Testing of a 3-D Sonar for Future Deployment to Image Solids on the Floor of Hanford, HLW Conditioning Tanks – 15646

David Roelant* and Dayron Chigin*
* Florida International University

ABSTRACT

Florida International University (FIU) has tested the capability of 2-D and 3-D sonar systems to image solids settled on the floor of tanks, on the bottom of streams and small rivers, and in 55 gallon drums. FIU developed and successfully tested the Solid-Liquid Interface Monitor (SLIM) for mapping the interface between supernatant and settled solids in several test tanks. SLIM is comprised of: a sonar, a mechanical system for deploying the system into large high-level radioactive waste (HLW) tanks, and imaging programs and algorithms developed at and by FIU faculty and staff. Early testing had the objective to demonstrate the ability of SLIM to image and quantify the height and volume of settled solids on the floor of 1-million-gallon, HLW tanks at Hanford. Testing showed that SLIM: (1) functions accurately in liquid radioactive HLW tank conditions [i.e., caustic (pH>14), warm (up to 45 degrees Centigrade), and highly radioactive]; (2) provides accurate imaging of solids surfaces (1-2% relative error in the height of interfaces); and (3) provides an excellent volume estimation of the solids, thereby allowing engineers to fill tanks closer to the maximum allowed level and optimize solids retrieval; and (4) enables better placement of pumps inside tanks during retrieval to minimize the potential for plugging. The NEW Hanford technology need is for rapid imaging (even during vigorous mixing) of solids on the floor of conditioning (mixing) tanks. Results of recent successful testing show imaging times under 1 minute, solids volume estimates with <5% error and effective filtering and visualization.

INTRODUCTION

The retrieval, treatment, storage and final disposal of high-level radioactive waste (HLW) is estimated to cost hundreds of billions of dollars. While Savannah River has been retrieving and treating HLW for almost 20 years, Hanford is over a decade away from being able to treat HLW. Recent delays in the planned opening of the Waste Treatment and Immobilization Plant (WTP) is currently forcing DOE to plan for other HLW treatment until the WTP comes online.

Florida International University (FIU) has developed and tested several technologies and associated deployment platforms for use in HLW tanks (sonar, electrical resistance tomography, ultrasonics, robotic crawlers, and more).[1, 2] This paper focuses upon one in-tank technology, the Solid-Liquid Interface Monitor (SLIM). FIU has built and tested multiple prototypes of SLIM which consist of: (1) a commercial (custom designed) sonar; and (2) a deployment platform to safely and effectively insert the sonar into a Hanford HLW tank via a 4-inch (10 cm) dia. riser. A new Hanford HLW need has arisen to deploy a rugged imaging technology into HLW mixing tanks to determine if all solids are completely mixed (i.e., suspended and not on the floor) during all phases of mixing and retrieval. Select, recent research on FIU's 2-D and 3-D sonars for these two very different Hanford technology needs is presented.

The technology needs for SLIM deployment in 1M gallon HLW tanks include:

- Accurate positioning of pumps in tanks to be emptied to prevent possible plugging; and
- Imaging of the rising solids layer in double-shelled tanks (DSTs) receiving retrieved waste (More important technology need for Hanford).

SLIM was envisioned as a technology to provide imaging to help site operators fill HLW DSTs with solids right up to the maximum level allowed from safety considerations of possible gas generation. Without SLIM, conservative measures are required to ensure that the solids remained below the critical safety height in the tank. With the deployment of SLIM, there was the potential for an enormous cost saving. The retrieval of HLW from single-shelled tanks was costly and time consuming due to the very limited unfilled volume in the DSTs at Hanford. Retrievals required the addition of millions of gallons of water to retrieve waste and then the evaporation of this water once the waste was in the DSTs.

Functional requirements for SLIM in 1-million-gallon HLW tanks were:

- Detect a solid-liquid interface during light mixing and after settling;
- Withstand exposure to both high-level nuclear radiation dose and the highly caustic solution (pH > 14);
- Be deployable through a 4-inch (10 cm) dia. riser at the top of the tank;
- Operate in liquid 61 cm or more above the settled solids layer;
- Identify the average interface elevation integrated over an area of at least 0.46 m^2;
- Avoid disturbing the interface by the act of measuring;
- Be capable of at least hourly readings of the interface;
- Provide isolation between the sonar deployment system and tank headspace while in a retracted state;
- Provide system containment from the outside, open-air environment (top of risers above tank and overlain soil); and
- Minimize potential for shear loads to be applied to the riser used.

Numerous experiments were performed by FIU with support from Hanford scientists and engineers over the years. The titanium sonar with polyurethane cover was tested to caustic conditions in the tanks (pH>14), past the maximum temperature in the tanks (45 degrees Centigrade); and with active, vigorous mixing of solids (suspended solids up to 30% of the volume of the tank liquid). Kaolin clay was used as the surrogate HLW solids with settling rates similar to Hanford HLW solids. All tests were very successful. The sonars accurately imaged the dimensions of objects such as bricks as well as the height of settled solids such as glass beads, plastic beads, kaolin clay particles, and soil sediments. Sonar testing was performed in: a 55-gallon barrel; a large private swimming pool; and in a large, water channel in a state park. Most of the testing was carried out in 3 different test tanks.

RESEARCH DESCRIPTION

Fig. 1 contains a photograph of FIU's 2-D profiling sonar and Fig. 2 shows FIU's 3-D sonar.

Fig. 1. Custom-built 2-D Profiling Sonar at FIU.

In Fig. 2 is a photograph of FIU’s custom designed and built 3-D Sonar.

Fig. 2. FIU’s 3-D Sonar

Many experiments were performed on the 2-D profiling sonar for application inside 1 million gallon HLW tanks. The select experimental result shown below is informative for cases where a HLW technology need requires imaging during vigorous mixing. The sonar image in Fig. 3a shows no mixing of kaolin particles while the image in Fig. 3b shows vigorous agitation and mixing of kaolin such that 30% by volume of the liquid contains suspended kaolin particles. Both sonar images were generated in FIU's metal test tank with a 218 cm diameter and 229 cm height. At the bottom of the test tank was 30 cm of settled kaolin.

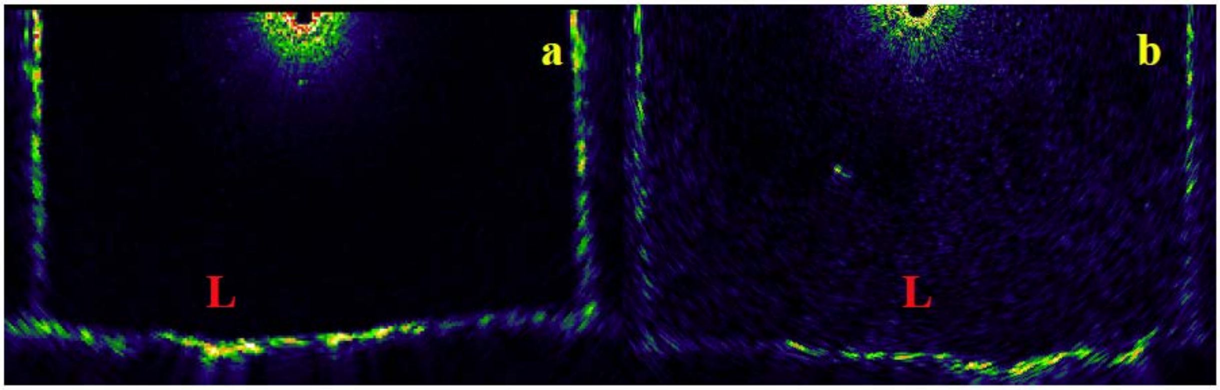

Fig. 3. 2-D Sonar Image of 30 cm of settled kaolin on the floor; a) without mixing; and b) with mixing such that 30% of the liquid volume was from entrained solids. Radius of the tank, L, is 109 cm.

Tests were conducted on the accuracy in measurement of the heights of solid layers and the dimensions of objects. Results for spatial accuracy are shown below in Table I for 3 tests (out of hundreds). The speed of sound was corrected for temperature and fluid density. Note that the relative error in layer heights and object dimensions as measured by the 2-D sonar are typically less than 1%.

Table I. Measured Spatial Accuracy of SLIM 2-D Sonar

Accuracy	**Sonar to Object Distance (meters)**	**Additional Conditions**
+/- 0.36 cm	2	None
+/- 0.91 cm	2	30% solids in liquid during mixing
+/- 1.2 cm	6	None

Hanford recently identified a technology need to image inside HLW mixing (conditioning) tanks during mixing and retrieval operations to ensure that HLW mixing is complete (i.e., all particles are suspended) prior to retrieving the waste from the tank. This technology need requires the ability to rapidly image limited floor areas of Hanford HLW mixing/conditioning tanks throughout the mixing cycles. In-tank pulsed jet mixers (PJMs) are used in these HLW mixing tanks. Site engineers desire a technology that can rapidly (<1 minute) monitor for settled solids on tank floors during the PJM cycles. The mixing in these tanks is expected to put greater forces on the sonar; entrain more solids in the HLW liquid; and most importantly, require very rapid sonar scans. All previous testing allowed timeframes of 2-10 minutes to generate the 10-400 2-D sonar scans to accurately image solids on the tank floor. The commercial imaging software for the 3-D sonar is not able to generate images in the short times now required (e.g., less than 30 seconds) for application in mixing tanks. Therefore FIU has created its own sonar imaging software to post-process the data. FIU has also developed several sonar data filters to remove the effect of scattering off walls, entrained solids and double-scattered sonar pulses. Summarized below are: the background of the current testing; the results to date and a detailed description of the ongoing testing of the sonar during mixing operations.

The FIU 3-D sonar was designed by FIU and custom-built by a commercial firm. Its materials ensures compatibility with caustic HLW (pH>14). Its design with minimum electronics inside the sonar ensures a much longer lifetime compared to standard sonars from exposure to high nuclear (gamma) radiation dose rates. The 3-D nature of the sonar with 2 internal motors greatly simplifies the design of the platform needed for deploying into HLW tanks.

Sonar testing for rapid imaging in Hanford HLW mixing/ conditioning tanks started in early 2014 with the following objectives:

1. Determine the sonar system parameters to optimize the image resolution;
2. Measure the time required to create sonar images for relevant sonar system parameters and ranges; and
3. Identify if mixing is complete (i.e., solids are all mixed with none remaining on the tank floor). If solids are on the tank floor during any of the PJM cycles, then FIU is to roughly estimate the volume of the settled solids.

Results demonstrated that limited floor areas could indeed be imaged with good resolution in less than a minute (results ranged from 15 to 45 seconds). Testing also revealed the optimal settings for the sonar system for this application. The 3 critical parameter optimizations are:

1. Maximum number of steps along each 2-D scan and hence the number of pulses along each 2-D scan;
2. Minimum number of rotation motor steps (fewest number of 2-D scans taken since the time for the motor to rotate between scans is long compared to the time between pulses along a 2-D scan);
3. 30-degree viewing angle setting allowing for sonar to be placed close to the floor area with settled solids in order to maximize the number of sonar pulses on the field of view.

Our research analysis showed that several post-processing algorithms were needed to filter out sonar pings directly scattered off entrained solids and walls, or double scattered before detection. For 2-D sonar scans with data missing due to the short imaging time, corrected data is required for further processing of the sonar image. Finally, interpolation was needed to fill in the height of the solids layer between 2-D sonar swaths to enable a 3-D volume calculation of the solids on the tank floor. Filtering, interpolation and correction algorithms were developed throughout the summer of 2014. Software to display the sonar data was developed since the commercial sonar visualization software will not develop any images when the number of surface points imaged is limited in number (common for our application with short imaging times).

To demonstrate some of the data visualization and filtering techniques developed at FIU, the 3-D sonar images below are for a brick in a test tank. In this test, we contrast results for the highest and lowest resolution settings. The highest resolution scan takes 2-10 minutes, more time than allowed for scanning during a single PJM cycle. At the lowest resolution setting, the sonar imaging software from the manufacturer will not interpolate the data to create a 3-D image. The software does, however, collect the data into an ASCII file which can be imported into external imaging programs. One such simple program was first tested using the sonar image in the high resolution image to validate its accuracy. The algorithm was then used to generate maps of the low resolution image. Fig. 4 shows the sonar graphical user interface for the high resolution image. Fig. 5 shows 3 different views of the 3-D brick and tank bottom surface using the 3-D mapping algorithm. The images align and the depth locations are the same as produced by the sonar software.

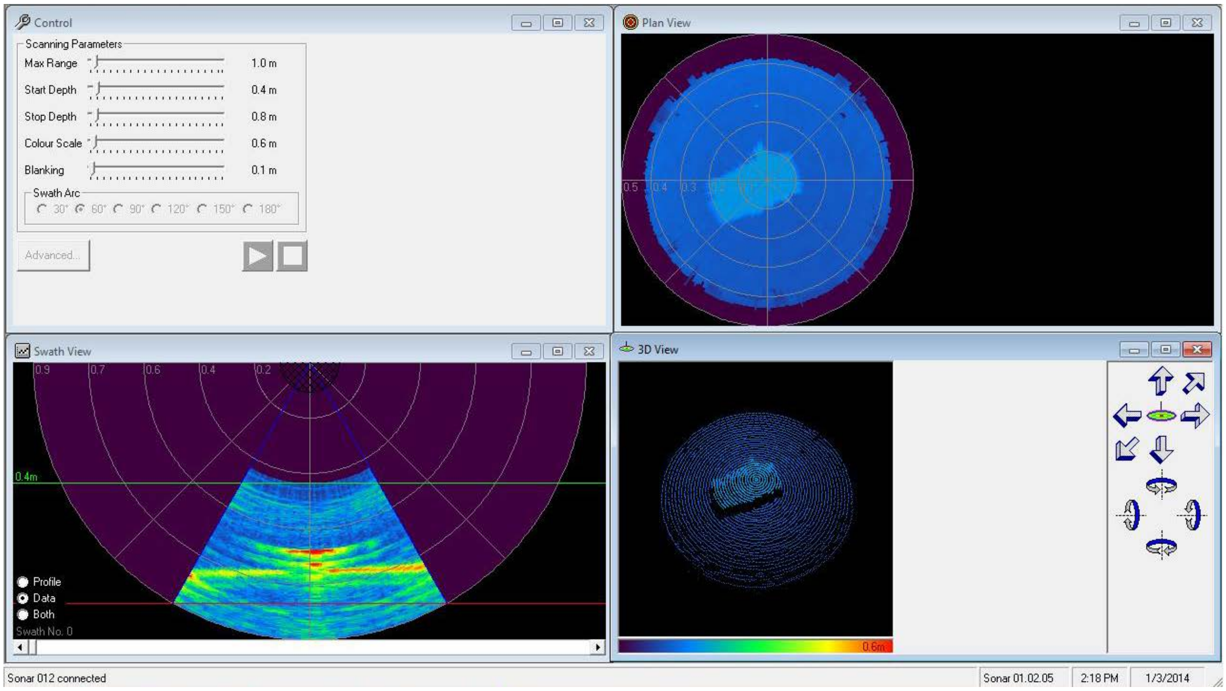

Fig. 4. High resolution image using sonar manufacturer's graphical user interface. The 4 views include: sonar settings (upper left), top view (upper right), side view (lower left) and a 3-D map of the brick in the bottom of the test tank (lower right).

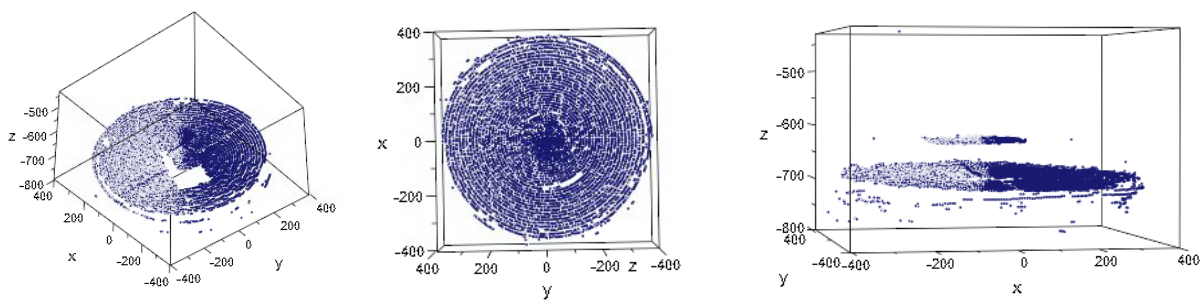

Fig. 5. High resolution images from 3D mapper.

The low resolution image from the sonar's graphical user interface shows the 4 swaths the sonar obtained from the tank bottom but no images were generated (see Fig. 6). Fig. 7 shows the 3-D plots obtained from the external mapping algorithm. To estimate the volume of those solids in certain floor areas, FIU will improve the 3-D mapping to allow for more robust interpolation of points between the individual sonar swaths.

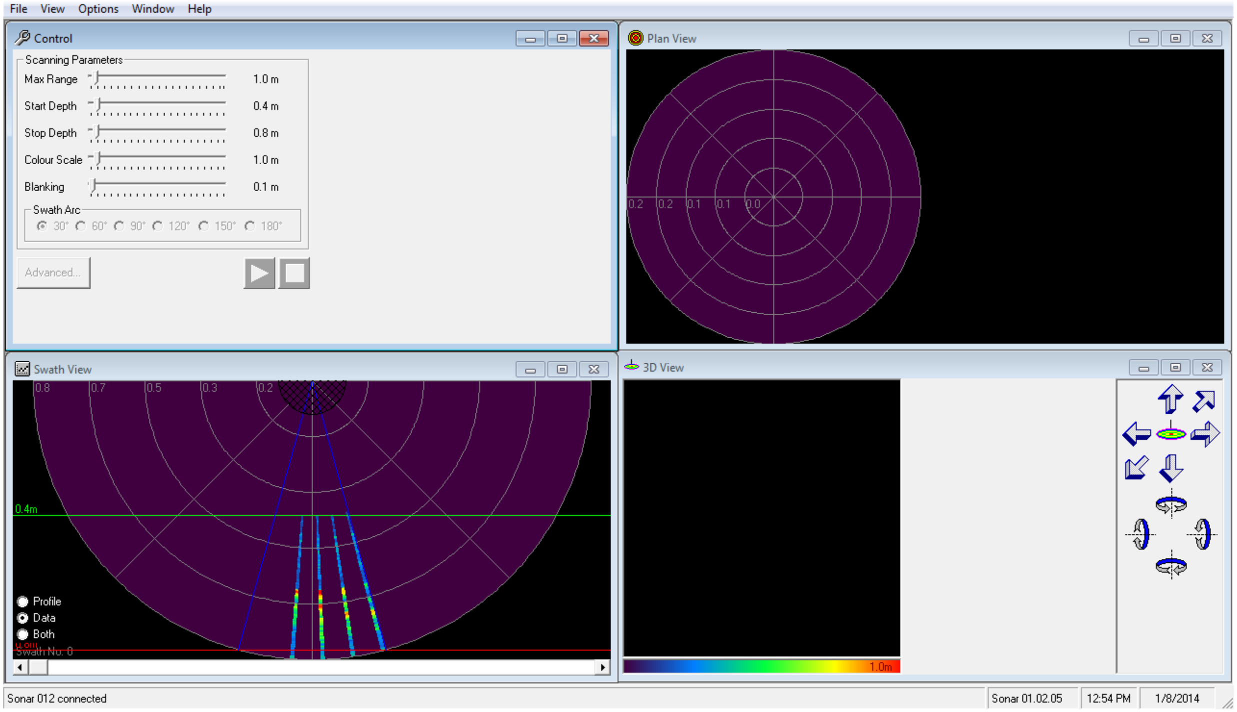

Fig. 6. Low Resolution Image – commercial sonar does not create an image with low density of data points.

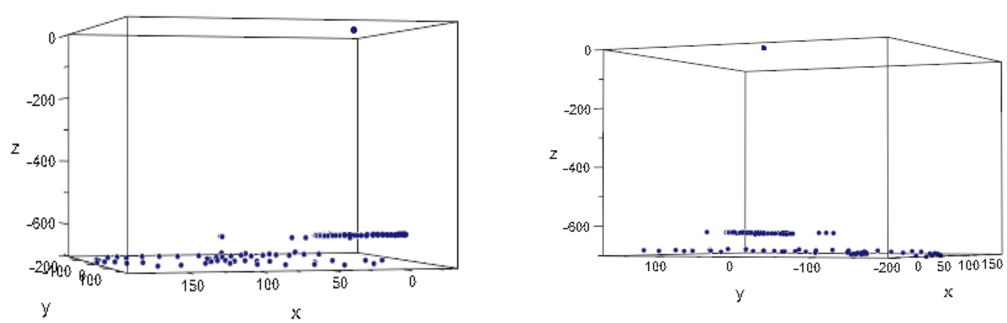

Fig. 7. Low resolution plots from 3D mapper.

The current phase of testing of FIU's 3-D sonar is evaluating the sonar's ability to image solids on a tank floor with the sonar located 0.3 – 1.3 m above the tank floor while vigorous mixing of kaolin clay suspends up to 30% solids in the tank liquid. These tests are evaluating the accuracy of the sonar to collect images of solids on the tank floor to estimate the volume of settled solids while entrained solids are attenuating the sonar signals penetrating to the floor and again returning to the sonar. The volume percentage of kaolin suspended in the tank liquid is being varied from 0% to 35% or until the image of a solid object on the floor is lost due to sonar signal loss and noise from scattering off entrained solids. FIU is ensuring that air mixing in the liquid is minimized since even 1% air entrainment has been shown to completely attenuate strong sonar signals. Rapidly mixing water from nozzles is being controlled since it can result in the scattering of sonar pings and signal loss. This testing will demonstrate whether it is possible to image solids on a tank floor while mixing conditions mimic those of PJMs in HLW conditioning tanks.

FIU has initiated the experimental tests of the 3-D sonar for its ability to image solids on the tank floor while solids are beings mixed (suspended) in a tank. Kaolin clay with a diameter of 1 micron is an excellent surrogate for the settled solids in Hanford high-level radioactive waste tanks. Initial testing was completed for 0%, 1% and 3% volume of Kaolin in the water. Data was collected for both 30 degree and 60 degree swath arcs with scans taking 29 seconds and 42 seconds, respectively. The unfiltered images for both the 30 and 60 degree arc scans are shown below for 3% Kaolin by volume.

The sonar image in Fig. 8 is for a 30 degree swath arc. It is a scan that focuses upon the center of the tank. The dark blue shows the tank floor, the light blue is the top of the piece of unistrut and the orange/red/yellow layer is the kaolin that was not lifted by the pump. It is important to note that the pump inlet and outlet were on opposite sides of the tank at the bottom and the direct fluid flow was in direct alignment with the unistrut and this is why all there is no settled Kaolin in the blue flow field.

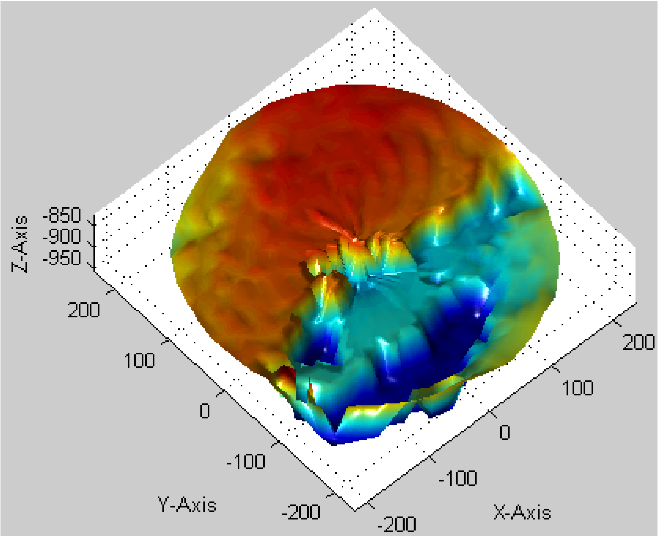

Fig. 8. 3-D Sonar Scan for: 30 Degree Swath Arc; 29 seconds; and 3% vol. Kaolin

The pump size, positioning and flow design for the experimental setup will be modified to assure that solids at 1-20% volume of Kaolin will all remain suspended and not settle on the floor. Calculations and empirical tests will be used to confirm that the pump flow field is properly designed for complete mixing and suspension of particles.

Upon completing the 3% kaolin tests, the 3-D sonar began to give faulty, unreproducible data. Troubleshooting for extensive “ghost” scattering imaging from liquid around the sonar is underway. Initial testing demonstrated that the power source and pins in the sonar cable are not the source of the problem. Images of the sonar unit has been shared with the instrument manufacturer to identify the problem and find a solution. A few additional sonar images were collected to help with the diagnosis.

Once the sonar problem is resolved, the mixing tests will be completed and shared with DOE Hanford site engineers and scientists. The next phase of testing in 2015 will involve meeting any system functional requirements and deployment requirements to allow the system to be deployed inside Hanford HLW mixing tanks.

CONCLUSIONS

FIU successfully developed and tested Solid-Liquid Interface Monitors. Results showed that SLIM met the functional requirements as well as the safety and operational requirements to allow it to deploy in

Hanford HLW tanks. SLIM also showed that it could be used to provide imaging to help site operators fill HLW DSTs with solids right up to the maximum level allowed from safety considerations of possible gas generation. The deployment of SLIM for this purpose holds the potential for enormous cost savings.

Many experiments were performed by FIU with support from Hanford scientists and engineers. The 2-D sonar was shown to be impervious to highly caustic liquids (pH>14); was able to operate at the highest temperatures expected in HLW tanks (45 degrees Centigrade); and was able to easily image through 2 meters of liquid during vigorous mixing of solids (where suspended solids constituted up to 30% of the volume of the tank liquid). Most testing showed that the sonar was accurate to better than 1% relative error in distances. Some tests at elevated temperature as well as some tests with highly caustic liquids caused relative errors of as high as 5-6% due to the change in the speed of sound from the number assumed.

Testing in 2014-2015 on FIU's 3-D sonar has been successful to date. Early testing objectives include: 1) Determine sonar system parameters to optimize the image resolution; 2) Measure the time required to create useful sonar images; and 3) Identify if mixing is complete and estimate the volume of any settled solids on the tank floor. Objectives 1 and 2 have been met and testing to meet objective 3 is ongoing. Results to date have demonstrated that limited floor areas can be imaged with good resolution in less than a minute (results ranged from 15 to 45 seconds). Testing also revealed the optimal settings for the sonar system for this application.

Research analysis has shown that several post-processing algorithms were needed to filter out sonar pings directly scattered off entrained solids and walls, or double scattered before detection. For 2-D sonar scans with data missing due to the short imaging time, corrected data is required for further processing of the sonar image. Finally, interpolation was needed and therefore developed to fill in the height of the solids layer between 2-D sonar swaths to enable a 3-D volume calculation of the solids on the tank floor. Filtering, interpolation and correction algorithms were developed throughout the summer of 2014. Software to display the sonar data was developed since the commercial sonar visualization software will not develop any images when the number of surface points imaged is limited in number (common for our application with short imaging times).

REFERENCES

1. Monitoring the solid-liquid interface in tanks using profiling sonar and 3D visualization techniques, Author(s): Nitin Sood; Jinsong Zhang; David Roelant; Rajiv Srivastava, Proc. SPIE 5669, Visualization and Data Analysis 2005, (11 March 2005); doi: 10.1117/12.587979.

2. WM2010 Conference, March 7-11, 2010, Phoenix, AZ Remote Monitors for High Level Waste (HLW) – 10098 Jose M. Varona, Amer Awwad, Dwayne McDaniel, David Roelant, Jairo Crespo and Reny Rosales.