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Design and Testing of a Solid-Liquid Interface Monitor for High-Level Waste Tanks

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ABSTRACT

A high-level waste (HLW) monitor has been designed, fabricated and tested at full-scale for deployment inside a Hanford tank. The Solid-Liquid Interface Monitor (SLIM) integrates a commercial sonar system with a mechanical deployment system for deploying into an underground waste tank. The system has undergone several design modifications based upon changing requirements at Hanford. We will present the various designs of the monitor from first to last and will present performance data from the various prototype systems. We will also present modeling of stresses in the enclosure under 85 mph wind loading. The system must be able to function at winds up to 15 mph and must withstand a maximum loading of 85 mph. There will be several examples presented of engineering tradeoffs made as FIU analyzed new requirements and modified the design to accommodate. We will present our current plans for installing into the Cold Test Facility at Hanford and into a double-shelled tank at Hanford. Finally, we will present our vision for how this technology can be used at Hanford and Savannah River Site to improve the filling and emptying of high-level waste tanks.

INTRODUCTION

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 is a priority. Retrieval and treatment of waste from these tanks pose a considerable challenge.

During retrieval of waste over the years, there have been several transfer pipelines that have been plugged due to the pumping of liquids containing high solids concentrations. Costs exceeding $3M dollars have been expended dealing with issues related to the plugged line and to install a single, new pipeline section next to the plugged line. The inability to monitor the actual solid-liquid interface 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 very aggressive schedule for treatment of a portion of the waste over the next decade, the ability to map the solids interface could save many millions of dollars by shortening schedules, lowering risks of delays, and avoiding the costs of plugged pipelines.

Presently the procedure at the DOE Hanford site for locating the level of solids in 70' diameter tanks is to lower a weighted ring into the tank and measure the level at a single point. This method is problematic since: it is at one point in a 70' diameter tank; 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. In January 2003 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). The plan was for a multiyear project that would culminate with the deployment of the technological solution into a Hanford tank. During the first year, 2003, FIU studied various options for a technological solution and worked with the Hanford site personnel in selecting the best candidate solutions.

To overcome the uncertainty of the solids level across the tank Hanford set a minimum criterion for mapping the solid-liquid interface (see listing of functions and requirements at the end of this section). The most discriminating requirement is for the system to be deployed through a 4-inch riser (pipes that provide access to the headspace of HLW tanks), operate in HLW environment, and map the interface over at least 5 square feet.

After screening several hundred sensors and imaging technologies from four different specialized databases, FIU identified several technologies that based upon physical principles could achieve the determination of the interface level over 5 square feet. After consulting with experts from FIU and from across the country and stressing that the monitor would have to be mature enough for deployment in a real waste tank within a few years, the list of technologies was shortened to two promising imaging technologies and a few technologies that would open mechanically to make several point measurements over an area at least 5 square feet in size. After viewing several potential mechanisms for deploying a system through a 4-inch riser and then mechanically spreading the sensors over the minimum 5 square feet and after viewing the failed history of mechanical systems deployed in the hostile tank environment, it was decided that the two imaging technologies were more promising. The imaging technologies would be able to image a larger area with more resolution and due to their simpler design, would lower the risk of operational failure.

Bench-scale testing of electrical resistance tomography (ERT) and sonar imaging, the best two candidate technologies was completed during the first year. Both technologies showed the ability to image the solids layer and to meet the other technical requirements. Both could image the interface over an area much larger than the minimum required five square feet. The ERT system deployed was a single linear array with 14 electrodes on a single Teflon rod. This electrode configuration is far inferior to the multi-ring electrode configuration typically used for in-tank process monitoring. In contrasting the imaging results of the two technologies it was obvious that sonar was far superior in imaging area and resolution, and less technically risky when scaling up for use in million gallon tanks. The results of all tests and R&D for 2003 can be found in the 2003 Year End Report [1] for this project. Based upon the success of 2003 testing, the Hanford site personnel agreed that during the second year, 2004, FIU should design and build a sonar-based SLIM and continue testing the sonar under more challenging conditions. The SLIM platform has to be able to safely and effectively deploy the sonar head into the 1 million gallon HLW tanks at Hanford through a 4-inch pipe riser.

Testing of the sonar in 2004 included: tests of the effect of solid objects inside the tank that were near (0 - 2 feet) from the sonar probe on imaging; tests with solids that have a density only slightly more (5%) than the liquid to mimic the light, slowly-settling solids found in the uppermost layers of settled solids in the bottom of HLW tanks; tests on ability of the sonar to image the solids layer even when there are significant amounts of solids still suspended in the liquid during or for several minutes after cessation of agitation. The sonar did extremely well in all these tests. The experimental results include the analysis of many high resolution sonar images generated and are shown in the 2004 Year End Report [2] for this project.

Since the sonar proved to be able to withstand the harsh environment of the HLW tanks, in the third year, 2005, work started on the design of a manually operated tank deployment system for the sonar. After obtaining approval of the design by the Hanford site personnel, the first-generation deployment system was fabricated and put through several tests on a tank riser mockup. The tests showed that the deployment system was an effective method of deploying the sonar through the 4” tank riser.

A change in the site’s tank operating procedure required the deployment system be completely operated via remote control. In the fourth year, 2006, the deployment system was redesigned to be fully automated. After obtaining approval of the design by the Hanford site personnel, the second-generation deployment system was fabricated and put through several tests on a tank riser mockup. The tests that were witnessed by Hanford site personnel proved that the deployment system could be operated remotely.

During design reviews for the SLIM Hanford engineers identified a new requirement that the system be sealed against possible wind dispersion of HLW contamination on the system. The third-generation system design addressed this concern with the addition of three 10-foot sections of 5-inch diameter aluminum pipe along with an aluminum box to completely enclose the system. Along with other smaller modifications, this led to the need for a more sophisticated wind load calculations (85 mph requirement) and lightning mitigation.

During final design reviews, Hanford engineers stated that for the removal process, SLIM and the enclosure need to be bagged and the tank riser needs to be isolated from the atmosphere. This requirement led to use of a longer enclosure mast and the addition of the ball valve below the enclosure box. In addition, the Hanford engineers identified a requirement that the risers can only take a small moment and shear load. This precipitated a change in the support structure and the addition of a bellow between the riser and the enclosure box. At the time of this paper, FIU was in the process of obtaining final design approval for the enclosure so fabrication could begin.

EXPERIMENTAL RESEARCH

The U.S. DOE and the HLW contractor at the Hanford site requested technology development support from Florida International University (FIU) to help them identify a solution to meet their critical need for an in-tank, solid-liquid interface monitor (SLIM). The SLIM must be able to:

- Detect a solid-liquid interface during and after settling.
- Withstand exposure to both high-level radiation and highly caustic solution ($pH > 14$)
- 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
- 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 interface by the act of measuring.
- Be capable of at least hourly readings of the interface.

A sonar-based system capable of meeting the above requirements was designed and fabricated. The design utilizes Imaginex Model 881A Sonar, which was put through several rigorous tests in 2004 to determine its capability in meeting the SLIM requirements. The sonar performed extremely well in these tests, which included the analysis of many high-resolution sonar images.

Since the sonar proved to be able to withstand the harsh environment of the HLW tanks, in the third year, 2005, work started on the design of a manually operated tank deployment system for the sonar. After obtaining approval of the design by the Hanford site personnel, the deployment system was fabricated and put through several tests on a tank riser mockup. The tests showed that the deployment system was an effective method of deploying the sonar through the 4” tank riser.

A change in the site’s tank operating procedure required the deployment system be completely operated via remote control. In addition the site also required the deployment system be entirely enclosed to eliminate the risk of radioactive contamination exiting the tanks. In the fourth year, 2006, the deployment system was redesigned to be fully automated. After obtaining approval of the design by the Hanford site personnel, the second-generation deployment system was fabricated and put through several tests on a tank riser mockup. The tests that were witnessed by Hanford site personnel proved that the deployment system could be operated remotely. This paper presents progress to date on the design, fabrication and testing of the first and second-generation SLIM.

SLIM DESIGN

First-Generation SLIM Design

The first-generation SLIM is comprised of three components: sonar, deployment system, and a turntable base. The sonar is a commercial off-the-shelf technology capable of profile imaging. The sonar is able to use 310, 675 and 1000 kHz frequencies for scanning. The deployment system shown in Fig. 1 consists of commercial stainless steel U-channel, a custom fabricated connector for attaching the sonar to the U-channel and a retraction lever for moving the sonar between vertical to horizontal positions. The manually operated turntable base also shown in Fig. 1 is composed of a commercial turntable and fabricated aluminum parts. An electric wench is mounted on top and is used to control the vertical movement of the deployment system.

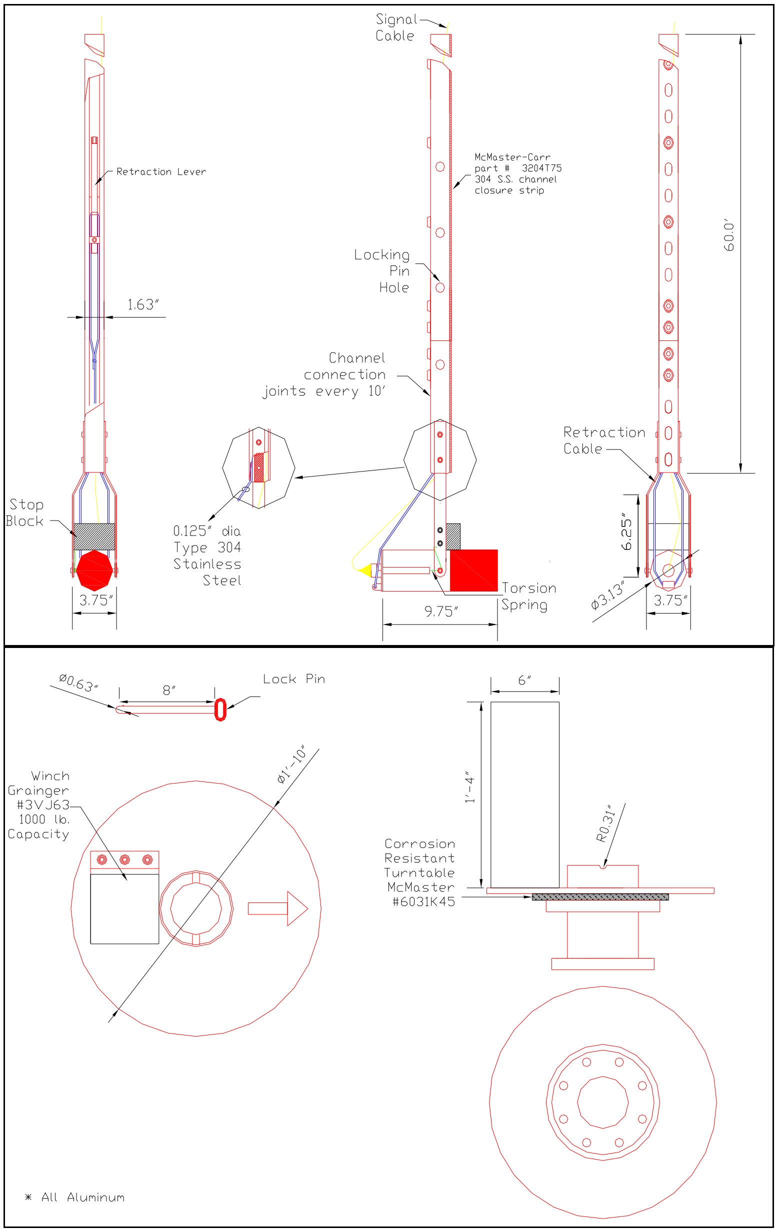

Fig. 1. First-Generation SLIM Deployment System and Turntable Base

Second-Generation SLIM Design

In order to meet the site's requirement that the SLIM be remotely operated, the second-generation SLIM design utilized electric gear motors to control the movement of the deployment system as well as a linear actuator to rotate the sonar. The sonar shown in Fig. 2 is the same commercial off-the-shelf technology capable of profile imaging utilized in the first-generation design. The second-generation deployment system design was modified to allow for remote operation. The system utilizes the same commercial stainless steel U-channel and custom fabricated connector for attaching the sonar to the U-channel, but the manually operated retraction lever was replaced with an electronically operated linear actuator for moving the sonar between vertical to horizontal positions. To allow for remote SLIM operation the second-generation turntable base shown in Fig. 2 was redesigned. Design changes included; addition of a rotation

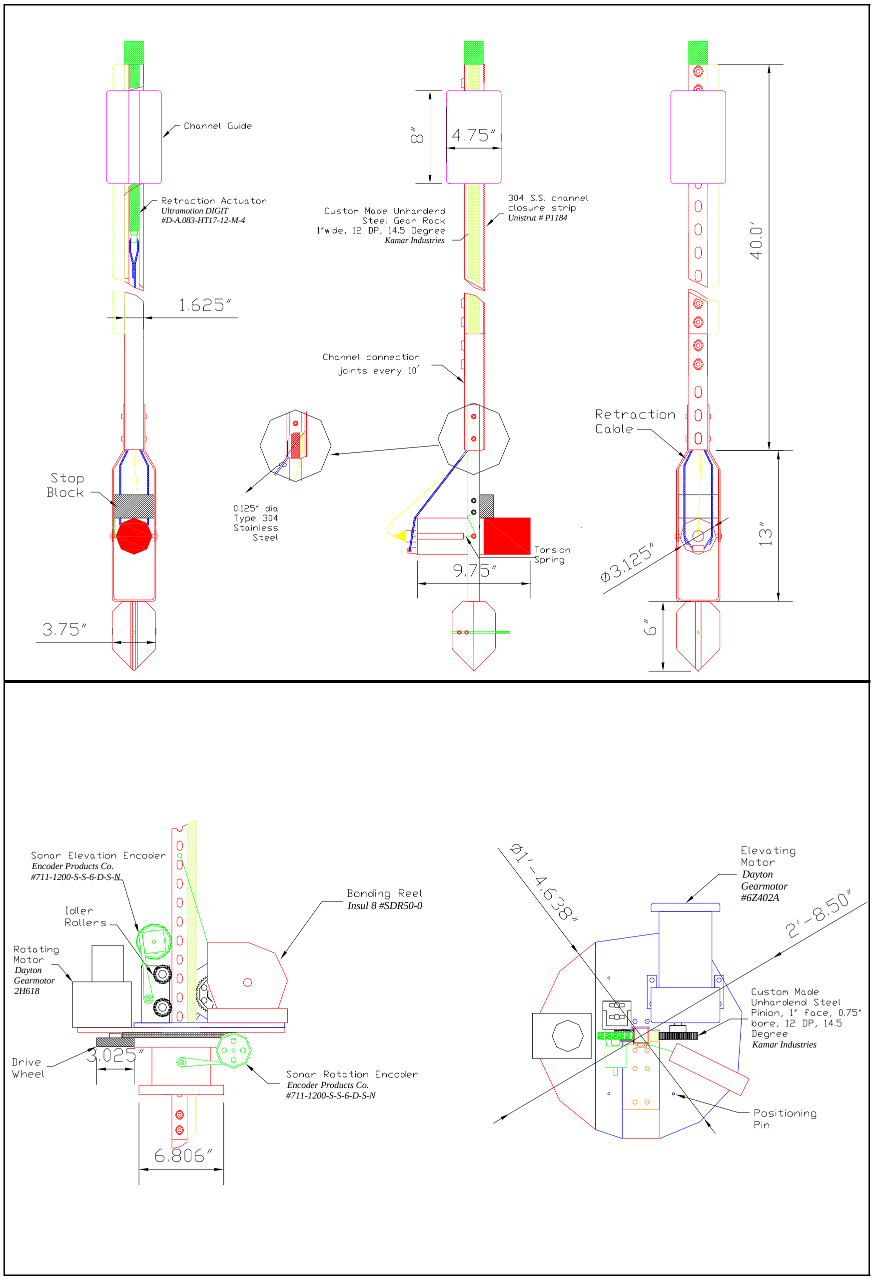

Fig. 2. Second-Generation Deployment System and Turntable Base

gear motor that allows the turntable to rotate remotely, a motorized rack-and-pinion system which allows for the vertical movement of the deployment system to be controlled remotely, and to determine the elevation and rotational angle of the sonar, an elevation as well as a rotation encoder were added. The turntable base is composed of a commercial turntable and fabricated aluminum parts.

Third-Generation SLIM Design

During design reviews for the second-generation SLIM, Hanford engineers identified a new requirement that the system be sealed against possible wind dispersion of HLW contamination on the system. The third-generation system design addressed this concern with the addition of an aluminum enclosure that encapsulates the entire system. The SLIM enclosure structure is comprised of a box and a mast. The box is made of 1-inch thick aluminum plates big enough to enclose the turntable base and the mast is made of three 10-foot sections of aluminum pipe that are bolted together to enclose the U-channel part of the deployment system. There are four vertical braces below the enclosure to support the weight of the enclosure.

Fourth-Generation SLIM Design

During the design reviews for the third-generation SLIM, Hanford engineers indentified the need to have SLIM fully retracted into the enclosure upon removal of the system. A ball valve was added above the riser to isolate the environment from HLW during the removal process. In addition, the ball valve can be used to limit HLW exposure of the sonar, when the sonar is not active and is retracted into the enclosure. In order to retract the sonar completely, the enclosure length had to be increased from 30 to 48 feet, which drastically changes the loading on the system. The additional loading called for an increase in thickness of the top plate of the box. To accommodate the loading on the mast, a commercial light pole was incorporated into the enclosure design, which contained certain features that reduced the risk of fatigue due to vortex shedding. The commercial pole is designed to handle wind speeds up to 150 mph.

Hanford engineers also noted that the riser load limits needed to be considered. Fairly low bending moment and shear loads are allowable, so a bellow was added in between the riser and the enclosure box to ensure that the riser does not support any of the loads seen by the enclosure system. With the increased loading on the system and the isolation of the riser, the vertical braces were replaced with larger capacity screw jacks. Fig. 3, below, shows a 3D drawing of the SLIM attached to a riser and concrete slab. One side of the box is removed to display the turntable assembly. The bellow (white), which is used to isolate the riser from the wind loads, connects a 4-inch diameter pipe section to the ball valve (blue). The ball valve connects the tank riser to the bellow and is used to isolate the entire system from HLW radiation.

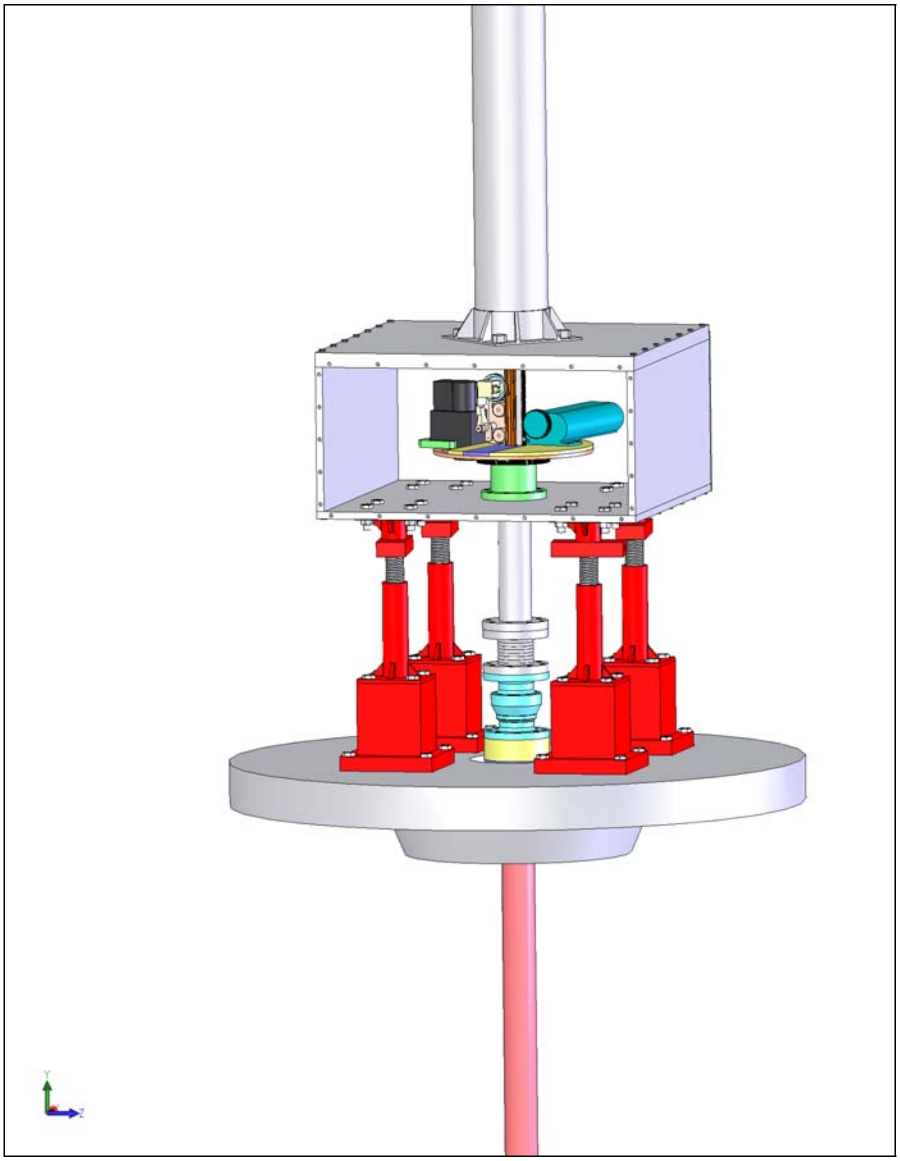

Fig. 3. Scale Drawing of the SLIM Mounted on an Underground Storage Tank Riser

The location of the structure required wind-loading calculations at 85 mph. The calculations for the third-generation SLIM enclosure are discussed below in the structural analysis section. At the time of this paper, FIU was in the process of completing the structural analysis for the fourth-generation enclosure and obtaining final design approval so that fabrication can begin.

THIRD-GENERATION SLIM ENCLOSURE STRUCTURAL ANALYSIS

The SLIM enclosure is essentially a tall slender structure that is potentially subject to extreme wind loading. Hanford site requirements dictate that the SLIM enclosure should be designed according to the ASCE 7-05 Minimum Design Loads for Buildings and Other Structures [1]. This code provides the procedure for determining the maximum wind loads on the enclosure structure. Based on these loads, maximum stresses are calculated and factors of safety are obtained for the enclosure components. This section provides an overview of the structural analysis and shows the significant results.

Based on the ASCE 7-05 code, the enclosure must be built to withstand loads derived from 85 mph wind speeds. Wind loads obtained for the three primary components of the enclosure and the weight of the motor/channel assembly are provided in

Table 1 below.

Table 1. Component Loads

Mast	**1077 lbs**
Box	**130 lbs**
Riser	**27 lbs**
Weight –Motor and Channel Assembly	**382 lbs**

Since the mast is a commercial light pole designed for use in Florida having AASHTO standards to handle 150 mph wind speeds, the stress and factors of safety for the mast components were not recalculated. A mast is included in the structural model to provide the correct loading distribution on the enclosure box. It should be noted that this analysis does not include the system modification that includes the bellow. That is, in the analysis, the riser is not isolated and will see some small loading from the transverse loading.

Stresses in the enclosure box, lower flange and riser are determined using finite element analysis (FEA) with ABAQUS. Fig. 4 shows the stress distribution of various components of the enclosure system. In a clockwise manner, the components are: the lower flange, the riser, the enclosure box with the lower flange and riser, the enclosure top plate, the upper flange and mast, the enclosure top plate and the mast.

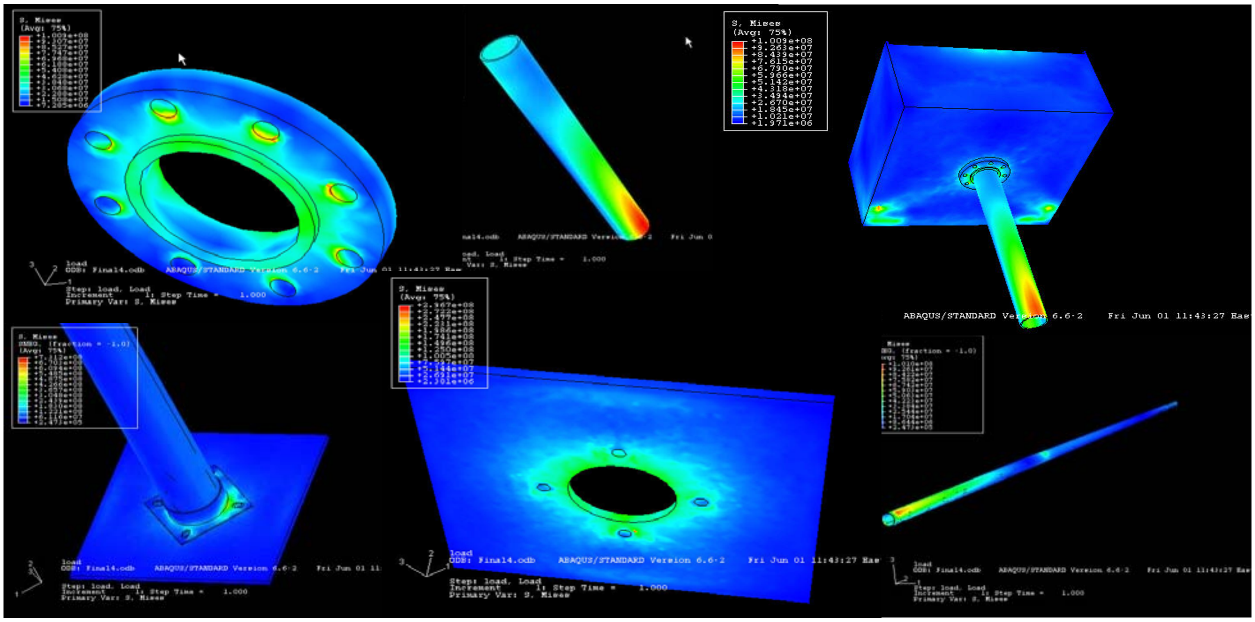

Fig. 4. Stress Distributions on the Various Enclosure Components

When subject to extreme wind loads, the mast will deflect and make contact with the channel housed inside the mast. After the contact is made, the channel and mast will deflect together resulting in stress in the channel. The channel is composed of a U-channel (UNISTRUT) that has a guide rack attached to its side. To obtain the maximum stress in the channel/rack body, the deflections due to the wind load and the transfer of forces between the channel/rack and the mast were established. The minimum principal inertia and its direction where determined to provide the maximum stress in the channel. The resulting maximum stress was found to be 9,000 psi and results in a factor of safety of 3.4 for the channel.

A summary of the factors of safety for the components considered in this analysis is provided in Table 2. Details of the complete structural analysis can be found in Reference [4].

Table 2. Factor's of Safety Summary

Component	**Factor of Safety**
Enclosure Box	**3.2**
Top Plate	**3.6**
3-Foot Riser	**3.2**
Lower Bolts	**1.6**
Lower Flange	**2.8**
Channel	**3.4**

SLIM TESTING

First-Generation SLIM Tests

In the testing of the first-generation SLIM design, SLIM was attached to a 10-foot section of a 4-inch schedule-40 steel pipe to simulate a HLW tank riser. While a forklift supported the entire assembly, the sonar was repeatedly deployed and retracted through the 4-inch pipe. The SLIM functioned flawlessly during these tests.

Second-Generation SLIM Tests

In the testing of the second-generation SLIM design, SLIM was again attached to a 10-foot section of a 4-inch schedule-40 steel pipe to simulate a HLW tank riser, but this time the assembly was placed on top of a utility pit to simulate the HLW tank. The sonar was repeatedly deployed and retracted remotely through the 4-inch pipe. The SLIM again functioned flawlessly during the tests.

Large Area Scan Tests

All previous scan tests were conducted inside of tanks of finite dimensions. In order to verify that the sonar will work in the HLW tanks (75-foot diameter), a set of scan tests were needed on a large area that has a bottom similar to the HLW tanks. These tests were conducted in Miami's Biscayne Bay.

Fig. 5 below shows two sonar scans of the same area. Fig. 5(a) is a scan at the 0^o angle while Fig. 5(b) is also the same 0^o angle but with a 12-inch diameter rock placed in the scan path. As can seen from the results shown below in Table 3 through Table 7 the sonar measurements are very accurate. The sonar measurements are precise, even at the furthest points.

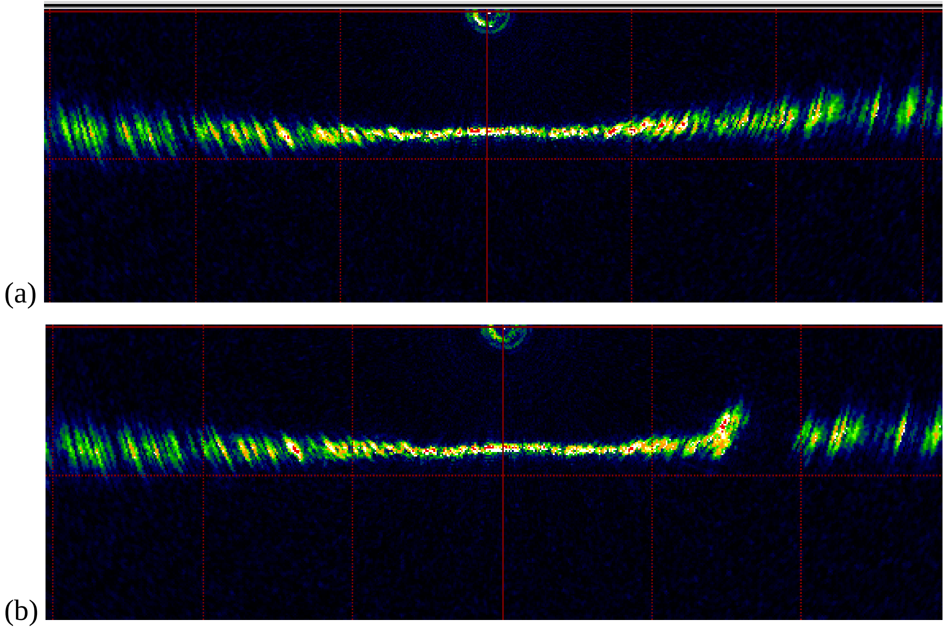

Fig. 5. Large Area Sonar Scan at 0° - (a) Nominal scan (b) Scan with a rock to the right of the sonar)

Table 3. Large Area Results at 0°

Angle = 0 degrees				
Distance (ft)	Physical Depth (in)	S-Depth (ft)	S-Depth (in)	% Error
2	34.00	2.43	33.16	2.47
4	33.50	2.36	32.32	3.52
6	33.00	2.30	31.6	4.24
8	31.50	2.23	30.76	2.35
10	30.50	2.10	29.2	4.26
12	29.50	2.03	28.36	3.86
14	26.00	1.71	24.52	5.69

Table 4. Large Area Results at 30^o

Angle = 30 degrees				
Distance (ft)	Physical Depth (in)	S-Depth (ft)	S-Depth (in)	% Error
2	33.00	2.49	33.88	2.67
4	33.00	2.49	33.88	2.67
6	33.00	2.49	33.88	2.67
8	32.50	2.43	33.16	2.03
10	31.00	2.36	32.32	4.26
12	30.50	2.30	31.6	3.61
14	29.00	2.17	30.04	3.59

Table 5. Large Area Results at -30^o

Angle = (-30) degrees				
Distance (ft)	Physical Depth (in)	S-Depth (ft)	S-Depth (in)	% Error
2	34.00	2.49	33.88	0.35
4	33.00	2.43	33.16	0.48
6	32.50	2.36	32.32	0.55
8	32.00	2.30	31.6	1.25
10	32.00	2.23	30.76	3.88
12	30.00	2.10	29.2	2.67
14	28.00	1.77	25.24	9.86

Table 6. Large Area Results at 45^o

Angle = 45 degrees				
Distance (ft)	Physical Depth (in)	S-Depth (ft)	S-Depth (in)	% Error
2	33.00	2.49	33.88	2.67
4	32.50	2.43	33.16	2.03
6	33.00	2.43	33.16	0.48
8	32.00	2.36	32.32	1.00
10	30.00	2.30	31.6	5.33
12	31.00	2.30	31.6	1.94
14	30.00	2.23	30.76	2.53

Table 7. Large Area Results at -45°

Angle = (-45) degrees				
Distance (ft)	Physical Depth (in)	S-Depth (ft)	S-Depth (in)	% Error
2	34.50	2.49	33.88	1.80
4	34.00	2.49	33.88	0.35
6	32.00	2.36	32.32	1.00
8	32.00	2.30	31.6	1.25
10	31.50	2.30	31.6	0.32
12	29.00	2.03	28.36	2.21
14	30.00	1.90	26.8	10.67

CONCLUSIONS

1. The manually operated first-generation SLIM is a viable option on tanks where personnel are allowed to work on top of the tank.
2. The remote controlled second-generation SLIM can be utilized on tanks where personnel access is limited.
3. The totally enclosed fourth-generation SLIM, when the design is finalized, can be used when the possibility exists for wind dispersion of any HLW that maybe on the system.
4. The profiling sonar can be used effectively for real-time monitoring of the solid-liquid interface over a large area.

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