THERMAL PERFORMANCE COMPARISON OF GLASS MICROSPHERE AND PERLITE INSULATION SYSTEMS FOR LIQUID HYDROGEN STORAGE TANKS

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ABSTRACT

A technology demonstration test project was conducted by the Cryogenics Test Laboratory at the Kennedy Space Center (KSC) to provide comparative thermal performance data for glass microspheres, referred to as bubbles, and perlite insulation for liquid hydrogen tank applications. Two identical 1/15th scale versions of the 3,200,000 liter spherical liquid hydrogen tanks at Launch Complex 39 at KSC were custom designed and built to serve as test articles for this test project. Evaporative (boil-off) calorimeter test protocols, including liquid nitrogen and liquid hydrogen, were established to provide tank test conditions characteristic of the large storage tanks that support the Space Shuttle launch operations. This paper provides comparative thermal performance test results for bubbles and perlite for a wide range of conditions. Thermal performance as a function of cryogenic commodity (nitrogen and hydrogen), vacuum pressure, insulation fill level, tank liquid level, and thermal cycles will be presented.

INTRODUCTION

Large liquid hydrogen storage tanks are typically insulated with perlite powder in the evacuated annulus of a double-wall tank. Glass microspheres, also known as bubbles, and

aerogel beads were studied as potential insulation system alternatives to perlite powder as part of the internal research and development project *New Materials and Technologies for Cost-Efficient Storage and Transfer(CESAT) of Cryogens* sponsored by the NASA Space Operations Mission Directorate [1]. This paper summarizes the core experimental element of the CESAT project in which the insulations were tested in a tank configuration using spherical 1000 liter demonstration tanks. The new data build upon prior work [2,3,4] to include considerations for liquid hydrogen temperature and spherical geometry. The demonstration testing provides the experimental data for sub-scale validation of a modeling effort to extend the results to very large tanks [5].

TANK TEST APPARATUS AND SET-UP

Two identical double-wall vacuum-jacketed tanks were custom designed and constructed for this project. With a liquid capacity of 1000 liters and an outer sphere diameter of 1.524 meters, the tanks are approximately $1/15^{th}$ scale versions of the liquid hydrogen storage tanks at the Space Shuttle Launch Complex 39 (LC-39). The research tanks, shown in Figure 1, offer an extensive thermal and mechanical test capability. The very low heat leak design includes a cable support system, fluid and instrumentation connections, and multipurpose viewports. A full complement of instrumentation includes the following elements: silicon diode temperature sensors, liquid level sensors, full vacuum range pressure transducers, load cells, and tri-axial accelerometers. The inner sphere skin temperature is measured at twelve locations from top to bottom. Two five-element temperature rakes measure the temperature through the 0.135 meter thickness of the insulation material. System fabrication and an extensive series of liquid nitrogen and liquid hydrogen tests were performed at PHPK Technologies. Further liquid nitrogen and thermal cycling tests were then conducted at the Cryogenics Test Laboratory at KSC.

INSULATION MATERIALS AND TEST METHODOLOGY

The two insulation materials tested were perlite powder (Silbrico, 100 kg/m^3) and glass bubbles (3M, 70 kg/m^3). Further details of these commercially available materials have been previously reported [1,2]. New thermal conductivity data for these material systems under cryogenic vacuum conditions is reported in the recent paper by Scholtens et al. [6].
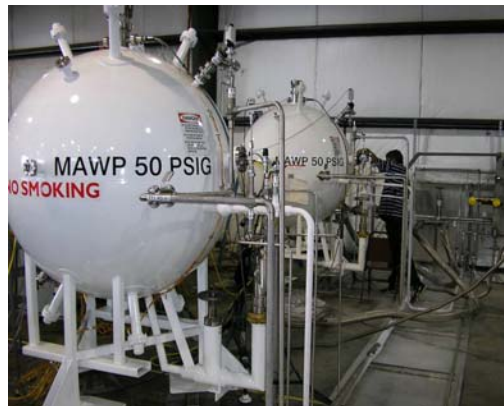

FIGURE 1. View of the 1000 liter tanks constructed and used for liquid hydrogen and liquid nitrogen thermal and mechanical performance testing.

Mass flow meters and weight scales were used concurrently to measure the evaporative boil-off rate of the cryogenic fluid. The heat transfer rate into the test vessel was calculated from the flow rate using the heat of vaporization. The thermal performance of the insulation system was calculated from the heat transfer rate, boundary temperature measurements, and the tank geometry data. Throughout this paper, the apparent thermal conductivity of the overall field installation, k_{oafi}, is the primary measure of comparative thermal performance, which includes parasitic heat leak. Weight scale readings were also helpful to gauge the liquid level, insulation material densities, and other experimental information throughout the test program.

Steady state evaporative boil-off tests were performed with vacuum annulus pressures ranging from 0.01 Pa (10^{-5} torr) to 101 kPa (760 torr) and liquid levels ranging from 100% to 0%. A high number of thermal cycles (ambient to full cryogenic) were rapidly accumulated on the tanks for each insulation material, with boil-off tests periodically performed between cycles.

TEST RESULTS: GLASS BUBBLES VERSUS PERLITE

Nearly 9000 hours of steady boil-off data spanning 94 tests was collected over a period of 19 months using two tanks, two insulations, and two liquid media. To minimize the effect of any inherent differences between the two tanks, testing was performed with nearly every combination of insulation conditions and verification that they have similar parasitic heat leak was obtained. Maintaining test conditions consistent over a two-year period of testing at two different test facilities was challenging, as the evaporative boil-off rate is affected by small variations in annulus vacuum pressure, liquid level, and ambient conditions. The test data was compiled and analyzed using time-weighted averaging and very consistent results were obtained over the course of testing.

The average performance of perlite and glass bubbles for both liquid nitrogen (LN2) and liquid hydrogen (LH2) is presented in TABLE 1. Each test included in TABLE 1 meets the following average conditions: annulus pressure less than 0.33 Pa (2.5 millitorr) and liquid level above 50%. The outer tank temperature was approximately 295 K and the inner tank temperature was 77 K and 20 K for liquid nitrogen and liquid hydrogen, respectively. The performance of the bubbles was 27% better for liquid nitrogen and 34% better for liquid hydrogen. The thermal performance improvement is represented graphically in FIGURE 2.

THERMAL PERFORMANCE ANALYSIS AND DISCUSSION

System analysis shows that the parasitic heat leak of the test tanks is higher than designed. The design heat leak from supports and feed-throughs is calculated to be 1.3 Watts for liquid

TABLE 1. Average performance of bubbles and perlite with LN2 and LH2 in 1000 liter demonstration tanks.

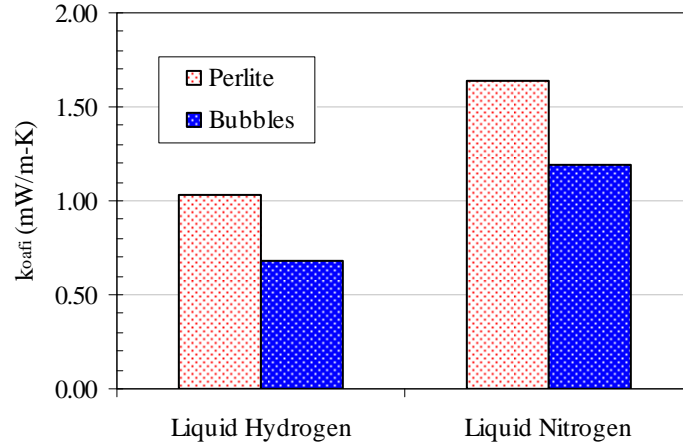|		Boil-off Flow Rate (sccm)	Heat Transfer Rate (W)	System Thermal Conductivity, k_{oafi} (mW/m-K)	Accumulated Test Duration (hours)	Average Tank Level (% Full)	Average Vacuum Level (Pa / millitorr)
LN2	Perlite	4142	15.9	1.63	1559	86	0.112 / 0.838
	Bubbles	3001	11.5	1.19	2210	86	0.081 / 0.606
LH2	Perlite	20,125	12.6	1.03	264	81	< 0.13 / 1.0
	Bubbles	13,212	8.3	0.68	1576	82	< 0.13 / 1.0

FIGURE 2. Thermal performance of bubbles shown to be 27% better for liquid nitrogen and 34% better for liquid hydrogen in 1000 liter demonstration tanks.

nitrogen. FIGURE 3 shows comparative analysis of the tank test data with recently published data for perlite and bubbles [6]. With the tank test data shifted downward by 0.5 mW/m-K (equivalent to 4.2 Watts), it correlates well with the absolute k-value of the Cryostat-100 test data. Therefore, the as-built parasitic heat leak for the tanks is approximately 4.2 Watts. This direct comparison holds for vacuum pressures below 13.3 Pa (100 millitorr). The difference between design and actual parasitic heat leak is likely due to the three anti-rotation stops that prevent large relative movements of the two spheres. The stops have small clearances and were not included in the design calculation. Since the actual parasitic heat leak is still a relatively small percentage of the overall system heat leak, the tanks are well suited to performing comparative testing of bulk fill insulation materials.

Two operational and life cycle factors were investigated that can affect the thermal performance of bulk fill insulations in vacuum jacketed cryogenic storage tanks. First, the vacuum level must be maintained to keep convective heat transfer in check and obtain optimum performance. In addition, settling of the insulation over time can result in thin areas and voids in the insulation, which can severely degrade thermal performance.
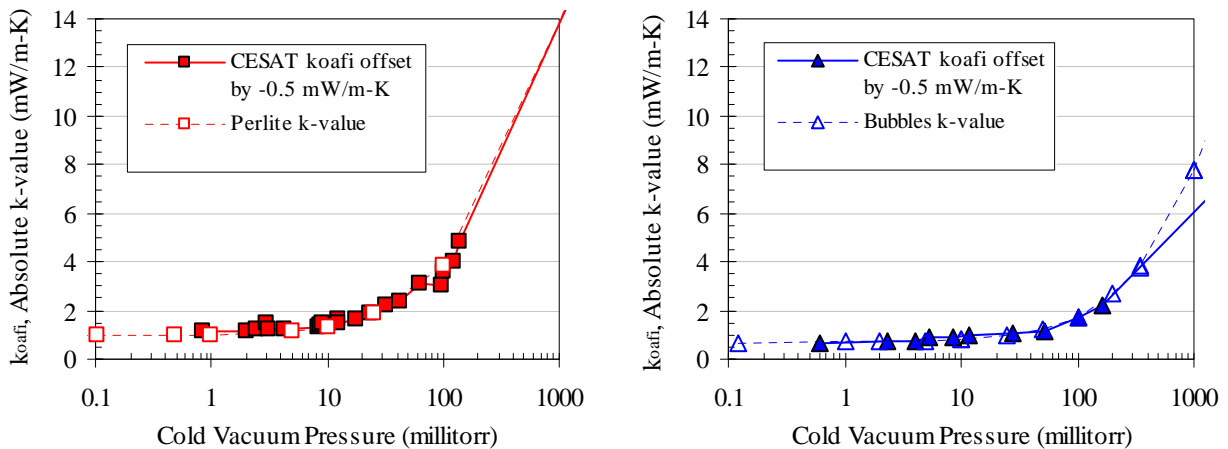

FIGURE 3. Correlation of the k_{oafi} of the test tanks with the absolute k-values for a) perlite and b) bubbles from Cryostat-100 [6] indicates the tank parasitic heat leak is approximately 4.2 Watts. (1 millitorr = 0.1333 Pa)

The vacuum pressures in the annulus were varied for each insulation in a range of 0.01 Pa (10^{-5} torr) to 101 kPa (760 torr), with concentration in the 0.13 to 17.3 Pa (1.0 to 130 millitorr) range. After each vacuum pressure change, the boil-off was monitored for approximately one day or longer to obtain a good average flow rate. FIGURE 4 shows how the overall thermal conductivities of the materials vary with pressure, as well as how the data compares with the absolute k-value for the materials from the Cryostat 100 test data [6]. The bubbles insulation not only performs better than perlite at high vacuum, but the performance gap widens as pressure increases. The bubbles maintain low conductivity well into the 13.3 Pa (100 millitorr) range at which many facility systems normally operate. At 13.3 Pa (100 millitorr), the thermal performance of the bubbles is approximately 46% better than perlite.

In the middle of the test series, the insulated tanks were transported over the road nearly 1000 miles. The resulting vibration is probably similar to the vibration that a tank might experience during a lifetime in a launch site or test stand environment. The perlite and bubbles insulations settled (not compacted) an equivalent amount on the trip. A thin layer of insulation remained covering the inner spheres. The thermal performance of the perlite degraded significantly in the settled condition. The settled bubbles out performed the settled perlite by 51%, and even performed 13% better than the baseline full load of perlite. Thus, the bubbles insulation exhibited more robust thermal performance than perlite for conditions that simulate reduced insulation levels as tanks age.

FIGURE 5 illustrates the vast performance improvement of bubbles as compared to perlite for degraded vacuum levels and low insulation levels. For comparison, the nominal liquid nitrogen performance from FIGURE 2 is also shown.

The relative dependence of evaporative boil-off on the tank liquid level was observed for the two insulation materials. The thermal conductivity of the insulation system determines the strength of this dependence, with better performing insulations exhibiting less liquid level dependence. FIGURE 6 shows boil-off data over a wide range of liquid levels for perlite and bubbles insulation, both at high vacuum ($\leq$ 0.13 Pa or 1.0 millitorr). Since the bubbles are a better performing insulation, the boil-off flow rate is a weaker function (lower slope) with respect to liquid level. Further illustrating this point, the slope of the same function for bubbles with no vacuum and much higher thermal conductivity is 40 to 50 times higher than the curves shown.
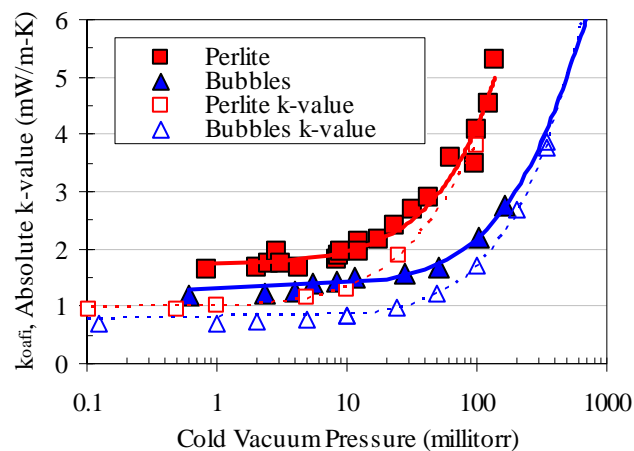

FIGURE 4. Thermal performance of bubbles remains low at degraded (higher) vacuum pressures, while the performance of perlite suffers even at very low vacuum pressures. (1 millitorr = 0.1333 Pa)
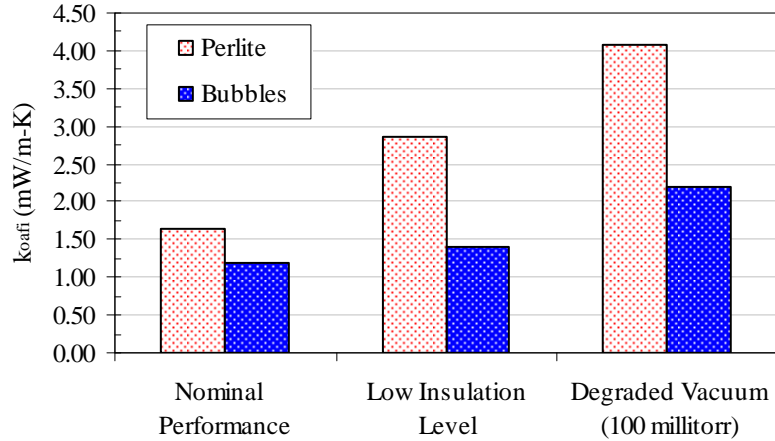
FIGURE 5. Bubbles significantly outperform perlite with respect to operational and life cycle considerations of low (settled) insulation and degraded (higher) vacuum pressure. (1 millitorr = 0.1333 Pa)

An interesting result from the 1000 liter tank demonstration testing was how warm the inner sphere wall temperature was as compared to the saturation temperature of the liquid cryogen in the tank. FIGURE 7 illustrates the temperature profile of the inner sphere for a test where the liquid hydrogen evaporated from 94% down to 71% liquid level. The wall temperatures in the ullage space (S1A, S1B, and also S6B below 81% liquid level) were significantly warmer than the liquid saturation temperature, even when in close proximity to the liquid surface. Similar temperature variations were recorded while testing with liquid nitrogen.

THERMAL CYCLE TESTING

Problems with perlite and thermal cycling have been known to exist for years. When the inner tank contracts upon cooling, the perlite insulation can fall within the increased vacuum space. When the inner tank expands upon warming, compaction of the fallen perlite insulation can occur in the lower regions of the vacuum space because perlite is compressible and does not readily flow out of the way of the expanding tank. With repeated thermal cycles, thin insulation
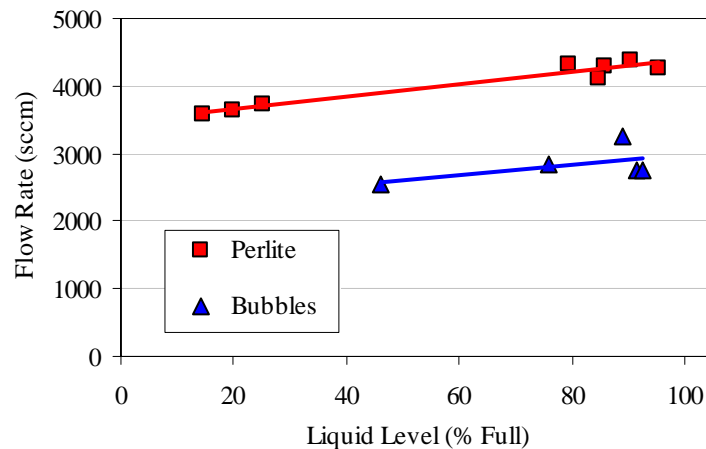

FIGURE 6. The effect of tank level on evaporative boil-off is less evident for better insulations.
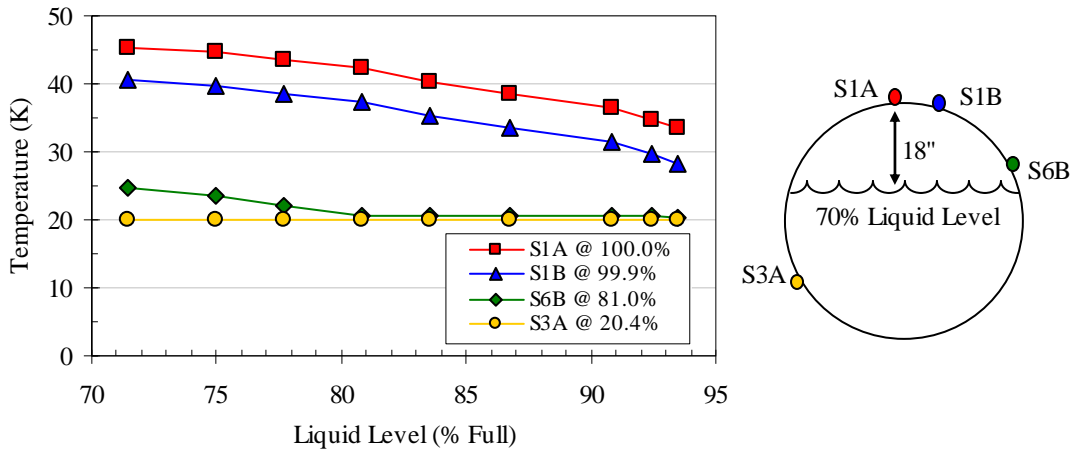
FIGURE 7. Wall temperature profile for a liquid hydrogen boil-off test with bubbles insulation spanning seven days.

levels as well as insulation voids can develop that can lead to increased heat load on the stored cryogens. Since bubbles have improved flowing characteristics over perlite and do not readily compact under compressive loading [1], it is expected that thermal cycling should be less of a problem as compared to perlite. A potential risk of thermal cycling with bubble insulation is bubble breakage. For this reason, vacuum levels were closely monitored during the accelerated thermal cycle testing of the 1000 liter demonstration tanks.

Initial thermal cycles of each insulation in the 1000 liter tanks occurred as a consequence of normal test activity. Additional testing was performed to rapidly accumulate thermal cycles. The tanks were generally warmed over a one to three day period. Once all of the inner tank temperature measurements were above 275 K, the tanks were rechilled and filled with liquid nitrogen, cold soaked for approximately one hour or more, and then drained in preparation for the next thermal cycle.

Throughout thermal cycle testing, no visible change was observed in the level of the bubble insulation. The thermal cycle performance test data is summarized in FIGURE 8. The thermal performance of the bubbles insulation was remarkably stable, even though the latter tests had slightly elevated vacuum levels. The rate of rise in vacuum pressure was typical of the vacuum
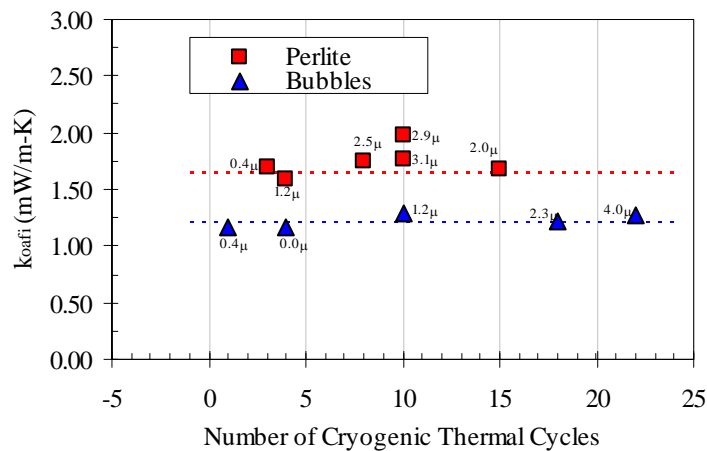

FIGURE 8. Thermal performance during thermal cycle testing of the 1000 liter demonstration tanks.

leakage rate for the 1000 liter tanks when not operating the vacuum pump over extended durations. If bubble breakage had been the cause, the sulfur dioxide (SO_2) gas that exists within the bubbles at $^1/_3$ atmospheric pressure should have been detectable in the vacuum annulus after warming the tank. Residual gas analysis after the final thermal cycle did not indicate the presence of SO_2 gas in the annulus [7]. The ability to detect SO_2 gas with the analysis equipment used was readily verified using a separate handheld setup to mechanically crush bubbles. The field demonstration reported by Baumgartner of 22,700 liter tanks also indicated that glass bubbles do not break to any significant degree [8].

CONCLUSIONS

Glass bubbles were tested in a spherical double wall tank configuration as a replacement for perlite insulation. The liquid hydrogen boil-off was 34% less at 0.13 Pa (1.0 millitorr) and 46% less at 13.3 Pa (100 millitorr) for the bubbles compared to perlite during testing of the 1000 liter demonstration tanks. The bubbles exhibited more robust performance than perlite for tank aging effects such as vibration/settling and degraded vacuum. Extensive thermal cycle testing was performed with no indication of bubble breakage.   The perlite and bubbles results were consistent with prior experimental work.
The thermal and mechanical test results indicate that glass bubbles are a superior bulk-fill insulation material for use in evacuated liquid hydrogen and other storage tank applications.

ACKNOWLEDGEMENTS

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