

COST-EFFICIENT STORAGE OF CRYOGENS

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ABSTRACT

NASA's cryogenic infrastructure that supports launch vehicle operations and propulsion testing is reaching an age where major refurbishment will soon be required. Key elements of this infrastructure are the large double-walled cryogenic storage tanks used for both space vehicle launch operations and rocket propulsion testing at the various NASA field centers. Perlite powder has historically been the insulation material of choice for these large storage tank applications. New bulk-fill insulation materials, including glass bubbles and aerogel beads, have been shown to provide improved thermal and mechanical performance. A research testing program was conducted to investigate the thermal performance benefits as well as to identify operational considerations and associated risks associated with the application of these new materials in large cryogenic storage tanks. The program was divided into three main areas: material testing (thermal conductivity and physical characterization), tank demonstration testing (liquid nitrogen and liquid hydrogen), and system studies (thermal modeling, economic analysis, and insulation changeout). The results of this research work show that more energy-efficient insulation solutions are possible for large-scale cryogenic storage tanks worldwide and summarize the operational requirements that should be considered for these applications.

KEYWORDS: Cryogenic tanks, thermal insulation, granular materials, liquid hydrogen boil-off, glass bubbles, perlite

PACS: 65.60.+a, Thermal properties of amorphous solids and glasses

INTRODUCTION

Cryogenic storage tanks in the size range of 50,000 gallons and larger typically have thermal insulation systems consisting of a double-wall tank with perlite powder insulation filling the annular space. For liquid hydrogen (LH2) tanks this annular space must also be evacuated to a high vacuum level in order to reduce boil-off losses to an acceptable level. For large liquid oxygen (LO2) tanks the annular space is often kept at ambient pressure with a nitrogen purge to ensure insulation material is maintained in a dry condition.

This paper is a summary of the research testing program entitled *Cost-Efficient Storage & Transfer of Cryogens* (CESAT) led by the Cryogenics Test Laboratory at NASA Kennedy Space Center. Glass bubbles and aerogel beads were studied as potential insulation system alternatives to perlite powder. We quantified the energy-efficiency improvements of these insulation materials in realistic tank configurations and addressed the engineering challenges that would be encountered in large-scale tank applications. Testing of several materials for a number of different applications, including piping and tanks, were performed under this program, but the focus was on the glass bubbles for evacuated tank applications.

The research test program was arranged along three lines of work: materials research, tank demonstration testing, and system studies. Materials research tasks were designed to characterize the physical, chemical and thermal properties of the insulation materials under representative tank conditions. Tank demonstration tests 1000-liter spherical research tanks as well as cylindrical industry tanks. Systems studies covered key operational issues including safety, technical, and economic considerations.

Future Operational Needs

Launch Complex 39 (LC-39) at Kennedy Space Center provides Space Shuttle launch operations with two launch pads, A and B, and will be reconfigured in the near future for the planned Ares launch vehicle. Current plans call for the reuse of the existing LH2 and LO2 storage tanks which have been in continuous operation the Apollo program of the 1960s. The benefits and risks associated with the changeout of the insulation material must be understood in order to make good engineering decisions regarding tank refurbishment or rehabilitation.

The LH2 tank at LC-39B is a candidate for glass bubble insulation retrofit based on its current operational performance. This 3,200,000-liter capacity tank is shown in Figure 1. Built by Chicago Bridge & Iron in 1965, the vacuum-jacketed spherical tank has a 21.3-m diameter carbon steel outer shell and a 18.3-meter diameter stainless steel inner tank. The 1.5-m thick annular space is filled with approximately 3,030,000 liters of high density perlite powder and maintains a vacuum level in the range of 15 millitorr. The daily hydrogen boil-off of 3,407 liters per day from this tank is approximately three times the amount of the identical tank at LC-39A and 50 percent higher than the design specification. Additionally, the tank has undergone three full thermal cycles and the tank manufacturer recommends insulation replacement after five thermal cycles.

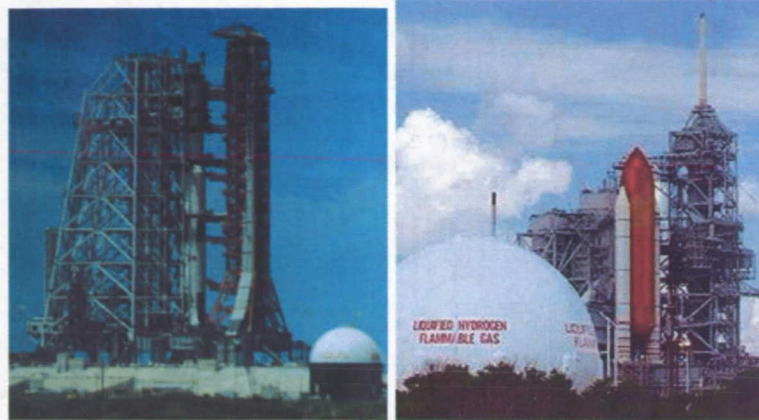


Figure 1. Past, present, and future views of the LH2 storage tank at LC-39: Apollo Saturn V (left), Space Shuttle (center), Ares (right).

Insulation Materials

Glass bubbles were studied for evacuated annular space tank applications and aerogel beads were studied for ambient pressure applications. Micrographs of the materials are shown in Figure 2. Several glass bubbles were evaluated but the focus was on Series K1 glass bubbles by 3M due to its wide availability and lower cost. The K1 microsphere is a thin-walled hollow lime borosilicate glass sphere with residual glass in the interstitial volume. The mean diameter of these bubbles is 65 microns and the bulk density is about 70 kg/m^3 . The aerogel material studied was a Nanogel product of Cabot Corporation. The aerogel beads are 1-mm spherical particles with a bulk density of about 80 kg/m^3 . The reference material was a cryogenic grade perlite, Ryolex Grade #39, by Silbrico Corporation. The bulk density of the perlite powder is nominally 112 kg/m^3 , but can vary from 60 to 220 kg/m^3 with handling.

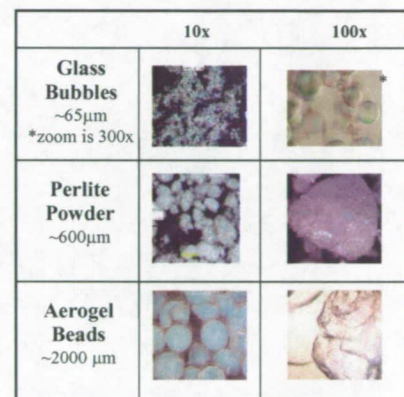


Figure 2. Microscope comparison of three bulk-fill insulations.

MATERIALS RESEARCH

Thermal Conductivity

Thermal conductivity testing was performed using three different methods. The Cryogenics Test Laboratory and the National High Magnetics Field Laboratory (NHMFL) used custom designed cryostats to perform heat transmission measurements by two different methods. Marshall Space Flight Center performed thermal conductivity testing by a third complementary method using ASTM C177. The results confirm that glass bubbles are best for high vacuum applications while the aerogel beads are the best insulation material for ambient pressure applications. Details of the thermal conductivity testing are given in separate papers [99,99].

TABLE 1. Thermal performance of materials for boundary temperatures of 78 K and 293 K.

Insulation Material	Apparent Thermal Conductivity (mW-m/K)	
	High Vacuum	Ambient Pressure
Perlite Powder	0.9	36
Glass Bubbles	0.6	27
Aerogel Beads	1.8	14

Mechanical Settling and Vibration Testing

Comparative testing was conducted using vertical tubes to provide insight into how each of the materials behaves under both dynamic (filling/draining) and static conditions. A test apparatus was devised to evaluate the material packing and flow characteristics expected during tank operations and material installation. The apparatus consisted of vertical clear plastic tubes filled with the different insulation materials and subjected to various external load conditions. Results show that the measured density of the glass bubbles consistently fall within the published bulk density range of 72 – 85 kg/m³ while the measured perlite density varies greatly depending on the external loads applied. The glass bubbles also exhibited improved flow characteristics over perlite in a series of draining tests [99].

Vacuum Pumping and Retention

Vacuum pumping and retention tests were performed using small vacuum chambers as well as the 1000-liter research tank. Initial testing in the small chambers showed that the pumpdown and retention characteristics of the bubbles and perlite were comparable under controlled laboratory conditions. Further evacuation testing was conducted in conjunction with the tank demonstration testing. The experience from many test preparations showed that the pumpdown of glass bubbles in larger volumes was somewhat more difficult due to the smaller particle sizes, but that the vacuum retention was much better. An additional observation in this area was that additional filtration was necessary with the bubbles to fully protect the vacuum pumping system.

Structural Integrity Testing

Structural integrity of the bubbles is a major item of interest for the long-term reliability of the insulation system. Series K1 glass bubbles have a specified crush strength of 1,724 kPa (250 psi), obtained by a nitrogen isostatic test procedure where the bubbles are subjected to a uniform hydraulic pressure. An additional test was devised to determine a more representative crush strength due to the point to point contact between individual bubbles. Pneumatic pressurization tests from 172 to 20,684 kPa were performed by placing the material in a chamber and pressurizing it for 5 minutes. Visual and microscope examination as well as a particle size analysis was conducted to quantify microsphere strength and breakage limits. Microscope inspection indicated breakage in the 517 – 689 kPa range (see Figure 3) and catastrophic damage at pressures of 3,447 kPa and higher.

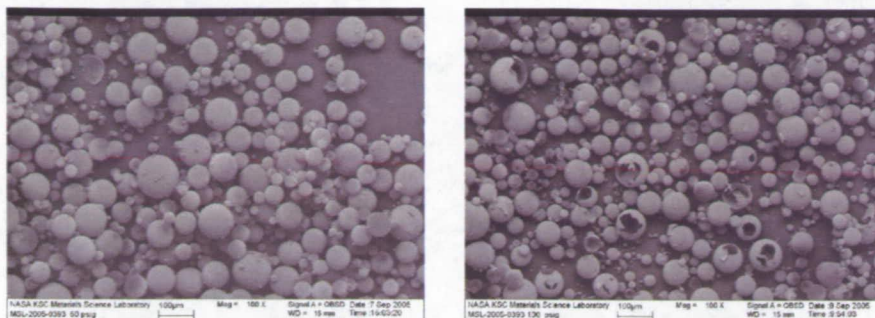


FIGURE 3. 344 kPa and 689 kPa pneumatic pressurization test micrographs.

Based these results showing that the pneumatic crush strength is lower than the isostatic strength, another test was devised to evaluate the strength of the bubbles with point-to-point mechanical loading. A moving wall test fixture was constructed consisting of a steel box in which one of the vertical 254-mm by 178-mm walls was compressed 75-mm using a hydraulic jack and load cell to measure the force. Results of the moving wall tests show that measurable glass microsphere breakage starts to occur at above 345 kPa, as indicated in Figure 4. It should be noted that a 20 percent change in the volume of the glass bubbles is required to create this pressure. This displacement is substantially higher than any volume change associated with a cryogenic tank thermal cycle.

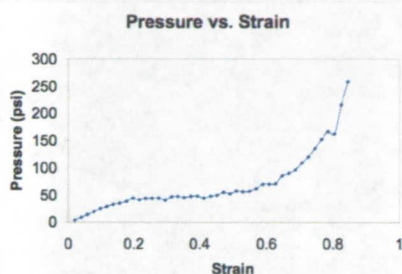


FIGURE 4. Experimental test results from the moving wall test fixture: glass bubbles (left), perlite powder (center), aerogel beads (right).

Electrostatic Property Testing

Series K1 glass bubbles are classified as statically dissipative under room humidity conditions (~50% humidity) and insulating at lower humidity (~20%) while perlite is statically dissipative under both humidity conditions. These results are in agreement with measurements of the dielectric constant. Corona Charge Dissipation testing showed that the glass bubbles have the ability to dissipate charge under both room and low humidity conditions. Discharge Incendivity testing was performed on perlite and showed that this material would not sufficiently charge up an insulating bag material to cause a large discharge during a filling operation. This testing on the glass bubbles was unable to be performed due to their fluidic behavior which prevented containment in the experimental test set-up. This fluid property is due to their ability to generate sufficient electrostatic charge when they come in contact with other glass bubbles to agglomerate particles. The final series of tests was to measure the generation of electrostatic charge formed on the particles in contact with a variety of materials (stainless steel, aluminum, copper, PTFE,

plastic and glass). Results showed very minimal electrostatic charge generated on the glass bubbles with any pipe material tested.

Material Compatibility Testing

Autogeneous Ignition Temperature (AIT) determination in high pressure oxygen testing in accordance with ASTM G 72-83 was conducted on all three insulation materials. No autogeneous ignition was observed up to 449°C (840 °F). Limited Oxygen Index (LOI) testing in accordance with ASTM D2863 showed the LOI for perlite and glass bubbles to be greater than 99.5 percent and that these materials could not be ignited in a 100% oxygen environment. The LOI for the aerogel beads was tested to be 28.1 percent which is well above the concentration of oxygen in air. Minimum Ignition Energy (MEI) testing was also conducted on both perlite powder and glass bubbles showing that both materials were unable to be ignited and that energies in excess of 10 Joules would be required to create an ignition of aerosols comprised of either material.

TANK DEMONSTRATION TESTING

Tank demonstration testing was designed to evaluate insulation performance from a total system perspective. As shown in Figure 5, three levels of testing were performed: 10-liter dewars, 6000-gallon industry tanks, and 1000-liter research tanks. Extensive dewar testing and sub-scale experiments showed validity of the new insulation systems using glass bubbles and aerogel beads (improved thermal performance and no compaction problems) [99,99]. Liquid nitrogen field testing of industry tanks was performed in 2005. Two 22,700-liter (6000-gallon) vertical cylindrical tanks were tested at ACME Cryogenics under the technical direction of Technology Applications, Inc. This work, part of a Phase II NASA research project, provided a side by side comparative test of perlite powder and glass bubbles. The LN2 boil-off and thermal testing showed that the glass bubbles were easy to install, reduced boil-off losses, and did not break over time [99].



FIGURE 5. Views of different test tanks: 10-liter dewars, 6000-gallon industry tanks, 1000-liter research tanks.

Demonstration testing of the 1000-liter research tanks was performed with LN2 and LH2 in 2005 and 2006, respectively. Two identical vacuum-jacketed tanks, each with a capacity of 1000 liters, were designed and constructed. The very low heat leak design is a 1/15th scale version of the spherical LH2 storage tanks at LC-39 and includes multipurpose viewports, feedthroughs, and flange mounts. A full complement of instrumentation includes the following elements: diode temperature sensors, liquid level sensors, full vacuum range pressure transducers, load cells, tri-axial accelerometers, and mechanical displacement indicators. These research tanks,

shown in Figure 4, offer an extensive thermal and mechanical test capability. System fabrication and an extensive series of LH2 tests were performed at PHPK Technologies. Further LN2 testing and thermal cycling was then conducted at the Cryogenics Test Laboratory. Test results show that the bubbles reduce boil-off and do not break nor compact with thermal cycling. The details of this testing are presented in a separate paper [99].

SYSTEM STUDIES

System studies and economic analyses were performed to fully understand the risks and benefits associated with the application of the new insulation materials in large cryogenic tanks. A preliminary study of the granular physics and large-scale mechanical behavior of the glass bubbles was also conducted. This area of research work is continuing for a number of applications including cryogenic tanks and piping [99].

Numerical Modeling of Cryogenic Tank Boil-off

Numerical modeling of both the 1000 liter test tanks and the 850,000 gallon LH2 tank at LC-39B was performed by Marshall Space Flight Center using the Generalized Fluid System Simulation Program (GFSSP). Numerical predictions of the LC-39B tank boil-off and ullage temperatures were produced. Modeling of the 1000-liter research tank was also performed. Analytical and experimental results were compared to validate the heat transfer mechanisms within the tank. The predicted daily boil-off rates for perlite and bubbles are 977 and 689 liters, respectively. Full details of the thermal modeling are presented in a separate paper [99].

Thermo-Economic Analysis

A thermo-economic analysis was performed to provide cost payback information to support engineering decisions on tank refurbishment options. A total LC-39B tank refurbishment project costing \$2 million was assumed. Insulation material costs were obtained for both perlite and bubbles. The predicted boil-off rates from the numerical model were then used to calculate a cost payback. Two cases were evaluated. The first case assumes a tank refurbishment that requires insulation replacement with either fresh perlite or new bubbles. The one time payback of 1.51 years is calculated based on the time required for the annual operational costs to offset the higher initial cost of the bubbles (cost of the refurbishment effort was assumed to be the same for either material). The second case considers a cost trade-off of the continued use of the LC-39B tank with degraded thermal performance (3,407 liters/day) versus refurbishment using bubbles. The one time payback in this case was 5.45 years, calculated by determining the time required for the significantly higher annual operational costs to offset the cost of the entire refurbishment project (that is, the other benefits of the project would be paid for by the reduced boil-off in about 5 years). A summary of this analysis is provided as follows:

LC-39B Tank Annular Space Volume	58,000 ft ³
Initial Cost of fresh perlite (\$1.12/ft ³)	\$64,960
Initial Cost of glass bubbles (\$2.13/ft ³)	\$123,540
Basic cost of LH2 (facility manpower and overhead not included)	\$1.40/gallon
Annual boil-off cost with fresh perlite (977 liters/day)	\$131,838

Annual boil-off cost with glass bubbles (689 liters/day)	\$93,002
Annual boil-off cost with current perlite (3,407 liters/day)	\$459,900
One time cost payback (glass bubbles vs fresh perlite)	1.51 years
One time cost payback - bubbles vs. current perlite	5.45 years

This example shows that retrofit of large cryogenic tanks with bubbles can provide reasonable cost paybacks based on cryogen savings alone and that significant life-cycle cost reductions can be realized. Depending on the tank design and mode of operation, bubbles can also provide long-term economic benefit by avoiding the compaction problem of perlite.

Insulation Installation Study

The logistics of transporting, staging, and on-site material handling were evaluated. For a baseline to the bubbles logistical plan, techniques for perlite installation in large tanks were reviewed. Typically, mobile processing units and raw perlite material is transported to the tank site. Finished perlite powder is produced on-site by heating the raw perlite material to 870 °C. The perlite is then installed warm to minimize moisture absorption. Glass bubbles would be produced ready-to-use at the manufacturing plant and transported to the site in mobile tankers. A slight purge of compressed air or nitrogen would be used to fluidize the material inside the tankers and facilitate the vacuum or pressure transfer of the bubbles into the annular space.

Granular Physics Study

Compaction and crushing behavior of the glass bubbles was studied to predict anticipated pressures that the glass bubbles would be subjected to during a typical cryogenic tank thermal cycle. Modeling of the spherical tank geometry showed that the glass bubbles in the top third of the tank would be in a frictional flow regime that would allow the them to flow easily during volume changes in the annular space while the bottom two thirds of the tank would be in a linear elastic regime where the bubbles would be constrained from flowing and subjected to higher compressive loads. Experimental testing was also conducted to determine the strength and elastic properties. The summary results of this study showed that the predicted maximum pressures at the glass bubbles would be subjected to in the bottom of the tank was in the 2-3 psi range (see Figure 6). It should be noted that this prediction is substantially less than than the 35 psi breakage pressure measured during structural integrity testing.

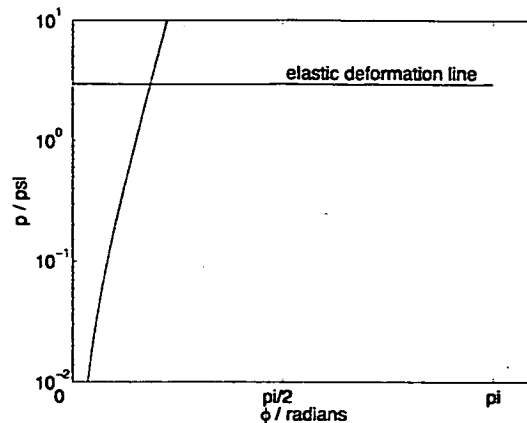


FIGURE 6. Granular physics model prediction of maximum pressure of glass bubbles within annular space of spherical tanks.

CONCLUSIONS

Glass bubbles and aerogel beads were studied as potential insulation system alternatives to perlite powder. Testing has shown that the best thermal performance for an evacuated tank application is provided by glass bubbles while the aerogel beads material is best for non-evacuated tank applications. Detailed experimental investigations were made for the case of large, spherical, vacuum-jacketed LH2 tanks. The hydrogen boil-off was found to be approximately 35 percent less for bubbles compared to perlite. Thermal cycling tests with liquid nitrogen confirmed that the glass bubbles do not break and that compaction does not occur. Thermal modeling of the existing LH2 storage tank at LC-39 and the new 1000-liter research tank was performed to predict boil-off rates and validate internal heat transfer mechanisms. Economic analysis shows reasonable cost paybacks for the retrofit of perlite-insulated tanks based on cryogen savings alone; additional long-term benefits can be obtained by avoiding the compaction problem of perlite.

Current cryogenic storage tank infrastructure remains based, to a large degree, on technology from the 1960's. Further work in the materials research area is recommended to include thermal optimization of glass microsphere composites, evaluation of higher strength bubbles for transfer line applications, and granular physics modeling of glass bubbles. Investigation of the life-cycle characteristics of over-the-road tanks along with vibration and environmental effects is also suggested. A field application is currently being considered for the perlite-to-bubbles retrofit of a 190,000 liter spherical, vacuum-jacketed LH2 tank at Stennis Space Center. The logistics and handling of glass bubbles on this large a scale will be a key feature of the work.

Demonstration testing of aerogel insulation is now proceeding for the case of large LO2 or LNG tanks. Other work stemming from this research testing program is to incorporate new features such as structural instrumentation, fluid system diagnostics, load-supporting insulation materials, and integrated cryocoolers. Considering the thermal insulation system as an integral part of the total system design is essential for making advances toward truly cost-efficient, reliable cryogenic systems and to be able to produce the "smart tanks" of the future.

ACKNOWLEDGEMENTS

Funding was provided by the NASA Space Operations Mission Directorate under the Internal Research and Development program *New Materials and Technologies for Cost-Efficient Storage and Transfer of Cryogenics*. We appreciate Alexis Hongamen and Nancy Zeitlin for their project leadership. We appreciate the many engineers and scientists from the following companies who contributed to this work: Florida State University, Clarkson University, Florida Institute of Technology, 3M, PHPK Technologies, Technology Applications, Inc., ACME Cryogenics, Cryogenic Technical Services, United Space Alliance, Marshall Space Flight Center, Stennis Space Center, and White Sands Test Facility.

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