Remote Monitors for High Level Waste (HLW) – 10098

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ABSTRACT

Several U.S. Department of Energy (DOE) sites have a need to measure the physical, chemical and radiological properties of high-level waste (HLW) in order to prevent plugging of transfer lines, provide verification of process flow sheet analyses of waste moved between tanks, and to assure that tanks are not filled beyond safe limits for gas generation concerns. Remote monitor technologies and/or instruments can help improve operational efficiencies and provide accurate information on the waste characteristics [1]. As part of Florida International University's (FIU's) research efforts, the development of technologies to improve monitoring of HLW characteristics has been an on-going effort for several years. FIU has completed the design of several HLW monitors for deployment within the HLW tanks. The monitors have been developed to provide real-time information on (1) surface contour of settled solids, and (2) waste solids weight percent during mixing. FIU has worked with Hanford and SRS site engineers in the development of these systems that provide significant improvements over baseline technologies.

This paper will discuss the development of these two systems and some of the verification testing results. In addition, the benefits of these technologies versus the baseline methods will be addressed by presenting research results at FIU and national laboratories.

BACKGROUND

The U.S. DOE Hanford site has the largest number of High-Level Waste (HLW) storage tanks and the largest volume of HLW in the United States. The safe storage, retrieval, treatment, and disposal of approximately 53 million gallons of highly toxic, high-level radioactive waste stored in Hanford's 177 underground tanks are a national priority. Retrieval and treatment of waste from these tanks pose a considerable challenge. Specifically, FIU has focused on two issues that could benefit from improvements in the measurement methods. The retrieval of highly concentrated slurry (>20% solids by weight) and the over-filling (or under-filling) of HLW double-shell tanks (DST) during waste staging operations are activities that require costly conservative actions or limits to be set due to time delay and lack of resolution in the available monitoring data.

During retrieval of waste over the years, there have been several transfer pipelines that have been plugged. Costs exceeding $3M dollars have been expended to bypass plugged pipeline sections. The continuous and in-situ monitoring of the slurry solids weight-percent in the tank or pipeline can ensure slurry homogeneity in a transfer or retrieval scenario. This data can help engineers ensure that slurries are maintained above their critical velocities. The monitoring can mitigate the potential for pipeline plugging by providing operators with real-time measurements of weight-percent solids, allowing them to adjust mixing/transfer parameters as needed [2]. Presently, all solids weight percent estimates at the Hanford site are performed via laboratory analysis of samples taken from a tank, or via an in-line, ultrasonic-based system for weight percent measurement in real time. Laboratory analyses are costly, time-consuming and not representative of dynamic solids concentrations. The ultrasonic technology lacks the accuracy achievable with laboratory or hot cell analyses. Ultrasonic measurements are better suited to track changes to solids concentration (trending) than to provide analytical results [3]. Based on the technological and logistic limitations, Hanford site personnel have identified the need for a real-time, in-situ monitor for solids concentrations in slurries.

The inability to monitor the actual solid-liquid interface in tanks leads to conservative estimates on when a tank has reached its safe maximum solids level. Due to the very limited space available in the HLW tanks at Hanford and the aggressive schedule for retrieval of a portion of the waste over the next decade, the ability to map the solids interface could optimize the loading of solids into tanks. Presently the procedure at the DOE Hanford site for locating the level of solids in a 70 ft diameter tanks is to lower a weighted ring into the tank and measure the level it settles. This is a single point measurement of the height of solids over a surface area over 3800 ft^2. This method is inaccurate because: it measures at a single surface point; the ring may sink into low-density solids; and the ring may form a depression in the solids surface with repeated measurements. Hanford site personnel identified this critical need for an interface monitor, which is capable of detecting the interface between the settled solids and the supernate liquid in a tank. There is no commercial off the shelf technology (COTS) available for imaging the solids layer level in the high nuclear radiation and highly caustic environment inside HLW tanks. The U.S. DOE and the HLW contractor at the Hanford site requested technology support from Florida International University to help them identify a solution to meet their critical need for an in-tank, solid-liquid interface monitor (SLIM).

Technology Requirements

The need for a slurry monitoring system has been a DOE complex-wide issue for several years. Research efforts during the last decade by ORNL [2], PNNL [3], and FIU [4] evaluated commercial and experimental technologies that could solve the problem of maintaining tank slurries within the appropriate solids weight percent range to ensure safe and effective retrieval. Several DOE-sponsored technical workshops and exchanges were held to better define site needs and develop technical functions and requirements for such a technology [4]. The efforts determined that a new system that utilized two Coriolis meters could provide accurate, real-time measurement of the solids weight percent in slurries. In order to achieve these goals, the system design requirements were agreed upon between Hanford site and FIU engineers. The requirements are provided below.

ITSM Technology Functions and Requirements

- The sampling device shall be inserted into the HLW tank through one of the existing 8-inch dia. (203 mm) inspection ports available on the tank;
- The system must be able to be positioned at various elevations in the tank;
- The system controls and data collection should be performed via remote methods;
- Minimum slurry flow rate of 6 feet per second (1.83 m/sec) in the monitor is necessary to assure flow without solids settling out of the slurry;
- Filtrate flow rate must be maintained above 0.5 feet per second (0.15 m/sec);
- Operational temperature range should be 10 – 85°C (50 – 185°F);
- Precision for a slurry with solids weight percent $\leq$ 20% needed to be +/- 5% (experiments with FIU system demonstrated 0.1 – 1.0% precision) [4];
- Ability to monitor a waste slurry within the fluid parameters defined in table 1 below:

Table 1 HLW In-Tank Properties and Conditions for Monitor Design

Parameter	**Value**	**Unit**
Particle Size	0.7-700	µm
Viscosity	1.0-5.0	cP
Percent Solids	≤10	vol%
Temperature	50-185	F
Specific Gravity	1.0-2.0	-
pH	≥9	-
Gamma Radiation	1000	R/hr
Critical Velocity	6	ft/s

In addition to research applied to a deployable slurry monitor, the need for a solids level monitor for HLW tanks has also been an on-going effort for some time. Various commercial technologies have been evaluated for the task, with an ultrasonic interface level analyzer by Royce Instruments tested in Tank 241-AZ-101 [7]. Although ultrasonic systems have been found as the most viable technology for solid level analyzer, the available platforms have not been "tank-ready", and the systems have lacked the resolution to make them useful. Based on discussions with site engineers, a detailed list of requirements has been developed for an in-tank solid-liquid interface monitor (SLIM). These monitor requirements will address baseline issues, and provide a monitor that can supplement the TSR AC 5.12 requirements for tank waste level measurement [6] by providing improved waste mapping capabilities. The requirements are listed below.

SLIM Technology Functions and Requirements

- Detect a solid-liquid interface during and after settling [5];
- Withstand exposure to both high-level radiation (up to 500 Rad/h) and highly caustic solution (pH > 7) [5];
- Operate in a range of 75-320 inches above the bottom of the tank;
- Be deployable through a 4-inch riser at the top of the tank [5];
- Operate in liquid 2 feet or more above the settled solids layer;
- Identify the average interface elevation integrated over an area of at least 5 ft^2;
- Avoid disturbing the solid-liquid interface by the act of measuring;
- Be capable of at least hourly readings of the interface;
- Provide isolation valve between contained system and tank interior;
- Remove all shear loads from the tank riser; and
- Be capable of installing on below-grade riser.

FIU used these defined technical functions and requirements to integrate existing commercial technologies with custom fabricated components into remote monitors for deployment at the Hanford site. These monitors are described in more detail in the next section.

SYSTEM DESCRIPTIONS

In-Tank Solids Monitor (ITSM)

The ITSM was designed to accomplish slurry weight percent monitoring in real-time, with improved reliability and accuracy over current technologies. The ITSM measures the slurry and liquid content density by pumping the tank slurry into the sampling loop. With the two measurements and the known undissolved solids density, the solid weight percent can be calculated using the following equation [8]:

$$Wt\% = 100 \times \frac{\rho_s(\rho_{sl} - \rho_f)}{\rho_{sl}(\rho_s - \rho_f)} \qquad \text{(Eq. 1)}$$

where

$Wt\%$ = Weight percent of undissolved solids in the slurry

ρ_s = Density of the dried undissolved solids

ρ_{sl} = Density of the slurry

ρ_f = Density of the filtrate

The sampling loop (Figure 1) consists of two Coriolis meters, a crossflow filter, and a flow control valve. The operating principle behind the Coriolis meter is that a fluid entering a vibrating tube will accelerate as it reaches/leaves the central point of the tube. The force applied as a result of the acceleration causes a deflection, or twist, that is directly proportional to the mass flow [9]. These meters are accurate to 4 significant digits and are able to handle corrosive and highly abrasive slurries. The first Coriolis meter (FM-1 in diagram below) in the loop measures the density, mass flow, viscosity, and temperature of the slurry. The slurry then flows over the crossflow filter (F-1), which separates a portion of the carrier fluid from the slurry. This allows a density measurement of the carrier fluid, or filtrate, by the second Coriolis meter (FM-2). The valve (V-1) regulates the flows by slightly restricting the slurry flow.

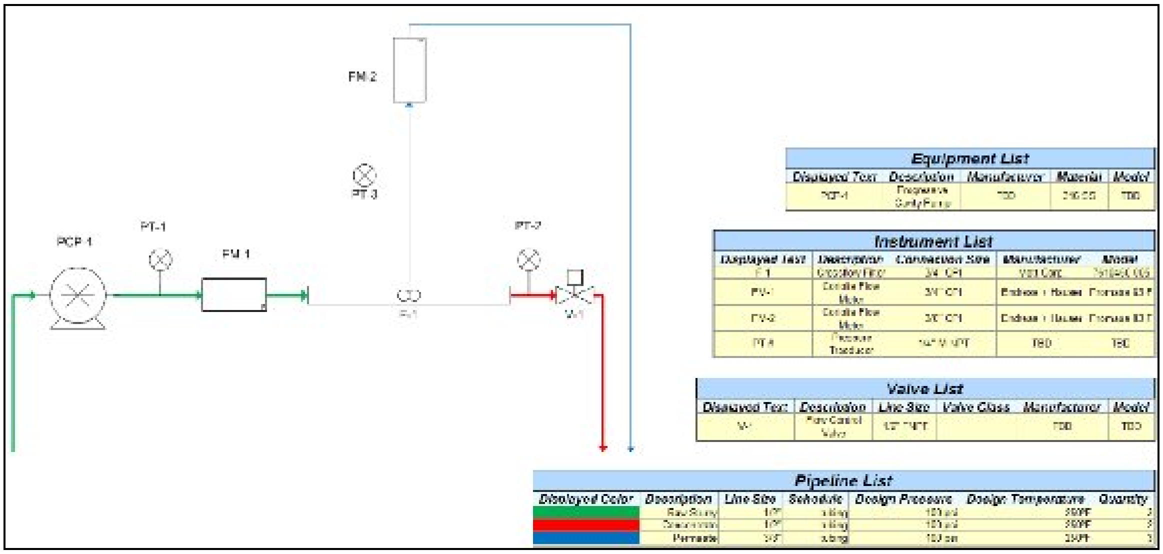

Figure 1: Process Flow and Identification

This sampling loop is housed in a 6-inch dia. pod that serves as the monitor's exterior. The entire monitor is lowered into the waste tank via a deployment platform. The entire sampling process is automated and can be initiated remotely via a computer program on the same data network.

In order to perform the solids weight percent measurement, the monitor with its internal sampling loop must be lowered to various depths in the HLW tank using a hoist. This is possible by having all of the functional components housed in a pod. The functions of this pod are to provide isolation to reduce equipment exposure to the environment within the tanks, prevent sampling loop equipment from being damaged as it is deployed, and add support and rigidity for the internal equipment and process loop. The main components in this pod are the slurry pump and drive, Coriolis meters, liquid phase extractor, housing and probe. Figure 2 shows a 3D drawing of the designed system; Figure 3 shows the fully assembled pod.

Figure 2: Sampling Pod

Figure 3. Assembled ITSM sampling pod (pump-side view).

Solid Liquid Interface Monitor (SLIM)

The SLIM uses sonar technology for mapping the tank solid waste layer, while submerged in the liquid supernate. It consists of a high-resolution profiling sonar that provides a 3-dimensional map of the surrounding environment down to a resolution of 15 mm (at 1 m). The SLIM is capable of: withstanding high-level radiation and highly caustic solution (pH>14), being deployed through a 4-inch riser at the top of the tank, operating in liquid 2 feet or more above the settled solids layer and identifying the average interface elevation integrated over an area of at least 5 ft^2. The sonar head is deployed with a motorized reel that is remotely controlled via the user through a network connection. When the sonar is in a retracted state, the entire system is isolated using a valve between the riser and system. The system is contained inside an enclosure box, with a cable connecting the control panel to the system inside.

The initial step for deployment requires the opening of an isolation valve, exposing the SLIM to the tank internal. An electric cable reel is used to lower the sonar head. The head is lowered into the tank on semi-rigid gooseneck tubing – with a sonar signal/power cable inside of it –for support. The sonar head contains an on-board water level sensor that detects when the head has been submerged into the supernate. At this point, the system must perform speed of sound calibrations, with the provided two points for calibration located near the head. Once calibrated, the system begins taking 2D scan "slices" of the tank solid waste surface (Figure). Two motors rotate the transducer into the required coordinates for scanning; one motor handles "slice" scanning, while the other motor repositions to a new rotation angle. The depth measurements are corrected for speed of sound adjustments using the control software, and the system commences to make a map of the tank surface. Once complete, the data can be plotted on a tank template to calculate total remaining volume.

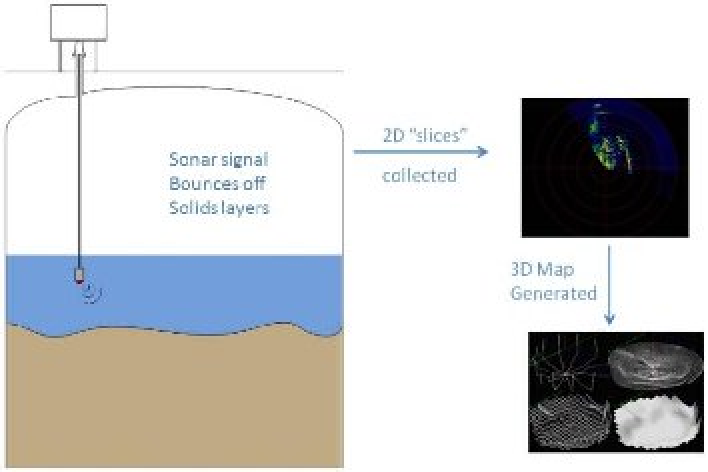

Figure 4. SLIM Theory of Operation (simplified).

The 3D sonar head (See Figure 5) consists of a 3.54-inch diameter, 12.6-inch long cylinder housing the sonar transducer, positioning stepper motors, wet sensor, and signal/power cable connector. The (1) sonar transducer is contained in an oil-filled dome located at the working end of the head. The dome is casted using Victrex® PEEK polymer, which has high chemical and radiation resistance. The (2) wet sensor is located along the side of the sonar, and is used to detect when the system has been submerged into the supernate. The (3) power/signal cable connector is MIL-style with a 19-pin configuration; it is manufactured of Polyurethane. The connector plate contains four ¼-in bolt holes (two U-bolts shown in position) to support the gooseneck tubing that will be used to lower and stabilize the sonar head. The sonar (4) custom housing consists of 4 Titanium “sections”, plus the sonar boot. The sonar has been sized to fit into a 3.54-inch housing, allowing the sonar head to fit inside a 4-inch riser. The sonar head provides enough clearance along the riser wall to support up to a 4-degree from-vertical deflection between riser joints.

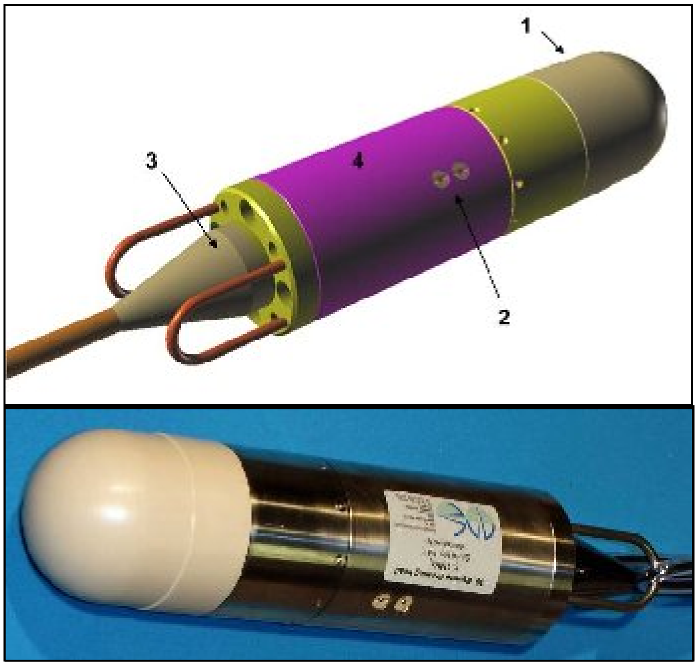

Figure 5. SLIM sonar head 3D model with parts labeled, and completed assembly.

The deployment system consists of the sonar lowered into the tank using an electric reel, and suspended via stainless steel gooseneck tubing. The SS Gooseneck tubing, also known as obedient or stayput tubing, provides a semi-rigid structure for support or positioning. It is manufactured of two a spiral wound strips of stainless steel 304L; one strip is cylindrical in shape, while the other is triangular. The shapes help provide rigidity when the gooseneck tubing is forced into a position; it also limits torsional displacement, which will minimize rotation of the sonar head during scanning. The SS Gooseneck for this application is welded with 1-inch NPT male fitting for connection on the cable reel, and a custom 3.5-inch connector for the sonar head. This gooseneck has a minimum bend radius of 12 inches. It will store the power/signal cable (minimum bend radius: 5 inches) for the sonar head. The gooseneck will provide the cable support and structural rigidity needed by the sonar head, with the flexibility to be lowered using an electric cable reel. The electric cable reel is a commercially available unit of 24-inch diameter drum and housing manufactured of SS 304L. The reel uses a chain drive configuration to provide up to 25 linear feet/minute feed rate for the gooseneck/cable. The drive uses a ½ hp, 24 VDC Permanent Magnet Motor (PMM) for driving the gear. In order to couple the cable between the sonar head and the spinning drum, an 18-conductor silver plated slip ring is used. The gooseneck routing is controlled through a stainless steel guide that is mounted on the reel. A series of stainless steel rollers are used to straighten the gooseneck before lowering it into the tank riser. Two incremental encoders mounted on the reel and against the gooseneck tubing monitors the amount of the gooseneck tubing that is deployed. One encoder has a spring-loaded wheel that is in constant contact with the gooseneck tubing. To keep the gooseneck tubing from coming off the reel in the event the sonar head encounters an obstruction during deployment, the top of the guide has a guard/guide plate.

VERIFICATION TESTS & RESULTS

The remote monitors described above are the result of several proof-of-concept experiments performed at FIU. Both these prototype systems were designed and assembled at FIU, and are currently undergoing verification testing. This section highlights some of the results from previous cold and proof-of-concept tests at FIU.

ITSM Sampling Pod Tests

The ITSM concept was originally configured in a bench-scale setup and evaluated with a matrix of slurries that varied the solids concentration, density, viscosity and temperature [4]. Upon proof that the system could provide laboratory accuracy in a field-deployable configuration, FIU designed the sampling pod, and put it through additional deployment tests. A summary of the tests and results are provided below.

1. System Integrity Test: The ability of the system to withstand the vibration imposed by the pump and other mechanical impacts was qualitatively assessed. No disturbing vibrations were noticed. The probe was taken apart and reassembled a few times in the course of experiments due to unanticipated pump malfunctions. The pump malfunctions were corrected and are not expected to arise in the second prototype. The joints did not loosen or malfunction during the course of the tests or when disassembled.
2. Vertical Alignment: The ability of the system to maintain a vertical alignment was studied by taking out-of-plumb measurements. These measurements were taken with all the hoses and cables attached to the system. No measurable out-of-plumb condition was observed. As per American Petroleum Institute (API) 5CT, the pipe mill manufacturing tolerances are stated as

   "*All pipes shall be reasonably straight*" and "*Deviation from straight, or chord height, shall not exceed either of the following:*

   a. 0.2 percent of the total length of the pipe measured from one end of the pipe to the other end.

   b. *0.125 inch in the 5-foot length at each end.*"

   This provides the confidence that the ITSM will not foul an 8-inch riser.

Figure 6. ITSM sampling pod in vertical configuration. The red lines are the plumb lines to measure "plumbness" of the probe.

3. Mechanical Positioning System: It was demonstrated that the sampling port could be repeatedly positioned at a desired height by a deployment winch. The port could be positioned with the accuracy of ±1 inch.
4. Steady State Slurry Test Matrix: The ITSM had already satisfied the performance criteria for a range of slurry conditions on the bench-scale setup. These tests focused on in-tank monitoring of weight percent suspended solids and under conditions anticipated in the tank. All slurry measurements were carried out on a test slurry tank on a ground level (Figure 7). Samples from the tank slurry were taken and analyzed in the laboratory to obtain reference undissolved solids weight percent. The slurry tank was 5-foot in height and contained well-circulated slurry for consistency. Table 2 summarizes the results obtained from the steady state prototype tests. The standard deviation was less than 0.05 for all the cases.

Table 2. Summary of the results obtained at all matrix conditions for first prototype testing

Set Density of Carrier Fluid	Set Temperature	Reference Wt% Solids	Average Measured Wt% Solids	Standard Deviation
g/cc	°C	g/cc	g/cc	g/cc
1.25	40	1.21	1.15	0.03
1.25	40	4.68	4.75	0.02
1.25	40	13.33	13.24	0.04
1.25	40	18.41	18.30	0.04
1.16	40	1.65	1.57	0.01

Figure 7. The slurry tank used during steady state tests. It has SCR-controlled heaters for temperature control and a pumping system that keeps the slurry well mixed by drawing slurry from the top and pumping it through the pump bottom.

5. Unsteady State Slurry Test Matrix: The ITSM was studied for the dynamic response to changes in solid weight percent and carrier fluid density. This was achieved by imposing a step change in weight percent solids and density of carrier fluid, respectively. It is noted that in the real situation weight

percent solids may show a dynamic variation, but the carrier fluid density is expected to remain constant. The tests revealed less than a 1 second delay between the step change and when stable readings were in accordance with the changed slurry weight percent and carrier fluid density.

6. Pump Performance: The initial pump installed developed problems due to the low clearance between the stator and rotor. This was subsequently modified to a pump with two stages and was found to perform adequately. The pump was allowed to run for a period of 12 hours continuously for endurance testing with slurry maintained at 70°C and showed no loss of flow. No leakages were observed.
7. Data Acquisition and Analysis: Data acquisition was carried out using LabVIEW. It was programmed to apply temperature correction factors and calculate average measured undissolved solid weight percent after each run. Although the filtrate temperature may be less than that of the slurry due to its slower flow rate and thermal loss to the ambient temperature, both the slurry and filtrate temperatures will be allowed to achieve thermal equilibrium prior to collecting data for analysis for steady state analysis.

SLIM Verification Tests

The SLIM system was the result of a down-selection of various techniques evaluated for detection and visualization of the solids level in the tank. After completion of this down-selection and preliminary bench-scale testing, FIU evaluated the capability of the sonar to perform accurate measurements with the varying liquid and environmental parameters within the HLW tanks. For example, Hanford HLW tanks are typically filled with highly saturated caustic solutions (pH>14) to minimize corrosion due to radioactivity [10]. The caustic nature of the solution causes low-density oxalate to form that remains suspended causing multiple layers of solids to form and slowly settle out. These oxalates can cause density variation between 1 g/cm^3 to 1.4 g/cm^3 in the liquid supernate while suspended, and can form a low-density layer above the settled tank solids. Without a detection method that can identify the oxalate layers or correct for the density variations in the supernate, can lead to inaccurate solid layer measurements. Also, the proximity of the tank wall and floor to the sonar head must also be taken into account as the multiple reflections off these surfaces can lead to a distorted image or “ghost image”. Another factor to consider was the re-suspension of solid particles due to pumping or mixing in HLW tanks. The scattered particles that result from these activities will affect propagation of sound wave by reflecting or deflecting it different directions resulting in faulty readings. FIU used these and additional issues in the development of experiments to validate the technology for deployment.

Two experiments were designed to test the sonar’s ability to accurately detect the solid-liquid interface in a 7-foot, 2-inch diameter by 7-foot, 4-inch tall test tank (Figure 8). Various interfaces created by a kaolin clay layer and water was imaged (Figure 9). The sonar was able to accurately measure the interface to within 1% of the actual physically measured value. In addition, a third experiment was designed to study the effect of scattered solid particles present in the fluid on sonar images. The kaolin clay present in the tank was re-suspended with the help of submersible pump to simulate the scattered particles present in HLW tank during mixing or pumping. The conclusion was that the profiling sonar can detect the solid-liquid interface accurately even when 30% solids (by weight) are present in the liquid. However, there is generation of ghost images in the scan data obtained from sonar software. This is due to the pump agitation causing air bubbles and solids to be present in the water. Because of the air bubbles and solids, the sound waves are scattered in different direction leading to the multiple reflections from single point. The ghost images cause errors in the measurement as they not easy to distinguish them from the actual interface.

Figure 8. FIU Test Tank (7-ft 2-in diameter) for the Solid Liquid Interface Monitor (SLIM).

Figure 9. Kaolin Clay in tank configured to take up half of tank bottom.

After testing sonar for its accuracy, a fourth experiment was designed to test the sonar's ability to detect solids having a similar density to the fluid. This experiment was performed in a fiber glass tank with plastic beads placed in water in various forms (Figure 10). These plastic beads had density of 1.04 g/cm^3, which is only 4% more than the water density and simulated the light density oxalates present in HLW tanks. The sonar was able to accurately detect the presence of the low-density beads within 1% of the actual measurement. Issues with waves reflecting off sharp edges within the experimental setup accounted for the relative error in measurement of object widths.

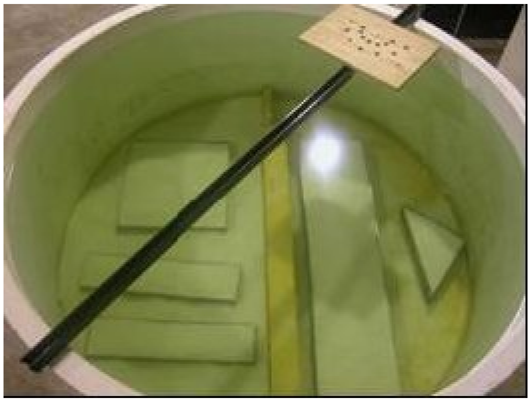

Figure 10. 6 ft plastic tank with 5 metal forms filled with plastic beads of density 1.04 g/cc.

To study the effect of a tank wall and floor near the sonar transducer, a two-phase experiment was developed. During the 1st phase, the sonar was placed at various heights from the tank bottom and images were recorded (Figure 11). The sonar head require a vertical distance greater than 0.6-foot from the top of the closest scanning object to ensure an accurate measurement. In the 2nd phase, a stainless steel metal plate (2 ft. x 2 ft.) was placed at certain distance from the sonar head and images were recorded. It was determined that the sonar requires a distance greater than 0.6 ft from the tank wall in order to ensure an accurate measurement of the objects in the scan area.

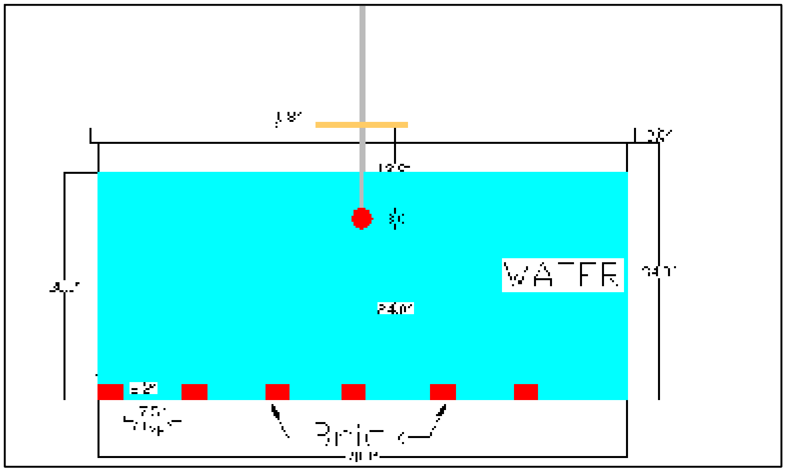

Figure 11. Sonar and test brick positions used to test effects of sonar to tank wall and objects. Note that the sonar head height can be adjusted from the tank wall and tank top.

After analyzing the sonar performance for detecting the solid-liquid interface in water, the medium was changed to a caustic solution. The sonar was placed in a caustic solution and heated to 45°C to determine any possible degradation in performance (Figure 12). The solution was heated to increase the reaction rate of the sonar hull (titanium and PEEK) with the caustic solution. This experiment validated the conclusions of prior literature searches that revealed minimal to no reaction between the caustic solution and the sonar head. The only effect of the solution on the head was on an Aluminum clamp used to secure the PEEK boot to the Titanium housing. The clamp has since been replaced with a stainless steel equivalent.

Figure 12. Sonar head suspended in caustic solution.

The final experiment on the sonar was designed to image objects placed in caustic solutions with varying density values. Correct sound speeds for all the solutions were calculated to correct the sonar reading. The density of the caustic solution was varied by adding appropriate amounts of sodium nitrate into the water. Sodium nitrate was chosen because of three reasons: its readily dissolves in water; HLW tanks have large amounts of sodium nitrate in their caustic solution; and it increases the density of water from 1 g/cm^3 to

1.4 g/cm^3 which is the required range of density of caustic solution present in HLW tanks. The experiment concluded that the sonar head would have to undergo speed of sound calibration within the tank during deployment. The effects of varying density, temperature and pH can shift the speed of sound in the solution by up to 30%, leading to gross measurement errors. FIU has since developed a procedure to calibrate the sonar within the tank by using a known object location.

CONCLUSIONS

The remote monitors designed and developed by FIU provide improved technologies for analyzing HLW retrieval and storage. Specifically, the ITSM provides the accuracy of lab-scale methods in a tank deployable configuration. The SLIM has been designed with the rigors of a HLW environment to ensure that the system can provide useful information throughout the retrieval campaign for each tank. These systems utilize advanced commercial monitors into exhibit how advancements in technology coupled with clever integration can greatly improve the tracking and analysis of HLW through the disposition lifecycle.

REFERENCES

1. Office of Environmental Management, “Radioactive Tank Waste Remediation Focus Area Technology Summary”, OSTI ID: 90180, US Department of Energy (USDOE), 1995.
2. Hylton, T.D., et al., "Comparative Testing of Slurry Monitors," Oak Ridge National Laboratory (ORNL), (1998).
3. Bamberger, J.A. and Greenwood, M.S., "Development of a Density Sensor for In-Line Real-Time Process Control and Monitoring of Slurries during Radioactive Waste Retrieval and Transport Operations at DOE Sites," Pacific Northwest National Laboratory (PNNL), (2001).
4. Bontha, J.R., et al., "Qualification of Three On-Line Slurry Monitoring Devices for Application during Waste-Retrieval Operations at DOE Sites," Pacific Northwest National Laboratory (PNNL), (2000).
5. Ebadian, M.A., et al., "Center of Expertise for the Development and Deployment of Tank Slurry Monitoring (Dual Coriolis)," Florida International University, (2002).
6. Carpenter, K., “Functions and Requirements for Automated Liquid Level Gauge Instruments in Single-Shell and Double-Shell Tank Farms”, HNF-4205, Rev. 0., Numatec Hanford Corp. (1999).
7. Danna, M.A., "Tank Farms Technical Safety Requirements, Vol. 1 Engineering Change Notices," HNF-SD-WM-TSR-006, Rev. 3, CH2MHill Hanford Group, Inc., (2003).
8. Andrews, J. E., "Acceptance Test Report for the 241-AZ-101 Ultrasonic Interface Level Analyzer," RPP-5681, U.S. Department of Energy (2000).
9. Hylton, T.D., "An Evaluation of a Dual Coriolis Meter System for In-Line Monitoring of Suspended Solids Concentrations in Radioactive Slurries," Oak Ridge National Laboratory (ORNL), (2000).
10. Webster, J.G., "The Measurement, Instrumentation, and Sensors Handbook," CRC Press (1999).
11. Washenfelder, D.J., "Double Shell Tank (DST) Integrity Project High-Level Waste Chemistry Optimization," Waste Management Symposia Inc. (2008).