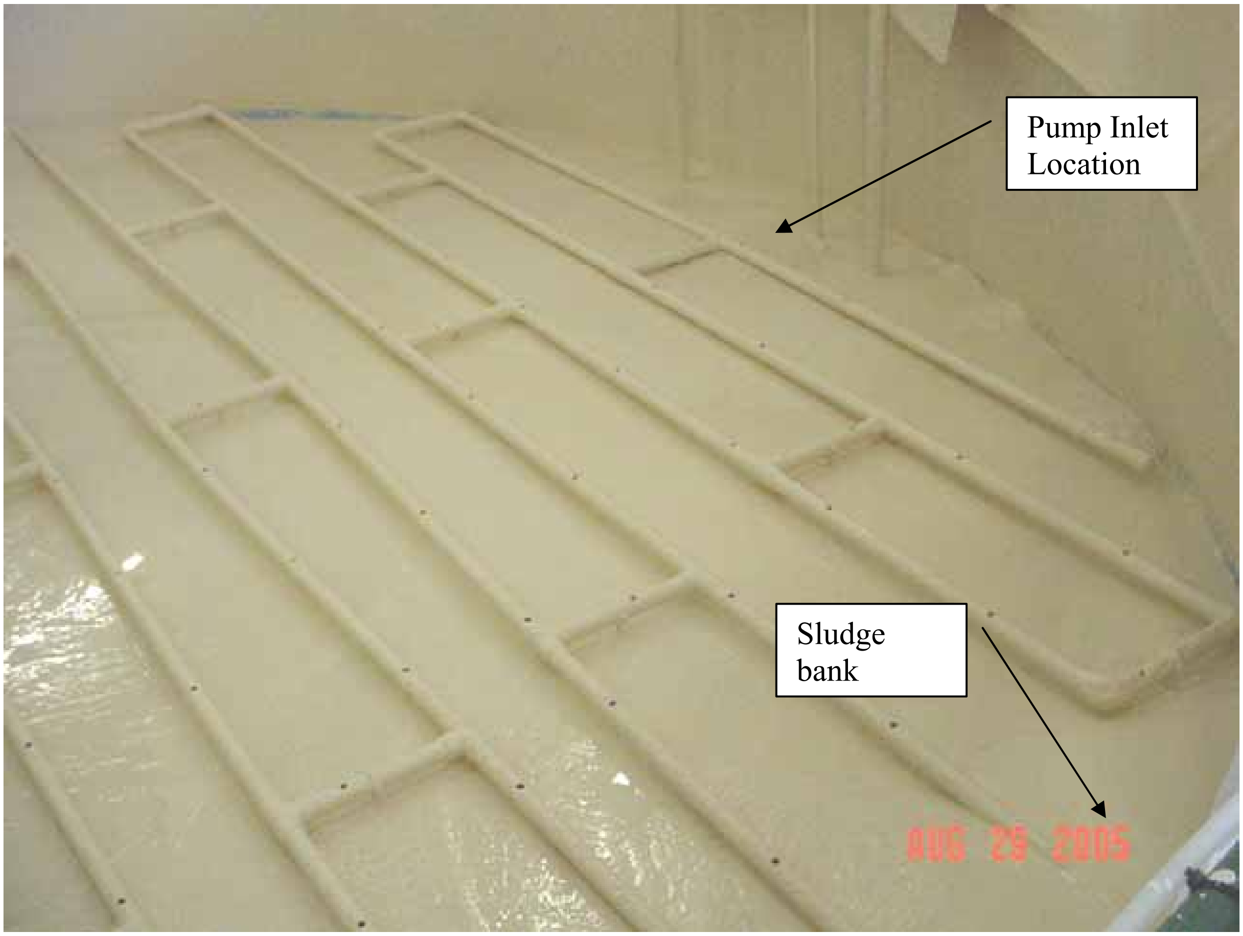

Figure 2: Condition of tank following bulk simulant retrieval

Heel Retrieval Trials

Retrieval of the heel after bulk simulant retrieval consisted of:

- Adding water to the tank.
- Operation of the mixers and/or wash nozzles to fluidize the remaining material.
- Pumping out the fluidized simulant using the fluidic pump.
- Repeating the process to retrieve as much material as practical while minimizing water addition.

In the first heel retrieval campaign, 8,706 liters of water were added to the tank through the mixer nozzles. This raised the level of the tank to 25cm, thus allowing the mixers to be operated at optimum efficiency. The mixers were then operated for 105 cycles over 3 hours. This operation removed the accumulated sludge banks noted previously during the mixing and bulk retrieval trials. At the conclusion of mixing, the specific gravity at all four measurement points in the tank was measured at 1.13 and a transfer campaign was started. 9,464 liters of material with specific gravity of 1.13 to 1.15 were transferred out of the tank during this campaign.

In the second heel retrieval campaign, 4,164 liters of water were added to the tank through one of the wash nozzles. This raised the level of the tank to 16.5cm, thus allowing operation of the mixers. The mixers were then operated for 48 cycles over 88 minutes at which time a transfer campaign was started. 6,057 liters of material with specific gravity of 1.06 to 1.08 was transferred out of the tank during this campaign.

In the third heel retrieval campaign, 5,678 liters of water were added to the tank through one of the wash nozzles. This raised the level of the tank to 16.5cm, thus allowing operation of the mixers. The mixers were then operated for 70 cycles over 120 minutes at which time a transfer campaign was started. The transfer campaign progressed by alternating cycles of transfer out of the tank with operation of the wash nozzle opposite the pump inlet to drive solids to the pump inlet for transfer. 7,192 liters of material with specific gravity of 1.01 to 1.03 was transferred out of the tank during this campaign.

In the final heel retrieval campaign, 3,785 liters of water were added to the tank through the wash nozzles. This raised the level of the tank to 10.8cm. During this retrieval campaign, the mixers were not operated. The retrieval progressed by first operating the wash nozzles to mix the material in the tank and then by alternating a wash nozzle cycle with a transfer cycle. 4,542 liters of material with specific gravity of 1.01 was transferred out of the tank during this campaign. The final level of material in the tank was 25mm which equals a volume of 1,363 liters. The final end state of the tank is shown in Figure 3 below. A summary of the heel retrieval campaigns is below in Table III.

Figure 3: Tank condition after heel retrieval. Outline of 3/8" cooling coil support plates were clearly visible.

Table III: Summary of the heel retrieval campaigns

Retrieval Campaign No.	Water addition prior to campaign (liters)	Amount of material retrieved (liters)	Specific gravity of material retrieved	Tank level after campaign (mm)	Volume in tank after campaign (liters)
1	8706	9464	1.13 – 1.15	75	4164
2	4164	6057	1.06 – 1.08	50	2650
3	5678	7192	1.01 – 1.03	25	1590
4	3785	4542	1.01	25	1363

Residuals Grouting

Two separate grout trials were conducted as part of the test demonstration. In the first, only the Pulse Jet Mixers (PJM’s) were used to mix the grout with the simulant. The PJM nozzles are located below the surface of the material they are mixing. In the second trial, the grout and simulant were mixed using only the wash nozzles which are fed via the Fluidic Pump Element and are located above the surface of the material they are mixing. These two trials are described in the sections below.

Following heel recovery, 1,363 liters of water with 3mm depth of settled residual material (residuals) was left in the tank. The residuals were treated by jet grouting them in place, thereby creating a uniform solidified mass of grout in the bottom of the tank. Initially, it was planned to spray the grout into the tank via the wash nozzles and direct it to push the residuals to a single location on the tank bottom, thereby increasing the depth sufficiently to feed the suction of a mechanical pump. However, the grout pump that was rented from a local concrete supply company had difficulty pumping the highly fluid grout and was configured to pump through a 76mm delivery line. This resulted in a high pressure, high velocity jet of grout being produced at the wash nozzle. The resultant force on the plastic lined tank and high splatter were not manageable with the test rig configuration. Therefore, the grout was deposited into the tank directly from the cement mixer trucks. Once the level of material in the tank was above the cooling coils, the PJM’s were operated to mix the tank continuously for 3.5 hrs to achieve thorough mixing. A reduced drive pressure of 2 barg was used because of concerns over tearing of the tank liner during an extended mixing time. Previous grout trials [8] have shown that the grout and simulant tend to form lumps upon contact that disperse when thoroughly mixed. Further, extended circulation/mixing of the grout has been previously demonstrated to reduce bleed water formation (i.e. the amount of over-standing water on the grout/simulant product at 24hrs curing).

Upon completion of mixing, the Power Fluidic System was thoroughly flushed. 189 liters of flush water was introduced through each mixer into the test tank. The mixer nozzles were then removed from the tank before allowing the grout to cure.

Several parameters were monitored during jet grouting and as the grout/simulant mixture cured. These included:

- Visual observations of the mixing.
- Key mixer parameters.
- Temperature of the grout as it cured.
- Visual observation and measurement of bleed water formation.
- Compressive strength of the cast samples taken just after the completion of mixing.
- Visual observation of the core samples
- Compressive strength of core samples at 60 and 120 days after jet grouting.
- Visual observation of the bottom of the cured product during breakup and disposal.

Qualitative assessment was made of the jet produced by the nozzle, the level of agitation in the tank, the effective range of the nozzle, and the mixing effectiveness of the system. The jets from the PJM nozzles were capable of reaching the opposite side of the tank even using the 50% reduced drive pressure. However, there was a "boundary" effect that caused the solids in the grout mixture to settle out near the wall of the tank furthest from the mixers. To improve overall mixing, the PJM's were operated to produce a swirling action in the tank. This proved effective at producing bulk movement of the material in the tank, however some solids settlement at the tank edges was still observed. The mixing action could be described as very gentle.

The grout/simulant mixture viscosity was measured and recorded at one hour intervals during mixing. The suction time, which is dependent on the specific gravity and viscosity of the material being mixed, remained constant over the three hours of mixing. This is an indication that the grout/simulant mixture was not setting over the mixing period. The mixture remained flowable for more than three hours mixing, with a slight decrease in the viscosity.

Temperature in the grout product was measured after the completion of mixing for approximately the first 7 days of curing. The temperature was measured using an RTD 15cm from the bottom of the tank in the bulk material as it cured. Probes were installed in three locations axially along the tank with location 1 being closest and location 3 being furthest from the RFD and location 2 in the center of the tank. The temperature peaked at 36.7°C fourteen hours after the conclusion of mixing. The low exotherm was expected due to the high water content of the grout leading to a slow curing process. It is significant to note that the temperature of the grout was influenced by the fluctuations in ambient temperature. In the demonstration, the 8.2m diameter tank was not covered following mixing, resulting in 53.2m^2 of surface area open to the atmosphere. In the previous year's trials, the tank was closed with the exception of access holes for equipment and viewing ports. In this configuration the effect of ambient temperature variation was not observed in the data [8]. This leads to the conclusion that in a closed system, the head space atmosphere may be warmed by the curing exotherm thereby limiting convection cooling from the surface of the grout. This in turn will result in higher peak temperatures and longer cool down times than were observed here.

Grab samples of the grout/simulant mixture were taken from the tank after three hours of mixing and cast into compressive strength cylinder samples. The samples were obtained from between the middle to the top of the grout depth, near the edge of the tank farthest from the mixers. These were allowed to cure and were tested by a commercial test laboratory at 28, 60, 90, and 120 days. It was seen from the data that the compressive strength was continuing to develop at 120 days, indicating a very slow cure rate for the grout formulation used.

After 24 hours cure time, the bleed water formation was observed and measured at 6.4mm to 9.5mm deep which amounts to 337 to 507 liters. This is roughly the amount of flush water added to the tank to clean the PJM system after mixing. Bleed was expected on the set product because the grout formulation was not adjusted for the reduced waste loading as compared to the previous year's trials. In the FY04 trials with a similar grout formulation but higher waste loading, no bleed at 24 hours was observed.

After a 26 day cure period, the stabilized tank heel was visually examined and cored to assess the effectiveness of the mixing. The cores showed the set product had a uniform appearance with no evidence of stratification or non-uniform mixing. The bottom of the core taken from the least agitated part of the tank (i.e. furthest from the mixer nozzles) had a trace quantity of simulant adhered to the bottom that was not mixed into the grout matrix. This is an indication that vigorous mixing is required to scour off material adhered to the tank bottom and effectively encapsulate it in the grout. More vigorous mixing would have been achieved uniformly across the tank had the tank been able to withstand the full drive pressure of 4 barg for the mixers. However, in the area of the tank near the nozzles that was mixed vigorously, the simulant material was effectively cleaned off the tank bottom and incorporated into the grout.

Compressive strength was measured on the cores. It was seen in the data that the grout product easily meets the 3.4MPa NRC compressive strength requirement for grouted LLW [14].

The final piece of data collected was visual observation of the grout matrix as it was being broken up for disposal. The grout was broken up 29 days after jet grouting. A skid loader and backhoe were used to break up the grout and dispose of it in a dumpster. During the break up, no dust was created and the grout broke up into large chunks. Areas where the grout and simulant were mixed less vigorously due to the fragile nature of the tank (e.g. the edges of the tank) had trace quantities of simulant material adhered to the bottom of the grout. This is pictured in Figure 4 below where image A) shows a broken section typical of the bottom side of the grout, image B) shows the bottom side of the grout near an edge of the tank where the nozzles were not directed C) shows the grout broken up before disposal.

Figure 4: Pictures of the grout during breakup. A) Typical condition B) Edge of the tank. C) Overall after breakup

CONCLUSIONS

The demonstration proved the efficacy of using a Power Fluidic mixing and retrieval system for the three phases of tank closure; bulk waste retrieval, heel retrieval, and residuals stabilization. Past work has demonstrated the systems ability to cope with debris, tank obstructions, and hardened material. The current work has demonstrated the systems ability to mobilize a non-Newtonian sludge in a large flat-bottomed tank. Utilizing this safe, proven and effective technology for a consolidated approach to tank closure has the potential to be of considerable benefit to tank waste retrieval and closure operations throughout the complex. The benefits of this approach include:

- Utilization of a single system for bulk waste and heel retrieval and residuals stabilization resulting in:-
  - decreased capital equipment costs

  - reduced secondary waste generation
  - shorter schedule / lower labor costs for field activities
  - lower radiation dose to workers
  - a consolidated approach to safety documentation preparation.
- A greatly improved waste end state, wherein contaminants are mixed and stabilized in a grout matrix rather than unmixed with pockets of mobile contaminants remaining.
- A final waste form that meets current US regulations for grouted LLW [14].

During the retrieval phases, nearly 24,605 liters of Non-Newtonian sludge were retrieved from a large, flat-bottomed tank using 22,334 liters of added water. The residuals were then jet grouted in place to produce a final grouted product that will meet the NRC Branch Technical Position for grouted LLLW [9]. All of this was accomplished using a single set of equipment installed once into the tank. The particular conclusions from each phase of operations are as follows.

Bulk Simulant Retrieval

A 30 $^{w}/_{o}$ mixture of kaolin clay in water was used to simulate a Non-Newtonian waste in a 8.2m diameter, flat-bottomed tank with horizontal cooling coils 15cm from the bottom. A Power Fluidic mixing and retrieval system was installed in the tank to retrieve the bulk waste without adding any water. After 11 hours of mixing and transfer campaigns using both Pulse Jet Mixers and the Fluidic Pump, 73% of the waste was retrieved and transferred to the tank farm. The transferred sludge was in the specific gravity range of 1.18 – 1.25 which is equivalent to 25 – 33 $^{w}/_{o}$. The final limitation on the amount of material that could be transferred was dewatering of the sludge which caused it to stop flowing to the pump inlet. The tank was left with a 12cm average depth of sludge which could not be retrieved without water addition.

Heel Retrieval

Following bulk simulant retrieval, water was added to the tank to facilitate mixing and transfer of the remainder of the material. Four heel retrieval campaigns were conducted over which a total of 22,334 liters of water were added to the tank. The material transferred out of the tank ranged in specific gravity from 1.15 to 1.01. Retrieval efforts were stopped when diminishing returns on solids retrieval were being achieved. The final end state of the tank was 25mm (1,363 liters) of clear supernatant liquid over 3mm(151 liters) of settled sludge with the tank walls and internals clean. This equates to greater than 99% solids removal.

Jet Grouting

The residuals left in the tank after heel retrieval were grouted in place using the Power Fluidic mixing and retrieval system. Two jet grouting trials were conducted; one using the Pulse Jet Mixers and one using the Fluidic Pump in conjunction with the wash nozzles to mix the grout with the residuals. While both approaches produced and acceptable result (i.e. a final product of greater than 3.4MPa compressive strength with minimal bleed water formation), better mixing was achieved using the wash nozzles from above the surface of the liquid. This resulted in improved incorporation of the simulant from the tank bottom into the grout matrix and a stronger end product. Upon breakup of the cured product after 28 days, no dust formation was observed and the product was easily removable using standard equipment.

Following the jet grouting trials the Power Fluidic system was cleaned by flushing it with process water into the waste tank. This proved effective for cleaning the equipment and did not adversely affect the grout product. Because the system can be effectively cleaned following jet grouting, the above ground components may be reused for other tank closure applications, thereby reducing capital cost associated with closure of multiple tanks.

IMPLICATIONS FOR FUTURE WORK

It should be emphasized that application of this technology to an active tank waste heel must include development work initiated as early in the process as practical.

The grout development work should include:

- Characterization of the waste heel
- Development of a representative simulant
- Formulation of a grout for the simulant with the broadest effective design envelope possible
- Complete testing of the grout/simulant mixture against applicable governing regulations
- Testing of the grout with a sample of the active heel material (when possible to do so)

Mixing system development work should include:

- Waste tank geometry (e.g. tank size, configuration, in-tank obstructions, etc.)
- Access options to the tank (e.g. number and size of current risers, etc.)
- Retrieval / Operational strategies to be employed (e.g. in-tank nozzle disposal, off-gas treatment, method of grout addition, etc.)
- Consideration of the site elevation with regard to Charge Vessel elevation above the waste tank – may lead to development of a lower density grout and thus feed into the grout development work above or alternative designs with in-tank charge vessels.
- Sampling requirements and methods
- System cleaning and decommissioning requirements

Two lessons learned from the jet grouting phase of the trials worth noting here are:

1. The gentle mixing imparted by the Pulse Jet Mixers running at half the normal drive pressure was not sufficient to fully incorporate the waste into the grout. Vigorous mixing of the grout and residuals is needed to fully incorporate the solids into the grout matrix. Simply pouring the grout on top of the residuals in unlikely to result in a full encapsulation and stabilization of the waste.
2. A significant difference in the strength of the grouted product was noted between the first and second jet grouting trials. While some of the difference may be accounted for by the better mixing in the second trial, close quality control of the grout supplier should be part of any tank grouting exercise on a radioactive tank.

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