Overview of the New LH$_2$ Sphere at NASA Kennedy Space Center

James E. Fesmire and Adam Swanger
Sr. Principal Investigator
NASA Kennedy Space Center, Cryogenics Test Laboratory, KSC, FL 32899 USA
james.e.fesmire@nasa.gov
Highlights

• World’s largest LH$_2$ storage tanks constructed in mid-1960s at NASA Kennedy Space Center in Florida by Chicago Bridge & Iron
  – These vacuum-perlite insulated tanks, still in service, are 3,200 m$^3$ capacity (ea.)

• In 2019, CB&I Storage Solutions (CB&I) began construction of additional 4,700 m$^3$ LH$_2$ storage tank at LC-39B

• NASA’s new Space Launch System (SLS) heavy lift rocket for Artemis program holds 2,033 m$^3$ of LH$_2$ in its flight tank

• New energy-efficient technologies implemented: passive + active control:
  – Evacuated glass bubbles insulation system has been shown to reduce LH$_2$ boiloff by 46% versus perlite in field demonstrations
  – Internal tank heat exchanger to enable controlled storage via IRAS: ullage pressure control, zero boiloff, zero-loss transfer, and/or densification
History of large-scale storage

- Launch Complex 39 (LC-39) A & B built in 1960’s for Apollo moon program
- Identical layout
- Cryogenic storage systems sized for Apollo missions (Saturn V vehicle)
- Both used throughout Apollo and Space Shuttle Programs
- LC-39B now for Artemis program
LC-39 CRYOGENIC STORAGE – APOLLO ERA

- 4 site-built tanks for LO$_2$ & LH$_2$
- **Saturn V**
  - Weight = 6.2 Mlbs
  - Thrust = 7.5 Mlbs
  - Total On-Board Cryo Prop.
  - LO$_2$ = 454Kgal, LH$_2$ = 335kgal

**Designed for Normal Boiling Point (NBP) storage**
**Liquid Oxygen (2 ea.)**

- 900,000 gal (3,407 m³) useable volume
- ~69 ft. (21 m) outer diameter; MAWP = 12 psig (0.83 bar)
- Double-walled w/perlite bulk-fill insulation (~4 ft. thick), purged with nitrogen gas (*no-vacuum*)
- Normal Evaporation Rate = 0.1% (900 gal/day)

**Liquid Hydrogen (2 ea.)**

- 850,000 gal (3,218 m³) useable volume
- ~69 ft. (21 m) outer diameter; MAWP = 90 psig (6.2 bar)
- Evacuated perlite bulk-fill insulation (~4 ft. thick)
- Normal Evaporation Rate = 0.0625% (530 gal/day)

🌟 Largest active LH₂ tanks in the world...for now!
• Head start provided by the Atomic Energy Commission around 1955 for LH₂ industrial-type development

• NASA went from a two m³ LH₂ storage tank to a pair of 3,200 m³ tanks by 1965

• Built by Chicago Bridge & Iron Storage under contract w/ Catalytic Construction Co., these two are still the world’s largest LH₂ storage tanks (and still in service today)

• NASA’s new Space Launch System (SLS) heavy lift rocket for the Artemis program includes an LH₂ flight tank holding 2,033 m³ of LH₂ in its 8.4-m dia. by 40-m height
• In 2018, construction began on an additional LH\textsubscript{2} storage tank at Launch Complex 39B
• This new tank will give an additional storage capacity of 4,732 m\textsuperscript{3}
• Total on-site storage capacity of about 8,000 m\textsuperscript{3}
OLD & NEW – OVERALL CONCEPT FOR LH2 STORAGE AREA AT LC-39B

Apollo-era 3,200-m³ LH₂ storage tank

New 4,700-m³ LH₂ storage tank
Scale comparison of new 4,700-m³ storage tank (left) and Apollo-era 3,200-m³ tank (right)
• Detailed design and construction by CB&I Storage Tank Solutions as part of the PMI contract for the launch facility improvements

• ASME BPV Code Section XIII, Div 2 and ASME B31.3 for piping

• Usable capacity = 4,732 m³ (1,250,000 gal) w/ min. ullage volume 10%

• Max. boiloff or NER of 0.048% (600 gal/day, 2,271 L/day)

• Min. Design Metal Temperature (MMDT) = 4 K (-452 °F)

• Pressure rating or Max. Allowable Working Pressure (MAWP) = full vacuum to 6.2 barg (90 psig) or 7.2 barg (105 psid)
Tank Configuration

• The 25.3-m outer diameter spherical tank has 15 support legs welded to the equator and stands at an overall height of 28.0 m.

• Tank is supplied from a tanker manifold and ambient air vaporizers for pressurization.

• Tank includes a vent stack on top for normal boiloff gas and is connected to a dedicated facility flare stack of 0.3-m diameter.

• Other standard piping nozzles include a 300-mm diameter vacuum-jacketed (VJ) liquid withdrawal lines.
Tank Design

Total heat load \( (Q_T) \) to the inner vessel is the combination of the thermal insulation system (evacuated), the structural support system, and the piping penetrations.

*Three key ingredients of LH\(_2\) tank thermal performance: evacuated insulation (left); structural supports (middle); and piping penetrations (right)*
• Usable capacity = 4,732 m³ (1,250,000 gal)
• Outer Dia. = 24-m (79-ft)
• MAWP = Full Vacuum to 6.2 barg (90 psig) or 7.2 bard (105 psid)
New Technologies

• Integrated Refrigeration and Storage (IRAS) heat exchanger
• Glass Bubbles thermal insulation system (evacuated)

Passive + Active = Full Control Cryogenics
• Two new energy-efficient technologies to provide large-scale LH$_2$ storage and control capability

• *Passive thermal control:* the glass bubbles insulation system (evacuated) is implemented in lieu of the perlite powder system which has been the mainstay in large-scale tanks for nearly 100 years

• *Active thermal control:* internal heat exchanger is implemented for the future addition of IRAS system for complete controlled storage capability
Part I

Integrated Refrigeration and Storage (IRAS) Heat Exchanger
IRAS HEAT Exchanger Concept

- Traditional storage tank - no control. Heat energy from ambient stores within the liquid, ullage pressure rises, relief valve opens to vent.
- IRAS tank – full control. Pressure and temperature are controlled by taking up the heat through the internal heat exchanger. No venting of boiloff gas.
IRAS HEAT Exchanger Design

• Upper and lower heat exchanger (HX) manifolds
  – Positioned at the 25% and 75% fill level elevations
  – Constructed of fully welded 38-mm (1.5-inch OD) 316L stainless steel tubing

• Total coil length = 43 m, for a heat exchange area of ~5.2 m²

• Helium refrigerant will be fed to the coils via 51-mm (2-inch NPS), 304L stainless steel piping routed through the lower annulus
  – One inlet; one outlet

• Bayonet connections and isolation valves provided for inlet and outlet flexible VJ lines to connect to a refrigeration system
Heat exchanger configuration inside the sphere (left); 3D view of refrigerant feedlines and manifold (right)

Top manifold and support tower being lifted into place
Part II
Glass Bubbles Thermal Insulation System
Glass Bubbles – Development Timeline

c1970  Accidental production of first glass bubbles at 3M plant in Guin, AL

c1975  Cryogenic research testing by G. R. Cunnington and C. L. Tien at UC Berkeley

1998  Initial cryostat testing and research of glass bubble products by NASA/KSC Cryogenics Test Laboratory (CTL)

2003  Proposal to National Rocket Propulsion Technology Development Board, NASA Stennis Space Center, *Glass Bubbles Retrofit of Perlite Insulated Cryogenic Storage Tanks*

2003  NASA/HQ Office of Space Flight (OSF) IR&D Proposal, *New Materials & Technologies for Cost-Efficient Cryogenic Storage & Transfer (CESAT)* by CTL (start of major project with national academic-industry team)

2003  NASA SBIR Phase I, *Cryogenic Propellant Insulation Project*, Technology Applications Inc. (TAI)

2005  Field demonstration of 6000-gallon LN₂ tank insulation system at Acme Cryogenics in Allentown, PA (TAI, SBIR)

2007  Completion of CESAT project and presentation of six papers at the Cryogenic Engineering Conference in Chattanooga, TN for publication in *Advances in Cryogenic Engineering*

2008  Start of field demonstration number one of a 50,000-gallon LH₂ spherical tank insulation system at NASA/SSC

2014  Completion of field demonstrations of 50,000-gallon tank with three complete thermal cycles (three fill up and boiloff) over a six-year time period

2016  Engineering study for implementation of glass bubbles insulation system as part of the planned 1,250,000-gallon LH₂ storage tank for NASA/KSC Launch Complex 39B

2021  Completion of new 1,250,000-gallon LH₂ sphere including evacuated glass bubbles system at NASA/KSC

2021  Start of joint government-industry project for thermal insulation systems and conceptual design for mega-scale storage and transport of LH₂


Starting Point – CS-100 Thermal Performance Data

Glass Bubbles thermal performance data in comparison with other materials/systems (Cryostat CS-100)

Notes:
1. Boundary Temperatures approximately 78 K & 293 K.
2. Residual gas nitrogen.
3. Legend data (25, 40, 55) means: 25 mm thickness, 40 layers, and 55 kg/m3 bulk density [x, n, ρ].
Common Questions about Glass Bubbles

Do bubbles break?

No.

Is evacuation a problem?

No.
10-liter Dewar Testing

Experimental 10-liter Dewar Test Apparatus
THERMAL TEST RESULTS: “HIGH VACUUM” SUMMARY

- D116 Glass Bubbles (0.060 g/cc)
- D117 Perlite Powder (0.100 g/cc)
- D115 Aerogel Beads (0.080 g/cc)

CBT = 78 K
WBT = 290 K
THERMAL TEST RESULTS: “NO VACUUM” SUMMARY

- **Insulation Heat Leak Rate (W)**
  - **Run 1**
  - **Run 2**
  - **Run 3**
  - **Run 4**

**Materials**:
- D115 Aerogel Beads (0.080 g/cc)
- D118 Opac Aero Beads (0.086 g/cc)
- D116 Glass Bubbles (0.060 g/cc)
- D117 Perlite Powder (0.100 g/cc)

**Temperature Values**:
- CBT = 78 K
- WBT = 277 K
COMPACTION LEVELS FOR THERMAL CYCLING + VIBRATION

- D117 Perlite Powder (0.100 g/cc)
- D116 Glass Bubbles (0.060 g/cc)
- D115 Aerogel Beads (0.080 g/cc)
Vibration Testing of Bulk Fill Insulation Materials

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

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

Vibration Testing of Bulk Fill Insulation Materials

K1 Glass Bubbles after X-axis vibration, 4% void (left) and after Z-axis vibration, 2.5% void (right). Photographs of typical results.

Glass Bubbles in the VTF before and after X / Z Random Shaker vibration: Glass Bubbles showed little degradation based on several samples. Typical micrographs 92X magnification.

High Density Perlite exhibited compaction in the range of 13-17% after X-axis vibration (left) and Z-axis vibration (right). Photographs of typical results.
1000-liter Spherical Cryostat Testing

Flow Rate (sccm) vs. Xth Day of the Year

- Ambience
- Ullage
- Propellant
- Outer Sphere
- Inner Sphere
- Insulation
- Vented to Ambience
- Moving Interface
1000-liter Spherical Cryostat Testing

1/15th scale version of LC-39 LH$_2$ storage tank

Glass Bubbles and Perlite Powder

LH$_2$ and LN$_2$
Internal Tank Wall Temperature Measurements

- Excellent indicator of liquid level
- Approximate indicator of ullage temperature
  - Significantly above liquid saturation temperature

Figure: Silicon Diode Temperatures

Silicon Diode Installation with Radiant Shield Removed (one of 12)
1000-liter Spherical Cryostat Testing

Thermal Performance vs. Thermal Cycles

- Accelerated thermal cycles
  - 77K to >275K on inner tank
  - 1 to 3 days per cycle, typical
- Total thermal cycle counts
  - Bubbles – 22
  - Perlite – 15
- No degradation in thermal performance was observed for either insulation
- Residual gas analysis performed on tank annulus after final thermal cycle
  - No sulfur dioxide detected
- Visual examination of insulation
  - No observable change

Graph: System Thermal Conductivity ($K_{oafi}$) against Number of Cryogenic Thermal Cycles
Demonstration Testing with 23-m³ Vertical Cylindrical Tank

- K1 Glass Bubbles versus Perlite Powder
- Two identical LN₂ Customer Stations (vertical cylindrical vacuum-jacketed tanks)
- ACME Cryogenics, Allentown PA, 2005

NER comparison test #1: perlite vs. K1 bubbles

Field demonstration testing of standard VT-250 22,700-L (6000-gal) tanks located outside the ACME facility for identical environmental conditions
Demonstration Testing with 190-m$^3$ Spherical Tank

- Material tanker offloading and installation at NASA Stennis Space Center in 2008
- Type K1 glass bubbles by 3M - filling the annular space
- Three complete thermal cycles over nine years, 2008 – 2016
- Average 46% less LH$_2$ boil-off compared to perlite

Half the weight of cryogenic-vacuum grade perlite
Demonstration Testing with 190-m³ Spherical Tank

 Tank filled with liquid hydrogen to 80% full
 Tank after nearly six months, the liquid level was at 66% full

 Boiloff reduced by 44% compared to baseline perlite data
 Stable vacuum at 1.3 Pa (10 millitorr)

<table>
<thead>
<tr>
<th></th>
<th>Baseline Perlite</th>
<th>Glass Bubbles</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Evaporation Rate (NER)</td>
<td>0.18 %/day</td>
<td>0.10 %/day</td>
<td>44 %</td>
</tr>
<tr>
<td>Boiloff Rate</td>
<td>386 L/day</td>
<td>216 L/day</td>
<td></td>
</tr>
<tr>
<td>Vacuum Pressure</td>
<td>4.5 Pa (34 millitorr)</td>
<td>1.3 Pa (10 millitorr)</td>
<td></td>
</tr>
</tbody>
</table>
3M K1 Glass Bubbles
(65 kg/m³)

versus

Perlite Powder
(132 kg/m³)

Cryostat-100 test data
(LN2) and 1000-liter
tank test data (LH2)

Notes:
1. Boundary Temperatures approximately 78 K (CBT) & 293 K (WBT) or as-noted
2. Residual gas nitrogen or as-noted
3. Legend data (25, 10, 80) means: 25 mm thickness, 10 layers, and 80 kg/m³ bulk density [x, n, ρ]
4. Test Series A129 means Cryostat-100, test specimen 129
Glass Bubbles Thermal Performance

- Effective thermal conductivity of glass bubbles compared to perlite powder, under identical test conditions in Cryostat-100 and in 1000-liter (CESAT) spherical test tanks
  - Typical operating point is a cold vacuum pressure (CVP) of **10 to 30 millitorr**: Bubbles are predicted to give from **40 to 100%** better performance compared to perlite
  - Field testing with a 190-m³ (50,000-gal) VJ LH₂ sphere at Stennis Space Center gave an **average boiloff reduction of 46%** over three thermal cycles in six years

![Graph showing the effective thermal conductivity of glass bubbles and perlite powder under various conditions.]
Are bubbles better?

Yes.

Bubbles are better.
Storage System Construction at Launch Complex 39B
Tank Construction

- **CB&I Storage Solutions** began construction mid-2019 with expected completion date late-2021
- Construction schedule is stretched out due to extensive testing requirements and shutdown windows for space launches
- Project included facility additions including a pair of vaporizer systems, flare stack, piping manifolds, connecting **VJ transfer line connecting** to the existing storage tank, as well as the site preparations, facilities, and electrical services
Tank Construction

• Installation of the glass bubbles insulation system is planned for September 2021
• Then, purging and evacuation of the annular space

Annular piping & final outer shell plate
Tank Construction
Tank Construction

Top Access Port
Tank Construction

HX Support Tower being lifted into place (looking up inside inner vessel)
Tank Testing & Commissioning

• Testing completed includes helium mass spectrometer leak testing in addition to the NDE requirement by the ASME Code

• Cold shock of the lower portion of the inner vessel, and connecting piping, was conducted using liquid nitrogen to a slight fill level

• Tank commissioning is planned for fall 2021
Conclusion

• New large-scale 4,700-m$^3$ LH$_2$ storage tank near completion:
  – Adoption of glass bubbles insulation system for about 50% less boiloff rate (estimated)
  – Construction of IRAS heat exchanger to enable future full-control and/or densification capabilities

• Incorporated new technologies for simplified operations and energy savings:
  – Potential for use in global logistics supply chains of LH$_2$ storage and transfer
  – From large-scale (up to 10,000 m$^3$ capacity) to mega-scale (up to 100,000 m$^3$ capacity)
Future

• IRAS to enable any combination of control capabilities:
  – Ullage pressure control, zero boiloff, no vent fill, zero-loss transfer, and/or densification
  – Study is underway for the refrigeration system design, specification, and planning

• Industry collaboration project soon to be underway:
  – Develop an insulation system and conceptual design for future mega-scale tanks
Codes, Standards, and Technical Resources
Main Documents for LH$_2$

- Starting places for technical guidance and reference on systems, process, and safety
- Here are the main ones:
Thank you

for your attention

Questions?

James E. Fesmire
James.e.fesmire@nasa.gov
1.321.747.7657