VIBRATION CONSIDERATIONS FOR CRYOGENIC TANKS USING GLASS BUBBLES INSULATION

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ABSTRACT

The use of glass bubbles as an efficient and practical thermal insulation system has been previously demonstrated in cryogenic storage tanks. One such example is a spherical, vacuum-jacketed liquid hydrogen vessel of 218,000 liter capacity where the boiloff rate has been reduced by approximately 50 percent. Further applications may include non-stationary tanks such as mobile tankers and tanks with extreme duty cycles or exposed to significant vibration environments. Space rocket launch events and mobile tanker life cycles represent two harsh cases of mechanical vibration exposure. A number of bulk fill insulation materials including glass bubbles, perlite powders, and aerogel granules were tested for vibration effects and mechanical behavior using a custom design holding fixture subjected to random vibration on an Electrodynamic Shaker. The settling effects for mixtures of insulation materials were also investigated. The vibration test results and granular particle analysis are presented with considerations and implications for future cryogenic tank applications. A thermal performance update on field demonstration testing of a 218,000 L liquid hydrogen storage tank, retrofitted with glass bubbles, is presented.

KEYWORDS: Glass bubble, perlite, aerogel, insulation, liquid hydrogen, storage tank, mobile tanker, vibration.

INTRODUCTION

Full understanding of the mechanical and vibration characteristics of bulk-fill insulation materials used for cryogenic storage tanks is important for effective applications. These reasons include conveyance properties during installation, settling upon filling, and operational life cycle. Operational factors include settling due to lower frequency vibrations, compaction and particle erosion due to higher frequency vibrations, and severe duty cycle environments associated with mobile equipment. Space launch complexes can impose the additional challenge of extreme short-term vibration environments due to the high-energy propulsion systems. High-efficiency, long-term storage of cryogens is the goal, but mechanical properties can be a strong factor in producing an effective operational system.

Vibration testing and modal analysis of three bulk-fill insulation materials, glass bubbles, perlite powder, and aerogel particles, is the main subject of this paper. The thermal conductivity data for materials and systems have been previously reported [1-2]. The vacuum performance and functional mechanical properties have also been reported. [3-4]. As the new thermal insulation systems using glass bubbles have been successfully implemented by perlite retrofit on existing cryogenic storage tanks, the applications are now being extended to other tank configurations as well as new construction [5-6]. Thus, it is necessary to further understand the vibration and mechanical properties of the glass bubbles materials through both comparative and absolute measures. An updated thermal performance report on the field demonstration tank is also provided.

EXPERIMENTAL

Four typical cryogenic tank annulus fill materials were evaluated: Glass Bubbles (K1 by3M), High Density Perlite (Ryolex #39 by Silbrico), Low Density Perlite (Ryolex 3-S by Silbrico), and Aerogel Particles (TLD100 by Cabot). The aerogel particles were tested with compression levels of 0, 10, and 30% while the remaining materials were tested with no compression. The comparisons used are percent change in volume (void fraction), visual appearance, microscopic visual appearance, modal frequencies and vibration damping. The level of vibration was arrived at by review of typical Shuttle launch vibration levels in areas where the piping and tanks could be located. The levels of random vibration and durations were designed to provide a very robust environment for future launch environment reference as actual vibration environments are largely unknown.

Vibration Spectrums

The goal was to come up with a severe but realistic vibration environment to compare the insulation materials. One of the most demanding installations at Kennedy Space Center is under the Shuttle in the Mobile Launch Platform (MLP) where pipes and tanks reside. This area is protected from heat and direct blast but receives intense vibration during liftoff. A very large database of vibration environments has been assembled over the 30 years of shuttle launches with a great deal of variability resulting from locations, orientations, interfaces and different launches. [1,2] After review of historical liftoff vibration spectrums, this admittedly subjective level for the input shaker vibration intensity was decided upon. Future Launch Environments have not been specified, but this level for materials incorporated into pipes/ tanks should encompass future specifications.. When a design is arrived at and a vibration environment defined, these comparison tests should envelope the levels. The Shaker Test Input Level Specification is:

Frequency (HZ)	**Level g^2/Hz**
10	.08
20	0.35
850	0.35
1200	1.4
1600	1.4
2500	0.25

The overall level is 42.8 G root mean squared (G_{rms}). The G_{rms} is a one number description of overall vibration intensity when specified over the frequency range such as 10-2500 HZ. Duration is another variable for these tests, 3 minute intervals are used which are from historical shuttle database durations.

Vibration Test Fixture

Each of the four materials was tested in the Vibration Test Fixture (VTF) which was designed to provide 0, 10 and 30% compression depending on how the lid was bolted on (see Figure 1). The thick walls (0.5 inches) and short height (10 inches) were designed to provide a stiff structure to transmit a wide range of frequencies to the specimen materials inside. Accelerations were measured in the X, Y (lateral direction and Z (vertical) direction using two lateral accelerometers and one vertical (cap mounted) accelerometer. Throughout the testing X axis and Y axis are in the same plane and only X is used to represent the lateral direction. The modal testing data utilized 4 channel Data Translation DT9837 data acquisition system interfaced to Matlab software. The response accelerometer locations were the same for Shaker testing and modal hammer testing.

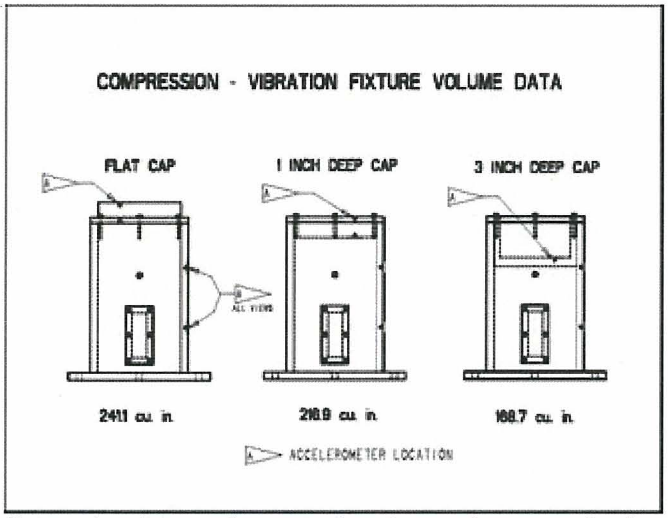


Figure 1. Vibration test fixture showing accelerometer locations and compression levels by different caps.

Figure 2 shows the VTF as mounted on the Unholtz-Dickie Model T-1000-14 Electro-dynamic Shaker dual control acidometers are shown along with three response accelerometers. As shown below an adapter plate is used to bolt the Test Fixture filled with the samples interface the Shaker armature which moves up and down to impose the vibration spectrum on the specimens. The setup was designed to have fewer responses known as modes in the input frequency range 10-2500 HZ. Some modes are unavoidable and affect the results, but only the type of filler material is changed between tests. To do valid comparisons care is taken not to vary how the test is run with the data analyzed the same way between specimens.

Figure 2. Lateral (X,Y) vibration test fixture with yellow arrows pointing to response accelerometers (left photo) and vertical (Z) vibration test fixture with blue arrows pointing to control accelerometers (right).

The testing is performed in the following sequence: a) Initial (empty), b) Following lateral X axis 3 minutes random shaker, c) Following vertical Z axis extended 9-15 minute shaker vibration. The fill volumes are made based on normal tap density for the materials. Photographs, micrographs, and modal frequency responses are also performed at each step.

RESULTS

Table 1 shows the fill volume changes after vibration testing. Compaction occurs progressively but at different rates and degrees depending on the material and duration of random vibration. The Glass Beads have the least compaction as shown below. Some typical photographic results are shown in Figures 3 and 4. Note that with the VTF in the lateral (X axis) the void occurred at the top of the fixture in a cone shape. Figure 5 shows typical Electro Micrographic images of the materials before and after the random vibration testing. The results could be influenced by exactly how the specimens are handled with the environment perhaps affecting the electrostatic charges in some samples more than others; therefore the pictures of such a small amount of material could be misleading. For example while representative samples were taken from near the edge and the center about 1 inch in depth, and this may not be representative of the whole column.

Table 1. Specimen Density pre and post vibration (% compaction).

Specimens	Virgin density kg/m^3 (calculated)	After X random shaker vibration (% void)	After Z random shaker vibration (% void)
3M Glass Bubbles	75.0	4	2.5
High Density Perlite	151.1	13.6	16.25
Low Density Perlite	44.6	16	17.5
Aerogel 0% compressed	88.6	6-7	12**
Aerogel 10% compressed	94.7	7.5	9
Aerogel 30% compressed	106.8	17.5	20***

** After transfer to bag and back Aerogel springs back 10% resulting in 2%

*** After removing lid spring back 10 %

Figure 3. : Glass Bubbles after X-axis vibration, 4% void (left) and after Z-axis vibration, 2.5% void (right). Photographs of typical results

Figure 4 HD Perlite exhibited compaction in the range of 13-17% after X-axis vibration (left) and Z-axis vibration (right). Photographs of typical results.

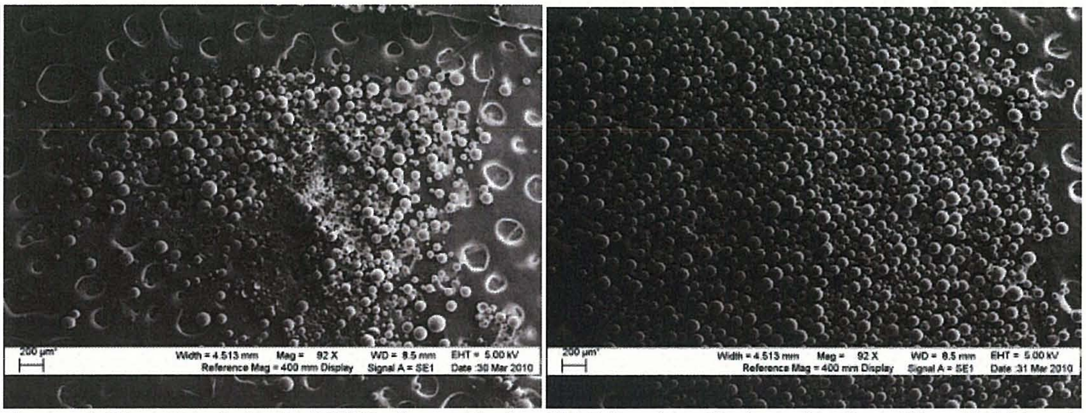


Figure 5.Glass Beads in the VTF before and after X / Z Random Shaker vibration: Glass Bubbles showed little degradation based on several samples Typical Micrographs 92 time's magnification.

The vibration testing input data is shown below the band shown in light orange is the desired input vibration range which is adjusted continuously by averaging the control accelerometers. When the combined unit under test has a mode (high response) the actual accelerations can be much higher at that area, the red arrows below at pointing to the Channel 15 and Channel 16 and the high g levels imposed as read by response accelerometers on the side of fixture.

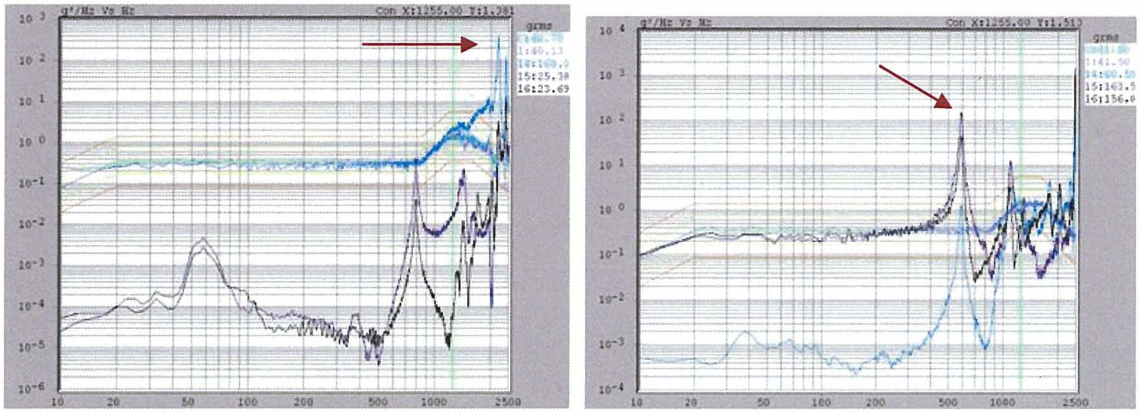


Figure 6. Typical Shaker data for glass bubbles: X Axis, 0% Cap Z-Axis (left) and 0% Cap Glass Bubbles (42 G_{rms}) (right). The red arrows indicate…

Before and after the random vibration a modal hammer test is performed, as shown in Figure 7, which provides transmissibility on the overall specimen between the input point (rubber tipped hammer) and one of the response accelerometers, in this report the lower side is used. This is the same accelerometer location on the shaker test at ch16. This modal test is used because it provides a consistent test for how various fillers in the fixture filter (modify) the input vibration through the fixture over a wide (1-5000 Hz frequency range).

Figure 7 Modal Testing using rubber tipped hammer in Z axis (Response accelerometers opposite).

The transmissibility of the fillers are compared in the following graphs for which the variables are identified as follows:

Txyabs01 refers to the Frequency Response Function (FRF) or transmissibility magnitude for input 0 to 1 (hammer input is 0 response accelerometer is 1).

EM = empty	heavy red line
GB=glass bubbles	dashed violet
LP=Low density perlite	light green

HP=High density perlite	dark green
AG= aerogel bubbles	light blue
10P=10% compressed	medium blue
30P=30% compressed	dark blue
0X before random vibration in the X axis	
1X after random vibration in the X axis	
0Z before random vibration in the Z axis	
1Z after random vibration in the Z axis	

Example: Txyabs01AG30P1Z = FRF magnitude for hammer to response accel Aerogel Bubbles compressed to 30% taken after the Z axis random shaker vibration.

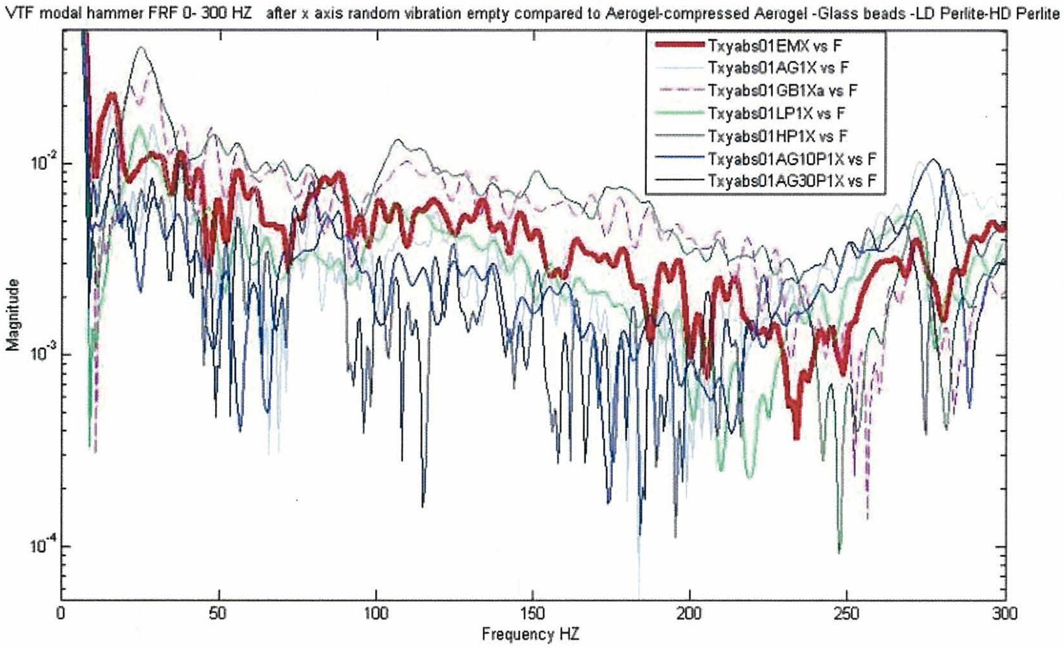


Figure 8. 1-300 Hz Frequency transmissibility of materials in Vibration Test Fixture (VTF) after 3 minutes X Axis Random Shaker vibration based on modal hammer tests

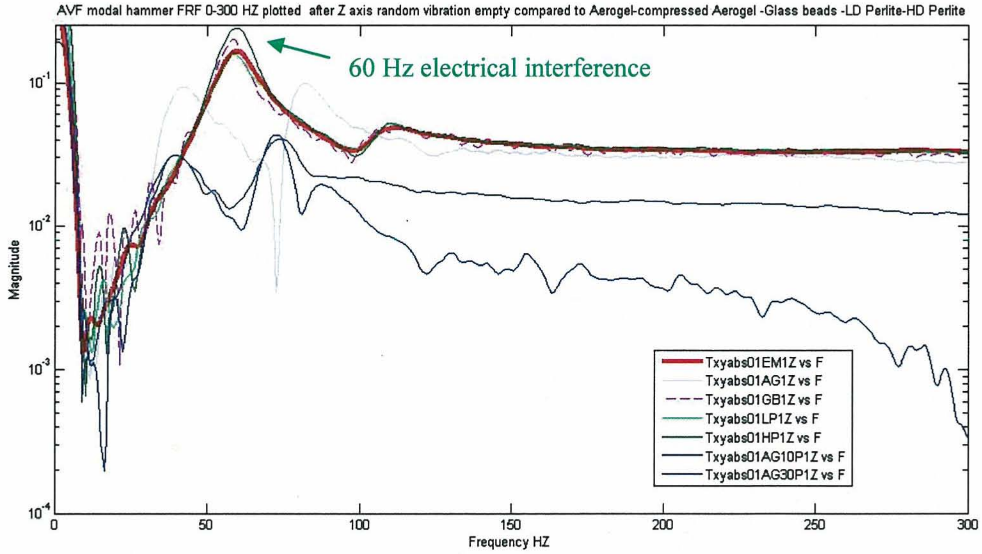
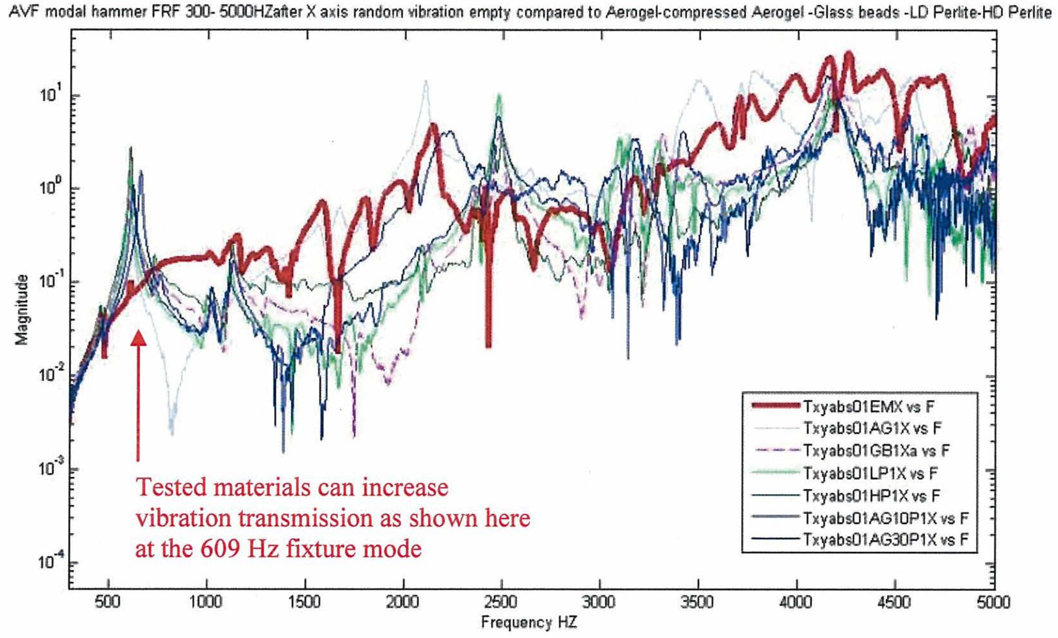


Figure 9. 1-300 Hz Frequency transmissibility of materials in Vibration Test Fixture (VTF) after 3 minutes Z Axis Random Shaker vibration based on modal hammer tests



Tested materials can increase vibration transmission as shown here at the 609 Hz fixture mode

Figure 10. 300-5000 Hz Frequency transmissibility of materials in Vibration Test Fixture (VTF) after 3 minutes X Axis Random Shaker vibration based on modal hammer tests

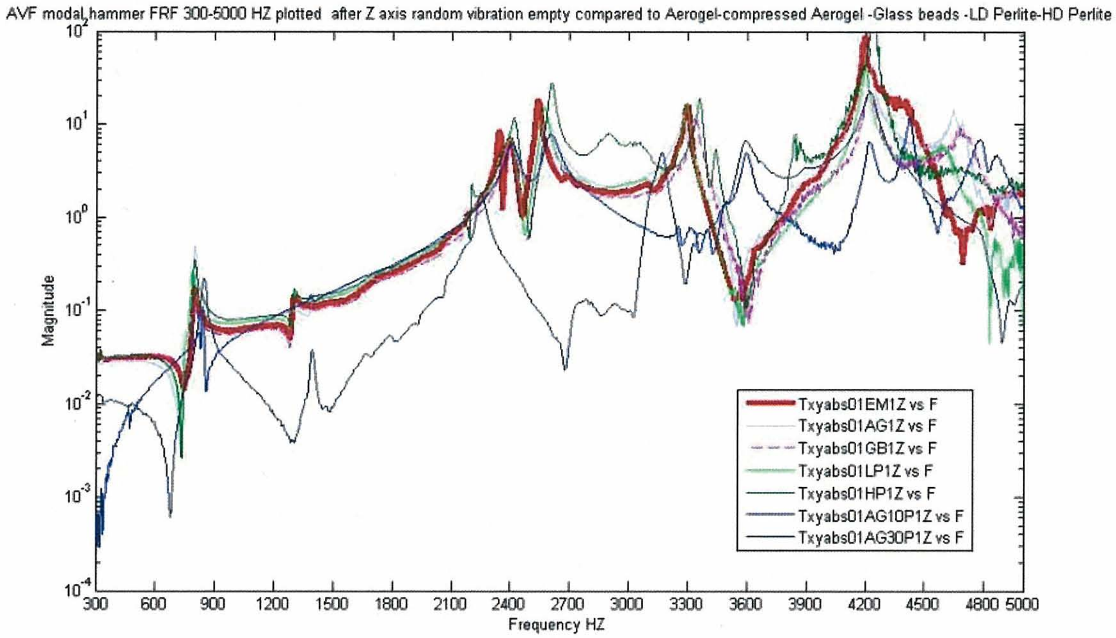


Figure 11. 300-5000 Hz Frequency transmissibility of materials in Vibration Test Fixture (VTF) after 3 minutes Z Axis Random Shaker vibration based on modal hammer tests

DISCUSSION & ANALYSIS

Figure 8 shows the low frequency (1-300 Hz) transmissibility after 3 minutes of lateral vibration best with 0% compressed Aerogel and worst with HD Perlite and Glass Beads which show slightly higher transmissibility than the empty fixture. Figure 9 shows low frequency transmissibility after extended Z axis vibration best with 10, 30% compressed Aerogel vs. the others. The peaks shown by the labeled green arrow are mostly 60 Hz electrical interference. Figure 10 higher frequency (300-5000 Hz) transmissibility after 3 minutes lateral vibration shows best with Glass Beads and 10,30% compressed

Aerogel worst with 0% compressed Aerogel. Note that some modes can even be increased with the tested materials as shown by the red arrow at 609 Hz. This is untypical and very specific to this fixture configuration. Figure 11 shows high frequency (300-5000 Hz) transmissibility after extended Z vibration best with 30% compressed Aerogel vs. the others. The damping ratio of the fillers in the VTF are shown in Table 4 below. The ratios are useful as comparisons but should not be taken as absolute, the ratios can be calculated differently and vary over different modes and time, refer to the literature reference for background on estimating damping in very lightly damped materials.

Table 4. Specimen VTF Damping Ratio estimates based on time history Decay curve Method

Specimens	First estimate damping ratio %	Second estimate damping ratio %
3M Glass Bubbles (bubbles)	0.028	0.020
High Density Perlite	0.020	0.0156
Low Density Perlite	0.0216	0.0038
Aerogel 0% compressed	0.037	0.010
Aerogel 10% compressed	0.0157	0.0072
Aerogel 30% compressed	0.0124	0.0094
Empty Fixture (Aluminum)	0.0040*	0.0025*

*Range from literature[7]

The Decay curve method estimates damping ratio based on time data from modal hammer impact using amplitude decreases from 2 consecutive peaks (equation below).

$$\textbf{Damping ratio (\%)} = \frac{\ln[\textit{second consecative peak height} \div \textit{first peak height}]}{[2\times\Pi]}$$

Mixing and movement visual data for Glass Bubbles and Perlite:

Figure 13. showing Spherical vessel Testing using 27 Hz cyclic input

Vibration settling testing was first investigated with K1 bubbles on top of 8 pcf perlite in a graduated cylinder using our Dewar vibration fixture from a few years ago. With 14 hours of operation at around 30 Hz, the bubbles remain on top of the perlite. After an hour or so, the overall level comes down slightly and bubbles/perlite interface remain constant. We also used a small spherical vessel (plastic bottle) set up the same way and got similar results (and the overall level remained 100% full).

LIQUID HYDROGEN TANK APPLICATION

Applications include large cryogenic tanks where multilayer insulation (MLI) is not practical as well as small tanks where the congestion of annular space piping and protuberances can be the dominant heat load. Higher density perlite is used for vacuum-jacketed tanks while lower density perlite is used for double-wall (non-vacuum) tanks. Aerogel particles are thermally superior to glass bubbles at ambient pressure, but glass bubbles have the lowest thermal conductivity under vacuum conditions. Compared to perlite at high vacuum, glass bubbles provide about 1/3 the heat leak. However, with a slightly degraded vacuum condition (for example, from 10 to 20 millitorr which is common for such tanks), the bubbles easily reduce the heat leak to ½ that of perlite.

The thermal performance benefits of using glass bubbles insulation has been shown through the successful field demonstration of a 218,000 L liquid hydrogen storage tank located at Stennis Space Center (SSC). [report on 1-yr boiloff data]

CONCLUSION

The effects of the intense Space Shuttle Launch vibration test levels on the attenuating effects of the selected cryogenic insulating materials are summarized as follows: Aerogel and glass bubbles show the least compaction or settling compared to the two densities of Perlite. Generally the tested materials show higher vibration attenuation over the higher frequencies (300-5000 Hz) than lower frequencies (1-300 Hz). The 3 minute duration lateral (X-Y plane) lowest transmissibility (best) material is glass beads at higher frequencies and 0% compressed aerogel at lower frequencies. The 15 minute duration vertical (Z axis) lowest transmissibility (best) material are 10, 30% compressed Aerogel while at higher frequencies only 30% compressed aerogel is effective. Damping ratios when measured and calculated by the time history decay curve method on the specimens before Shaker vibration indicate glass bubbles are highest with compressed aerogel the lowest. Mixing behavior at relatively low frequency (27-30 HZ cyclic) does not cause significant or progressive mixing with glass bubbles on top of perlite. The tested materials have differing levels of transmissibility varying over frequency and depending on vibration duration. The behavior is complex and application specific structures/interfaces over the expected vibration environments must be used to evaluate best performance.

The results provide a basis for further applications for both cryogenic tanks and piping. The glass bubbles system for vacuum-jacketed applications can provide significant product (and energy) savings on a global scale. The aerogel particles system for double-wall (non-vacuum) applications can provide much higher energy-efficiency as well as more effective tank and piping designs.

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