GLASS BUBBLES INSULATION FOR LIQUID HYDROGEN STORAGE TANKS

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ABSTRACT

A full-scale field application of glass bubbles insulation has been demonstrated in a 218,000 L liquid hydrogen storage tank. This work is the evolution of extensive materials testing, laboratory scale testing, and system studies leading to the use of glass bubbles insulation as a cost efficient and high performance alternative in cryogenic storage tanks of any size. The tank utilized is part of a rocket propulsion test complex at the NASA Stennis Space Center and is a 1960's vintage spherical double wall tank with an evacuated annulus. The original perlite that was removed from the annulus was in pristine condition and showed no signs of deterioration or compaction. Test results show a significant reduction in liquid hydrogen boiloff when compared to recent baseline data prior to removal of the perlite insulation. The data also validates the previous laboratory scale testing (1000 L) and full-scale numerical modeling (3,200,000 L) of boiloff in spherical cryogenic storage tanks. The performance of the tank will continue to be monitored during operation of the tank over the coming years.

KEYWORDS: Glass bubble, perlite, insulation, liquid hydrogen, storage tank.

INTRODUCTION

In 2001, Kennedy Space Center's (KSC) Cryogenics Test Laboratory (CTL) began testing glass bubbles as insulation for cryogenic systems [1-2]. A comprehensive evaluation of glass bubbles culminating in performance testing in 1000 L spherical liquid hydrogen tanks was completed by the CTL in 2007 [3-5]. The results of that work clearly indicated the thermal performance and operational advantages of glass bubbles over perlite using laboratory test methods and system studies. In the 1000 L tanks, bubbles were shown to reduce liquid hydrogen boiloff by 34 percent and to reduce liquid nitrogen boiloff by 46 percent with the vacuum degraded to 13 Pa (0.10 torr) [4]. A field test of glass bubbles versus perlite was conducted using a pair of 22,700 L vertical liquid nitrogen tanks and reported on by Baumgartner et al. [6] with similar beneficial results for glass bubbles.

KSC's current interest in high performance hydrogen storage tank insulation stems from the scope of the Constellation program. For the upcoming lunar missions, two rockets will be consecutively launched and rendezvoused in Earth orbit prior to departure to the moon. Significantly greater hydrogen storage (7,000,000 to 15,000,000 L) is needed at the launch pad to reliably launch two successful rockets within mission timelines. Given the relatively infrequent missions (one or two manifested per year), high performance insulation will minimize life cycle costs by reducing stand-by propellant boiloff losses.

To bridge the gap between the future massive hydrogen storage tanks and the small scale testing of glass bubble insulation conducted to date, the CTL partnered with Stennis Space Center (SSC) to retrofit a 218,000 L liquid hydrogen storage tank with glass bubbles insulation.

THE CRYOGENIC TANK

The tank utilized in this full-scale field application of glass bubbles insulation provides liquid hydrogen storage capacity at SSC's E-1 propulsion test complex shown in FIGURE 1. Having been manufactured by the same company, the tank shares many similarities with the existing 3,200,000 L liquid hydrogen tanks at KSC's launch pads for the Apollo and Space Shuttle programs. Specifically, the tank is a 1960's vintage spherical double wall tank with an evacuated annulus and internal rod supports near the equator. The diameter of the outer sphere is 9.3 m and the diameter of the inner sphere is 7.3 m, resulting in an insulation thickness of about 0.90 m. The volume of the annulus is 200 m^3.

FIGURE 1. The E-1 propulsion test complex at Stennis Space Center in Mississippi consists of a component test stand, high pressure gas storage, and cryogenic storage tanks. The liquid hydrogen storage tank used for this project can be seen in the distance at the right side of the photo (distorted by rocket exhaust plume).

FIGURE 2. The 218,000 L liquid hydrogen tank is shown with its annulus being filled with glass bubble insulation from an over-the-road pressure differential trailer. The flexible fill and vent hoses can be seen draped over the right side of the tank.

The tank was constructed and used on-site at another SSC facility and later relocated to the E-1 test complex. It was inactive for a period of years, but the annulus was kept under vacuum. It has been subjected to approximately three to five complete thermal cycles. The tank has been in operation at its current location shown in FIGURE 2 since the late 1990's. It has a history of good vacuum retention and normal propellant boiloff performance. From review of log books, the annulus pressure during its final months of operation with perlite averaged 4.5 Pa (0.034 torr) [7]. From log book data in 2002 with an average liquid level of 75 percent full, the normal evaporation rate (NER) was 0.18 percent per day, or 386 L per day [7]. From log book data in 2007 with an average liquid level of 26 percent full, the normal evaporation rate (NER) was 0.09 percent per day, or 201 L per day [7]. These marks serve as the baseline data for comparing performance of the original perlite insulation to the glass bubbles insulation. It should be noted that the tank does not have a flow measurement device in the vent line. To determine NER, log book entries of the liquid level were examined for periods of time with the tank vented to atmosphere and no operations performed using the tank. The liquid level is determined using a differential pressure transducer. The error in this method was reduced by using the longest periods of time available (at least one month). The original manufacturer's calculations were not available, but the observed boiloff was consistent with the calculations based on material and dimensional data from the construction drawings.

The original 45 year old perlite insulation removed from the annulus was in pristine condition and showed no signs of deterioration or compaction. The perlite was free-flowing and the majority was easily removed from the tank. Most of the perlite insulation was drained from the bottom of the tank through two ports connected to vacuum trucks. Once the bulk perlite was removed, technicians entered the annulus to suction out small amounts of residual perlite that were left on top of the inner sphere and in structural catch points. The annular space of the tank was fully inspected, including the internal tank support structure, and found to be in excellent condition.

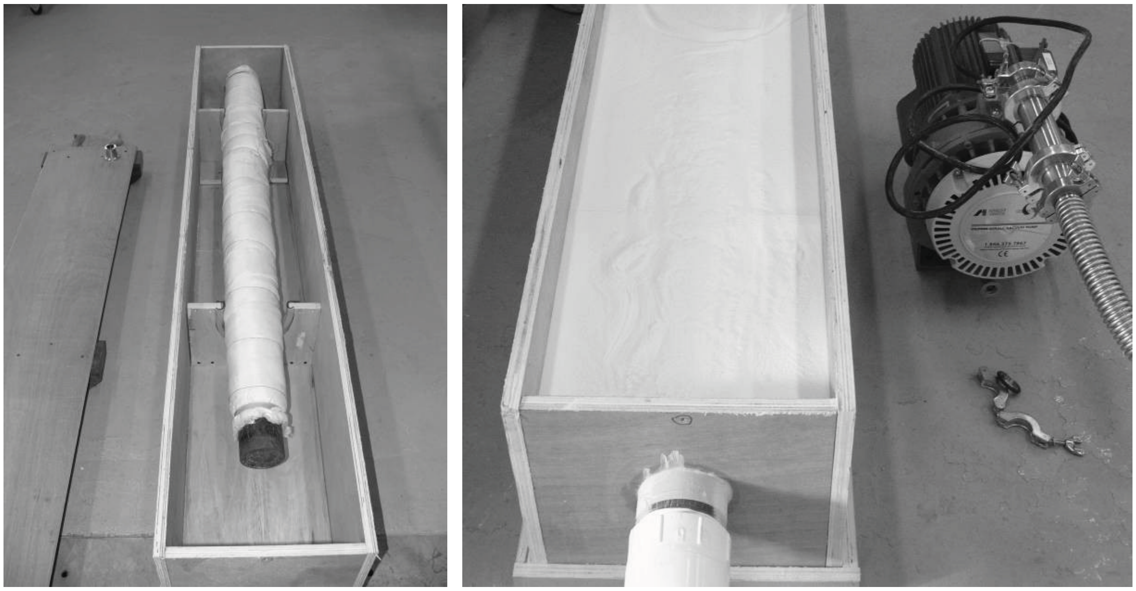

FIGURE 3. A filter element from the vacuum manifold is shown in its shipping container on the left. The shipping container filled with glass bubbles and the filter element under test is shown on the right.

The Vacuum Manifold

The annulus is evacuated via a circular piping manifold near the bottom of the annulus connected to a port on the bottom of the tank which is further connected to a permanently installed vacuum pump. The vacuum manifold has 16 1.8 m long filter elements threaded into it that consist of slotted 89 mm diameter pipe covered with filter blanket material. The tank drawings did not provide any specifications on the filter blanket material. Since glass bubbles are smaller than perlite and could potentially damage the downstream vacuum pump if not properly filtered, an original filter element from the vacuum manifold was removed and sent to KSC to be tested at the CTL as shown in FIGURE 3. The shipping container for the filter element was filled with glass bubbles. The threaded connection on the filter element was adapted to a portable vacuum pump with an in-line filter. The vacuum pump was operated for approximately 15 hours under high flow conditions and no bubbles material was observed to have passed through the tank filter element. Based on the results of this test, the original vacuum manifold was accepted for use with glass bubbles without modifications. The filter element was then sent back to SSC and reinstalled on the tank vacuum manifold.

INSTALLATION OF GLASS BUBBLES

The overall philosophy employed for the installation of the glass bubbles was to use processes that would be directly applicable to installation in tanks of any size and for any location. The main facility requirement for the installation process is physical access for an over-the-road tractor and trailer. The portable dust collector requires electricity that can be provided by a portable generator and 790 kPa pneumatic supply that can be provided by a portable gas bottle. A standard glass bubbles product was used: 3M™ Glass Bubbles Type K1. Normal industrial handling processes for the glass bubbles were used. The glass bubbles were installed through ports on the top of the tank while relying upon gravity and the very fluid-like behavior of glass bubbles to completely fill the annulus.

Bulk Delivery and Installation

3M provides bulk delivery of glass bubbles using over-the-road pressure differential trailers designed for their products as shown in FIGURE 2. The 74 m^3 trailer holds approximately 4100 kg of K1 glass bubbles. A 76 mm diameter static dissipative smooth bore clear flexible hose was specified for transferring the glass bubbles from the trailer to the tank annulus. The bubbles were conveyed using atmospheric air supplied by the high volume, low pressure blowers that are an integral part of the trailers. Consideration was given to utilizing the dry nitrogen gas that is readily available on the E-1 facility to transport the bubbles to minimize the introduction of moisture into the annulus. The air blowers were used instead because of the expense of using nitrogen, the difficulty it could pose at other remote locations, and removal of atmospheric moisture from the annulus due to the use of air in previous smaller scale testing did not pose a significant issue. Two hoses were used during the glass bubbles transfer: one for filling and one for venting. Two short aluminum pipe spools were fabricated to connect the hoses to two ports on the top of the tank. Each pipe spool was formed into a long radius 90 degree bend to minimize bubble breakage during transfer.

Just over four trailer loads of glass bubbles were required to fill the annular space. Each trailer took 1.0 to 1.5 hours to unload. Two deliveries per day were scheduled to allow the glass bubbles to settle overnight. During this process it was learned that the installation could be performed continuously until the annulus is nearly full, at which point some settling time is needed to minimize loading of the dust collector. Use of the fill port or vent port was alternated for unloading each trailer to even out the filling of the annulus. For larger tanks, filling from multiple ports at the same time would be feasible as long as sufficient vent area is provided to prevent building pressure in the annulus.

Since it was anticipated that slightly more than four trailers would be needed to fill the annulus, six 1.0 m^3 boxes of glass bubbles were on-site and available to top off the annulus. To fill from the boxes, a partial vacuum (approximately 70 kPa) was pulled on the annulus and the fill hose was inserted into the box of bubbles. A butterfly valve on the tank port was opened to initiate flow. Several cycles were needed to offload three boxes to finish filling the annulus. The same vacuum cycle process could be utilized using the bulk trailers to perform final topping above the level of the fill and vent ports.

Slightly more than 15,000 kg of glass bubbles was installed in the annulus, resulting in a bulk density of approximately 75 kg/m^3.

Dust Collection System

A portable dust collection system (see FIGURE 4) was designed specifically for this new application to enable offloading of a pressure differential trailer in a remote location. It was designed to collect and contain airborne glass bubbles that are conveyed during the loading and venting process. The dust collector continuously monitors the loading of its filter, and automatically releases a burst of reverse pneumatic flow to clear the filter. The bubbles liberated from the filter are collected in an integrated hopper to be recycled into the process later. This equipment performed efficiently, collecting airborne glass bubbles with no release to the surrounding environment.

FIGURE 4. The portable dust collection system designed for offloading bubbles in remote locations.

Evacuation of Tank Annulus

After the glass bubbles were installed, the temporary openings to the annulus were welded closed in preparation for evacuation. The vacuum pump down operation lasted about two months and was performed mainly on first shift, generally five days per week (see FIGURE 5). There were occasional periods of down time where pumping operations were suspended for reasons unrelated to the test. The initial pump down shown on the left side of FIGURE 5 was very rapid as expected, taking about 12 hours of pumping time over three days to reach 13 kPa (100 torr) from ambient pressure. Subsequently, significant amounts of moisture were being removed from the annulus and collecting in the pump oil. The pump oil was regularly changed over the course of the next month. The collection of moisture began to significantly decrease below 130 Pa (1.0 torr). The moisture removal operations could have been simplified by use of a cold trap upstream of the vacuum pump; however that addition would have required a piping modification. After one month of vacuum pumping operations, the vacuum levels were 27 Pa (0.20 torr) at the bottom and 67 Pa (0.50 torr) at the top of the tank. At the end of two months (42 days of pumping operations), the vacuum levels were 13 Pa (0.10 torr) at the bottom and 40 Pa (0.30 torr) at the top of the tank. The preferable target for the warm vacuum pressure was 6.7 Pa (0.050 torr), but because of an imminent price increase for liquid hydrogen, the decision was made to go forward with liquid hydrogen loading.

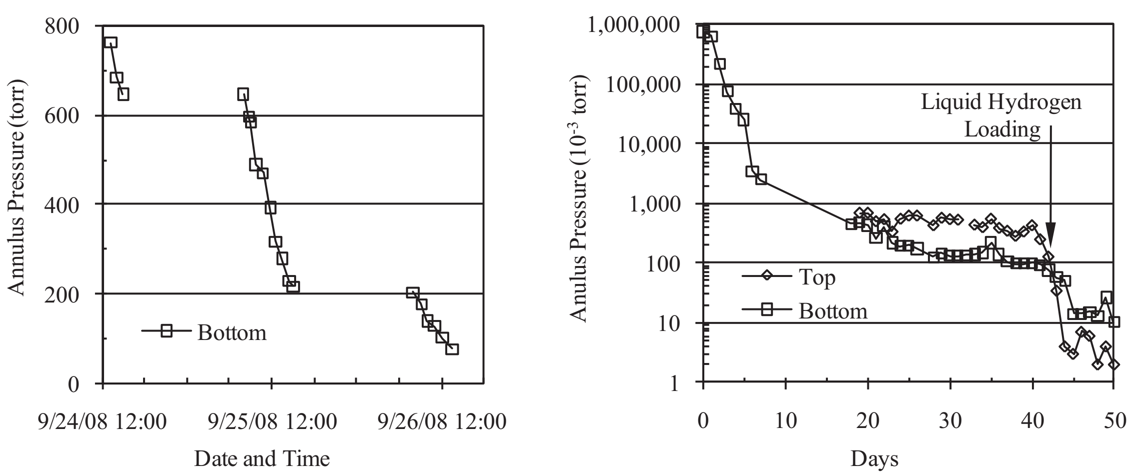

FIGURE 5. The annulus was evacuated to 13 kPa (100 torr) in just three days as shown on the left. After 42 days of pumping operations, the bottom annulus pressure was 13 Pa (0.10 torr). After liquid hydrogen loading of the tank, the cold vacuum pressure stabilized at 1.3 Pa (0.010 torr). [1.00 torr = 133 Pa]

PERFORMANCE TESTING

Cool down and loading of the tank with liquid hydrogen occurred on two consecutive days with two liquid hydrogen trailers off-loaded each day. The vacuum pump was operated during some of the initial tank cool down and then secured. The tank annulus pressure stabilized at a cold vacuum pressure of 1.3 Pa (0.010 torr) and has remained stable ever since. The liquid level was 80 percent full as the boiloff performance test phase began. After nearly six months of steady boiloff, the liquid level had decreased to 66 percent.

The liquid hydrogen boiloff rate has been significantly reduced and is consistent with the prediction based on prior smaller scale testing. For an average liquid level of 75 percent full, the normal evaporation rate (NER) is 0.10 percent per day, or 216 L per day. This represents a 44 percent reduction in boiloff after the transition from perlite to glass bubbles. These data also validate the previous laboratory scale testing (1000 L) [4] and full-scale numerical modeling (3,200,000 L) [5] of boiloff in spherical cryogenic storage tanks.

The tank will be monitored during operation over the coming years by calculating boiloff rates, observing the effect of thermal cycling on the glass bubbles, and monitoring the "health" of the new insulation using infrared imaging.

CONCLUSION

Glass bubble insulation for cryogenic tanks has now progressed from the laboratory to a full-scale field application on a 218,000 L liquid hydrogen storage tank. The thermal, mechanical, and economic indicators all point toward glass bubbles as being an excellent high performance insulation choice for future large storage tanks and when replacing the perlite insulation in existing tanks. The logistical aspects of installing large quantities of glass bubbles and the subsequent evacuation were straightforward to execute. No special facility requirements are necessary for the glass bubbles installation process. The boiloff rate was reduced by 44% compared to perlite. This field application builds confidence that glass bubble insulation is ready to be adopted in spherical tanks for storing liquid hydrogen or any other cryogen. Further demonstration tests are suggested to answer questions for more demanding tank geometries such as horizontal cylindrical tanks.

ACKNOWLEDGEMENTS

This work was supported by corporate and NASA funding through the Innovative Partnerships Program administered by NASA Headquarters. We thank Randy Galloway, Bartt Hebert, and Stan Gill of Stennis Space Center for their vision, cooperation, and support in bringing this full-scale field application of a laboratory technology to fruition. We also wish to thank all of the engineers and technicians at the E-1 test complex for their dedication to making this project a success.

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