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Overview of the New LH<sub>2</sub> Sphere at NASA Kennedy Space Center

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## Highlights

- World's largest LH<sub>2</sub> 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<sup>3</sup> capacity (ea.)
- In 2019, CB&I Storage Solutions (CB&I) began construction of additional 4,700 m<sup>3</sup> LH<sub>2</sub> storage tank at LC-39B
- NASA's new Space Launch System (SLS) heavy lift rocket for Artemis program holds 2,033 m<sup>3</sup> 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<sub>2</sub> 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<sub>2</sub> & LH<sub>2</sub>
- Constructed 1963-1965 by Chicago Bridge & Iron Co.
- Designed for Normal Boiling Point (NBP) storage

## **1965 CRYO STORAGE TANK SPECIFICATIONS**





#### Liquid Oxygen (2 ea.)

- 900,000 gal (3,407 m<sup>3</sup>) 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 m<sup>3</sup>) 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)
- $\bigstar$  Largest active LH<sub>2</sub> tanks in the world....for now!

- Head start provided by the Atomic Energy Commission around 1955 for LH<sub>2</sub> industrial-type development
- NASA went from a two  $m^3 LH_2$  storage tank to a pair of 3,200  $m^3$  tanks by 1965
- Built by Chicago Bridge & Iron Storage under contract w/ Catalytic Construction Co., these two are still the world's largest LH<sub>2</sub> storage tanks (and still in service today)
- NASA's new Space Launch System (SLS) heavy lift rocket for the Artemis program includes an LH<sub>2</sub> flight tank holding 2,033 m<sup>3</sup> of LH<sub>2</sub> in its 8.4-m dia. by 40-m height



SLS Assembly in VAB at KSC

## INTRODUCTION

- In 2018, construction began on an additional LH<sub>2</sub> storage tank at Launch Complex 39B
- This new tank will give an additional storage capacity of 4,732 m<sup>3</sup>
- Total on-site storage capacity of about 8,000 m<sup>3</sup>



NASA Kennedy Space Center's Launch Complex 39

## OLD & NEW – OVERALL CONCEPT FOR LH2 STORAGE AREA AT LC-39B





Scale comparison of new 4,700-m<sup>3</sup> storage tank (left) and Apollo-era 3,200-m<sup>3</sup> tank (right)

X.X+-0.1 X.XX+-0.03 X.XXX+-0.010 ANG.+-0.1

- 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 =  $4,732 \text{ m}^3$  (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 bard (105 psid)

- 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<sub>2</sub> tank thermal performance: evacuated insulation (left); structural supports (middle); and piping penetrations (right)

- Usable capacity =  $4,732 \text{ m}^3$ (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)



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

Passive + Active = Full Control Cryogenics

## **New Technologies**

- Two new energy-efficient technologies to provide large-scale LH<sub>2</sub> 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



Passive-only – no active control [Image: National Museum of American History]

# 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  $\sim 5.2 \text{ m}^2$
- 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

## **IRAS HEAT Exchanger Configuration**



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)
- Field demonstration of 6000-gallon LN<sub>2</sub> 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*
- Start of field demonstration number one of a 50,000-gallon LH<sub>2</sub> 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 1,250,000gallon LH<sub>2</sub> storage tank for NASA/KSC Launch Complex 39B
- 2021 Completion of new 1,250,000-gallon LH<sub>2</sub> 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 LH<sub>2</sub>

## **Glass Bubbles – Selected Publications**

- Scholtens, B.E., Fesmire, J.E., Sass, J.P., and Augustynowicz, S.D., Cryogenic thermal performance testing of bulk-fill and aerogel insulation materials, Advances in Cryogenic Engineering, Vol. 53A, American Institute of Physics, New York, 2008, pp. 152-159.
- 2. Sass, J.P., Fesmire, J.E., Nagy, Z.F., Sojourner, S.J., Morris, D.L. and Augustynowicz, S.D., Thermal performance comparison of glass microsphere and perlite insulation systems for liquid hydrogen storage tanks, Advances in Cryogenic Engineering, Vol. 53B, American Institute of Physics, New York, 2008, pp. 1375-1382.
- 3. Majumdar, A.K., Steadman, T.E., Maroney, J.L., Sass, J.P., and Fesmire, J.E., Numerical modeling of propellant boil-off in a cryogenic storage tank, Advances in Cryogenic Engineering, Vol. 53B, American Institute of Physics, New York, 2008, pp. 1507-1514.
- 4. Allen, M.A., Baumgartner, R.G., Fesmire, J.E., and Augustynowicz, S.D., Advances in Microsphere Insulation Systems, Advances in Cryogenic Engineering, Vol. 49, American Institute of Physics, New York, 2004, pp. 619-626.
- 5. Fesmire, J.E., and Augustynowicz, S.D, Thermal performance testing of glass microspheres under cryogenicvacuum conditions, Advances in Cryogenic Engineering, Vol. 49, American Institute of Physics, New York, 2004, pp. 612-618t
- 6. Werlink, R.W., Fesmire, J.E., and Sass, J.P., Vibration considerations for cryogenic tanks using glass bubbles insulation," Advances in Cryogenic Engineering, AIP Conference Proceedings, Vol. 1434, pp. 265-272 (2012).
- 7. Fesmire, J.E., Morris, D.L., Augustynowicz, S.D., Nagy, Z.F., Sojourner, S.J., Vibration and thermal cycling effects on bulk-fill Insulation materials for cryogenic tanks," in Advances in Cryogenic Engineering, Vol. 51B, American Institute of Physics, New York, 2006, pp. 1359-1366.
- 8. Baumgartner, R.G., Myers, E.A., Fesmire, J.E., Morris, D.L., Sokalski, E.R., Demonstration of microsphere insulation in cryogenic vessels, Advances in Cryogenic Engineering, Vol. 51B, American Institute of Physics, New York, 2006, pp. 1351-1358.
- 9. Sass, J.P., Fesmire, J.E., St. Cyr, W.W., Lott, J.W., Barrett, T.M., Baumgartner, R.G., Glass bubbles insulation for liquid hydrogen storage tanks, Advances in Cryogenic Engineering, AIP Conference Proceedings, Vol. 1218, pp. 772-779 (2010).
- 10. Fesmire J, Swanger A, Jacobson J, Notardonato W, Energy efficient large-scale storage of liquid hydrogen, *Advances in Cryogenic Engineering,* Cryogenic Engineering Conference, July 2021.

#### **Starting Point – CS-100 Thermal Performance Data**





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



3M K1 Glass Bubbles

Cold Vacuum Pressure - CVP (millitorr)

Do bubbles break?

No.

Is evacuation a problem?

No.

## Mechanical Testing of 3M K1 Glass Bubbles







Thermal+Vibration Cycles

#### **10-liter Dewar Testing**

## **Experimental 10-liter Dewar Test Apparatus**







#### **10-liter Dewar Testing**

## THERMAL TEST RESULTS: "HIGH VACUUM" SUMMARY



#### **10-liter Dewar Testing**

### THERMAL TEST RESULTS: "NO VACUUM" SUMMARY



### COMPACTION LEVELS FOR THERMAL CYCLING + VIBRATION



**Thermal+Vibration Cycles** 

## 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).

Ref: Werlink R, Fesmire J and Sass J, Vibration considerations for cryogenic tanks using glass bubbles insulation, *Advances in Cryogenic Engineering*, AIP Conference Proceedings, Vol. 1434, pp. 265-272 (2012).

## 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.



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.



**G**lass 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.



1/15th scale version of LC-39 LH<sub>2</sub> storage tank

> Glass Bubbles and Perlite Powder

 $LH_2$  and  $LN_2$ 







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



Silicon Diode Installation with Radiant Shield Removed (one of 12)

## 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



## Demonstration Testing with 23-m<sup>3</sup> Vertical Cylindrical Tank

- K1 Glass Bubbles versus Perlite Powder
- Two identical LN<sub>2</sub> 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<sup>3</sup> 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<sub>2</sub> boil-off compared to perlite

Half the weight of cryogenic-vacuum grade perlite



### Demonstration Testing with 190-m<sup>3</sup> Spherical Tank



2009 Performance Test

- Tank filled with liquid hydrogen to 80% full
- 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)

	Baseline Perlite	Glass Bubbles	
Normal Evaporation Rate (NER)	0.18 %/day	0.10 %/day	44 % Reduction
Boiloff Rate	386 L/day	216 L/day	
Vacuum Pressure	4.5 Pa (34 millitorr)	1.3 Pa (10 millitorr)	

## **Effective Thermal Conductivity Test Data**



Cryogenics Test Laboratory NASA/KSC

Cold Vacuum Pressure – CVP (millitorr)

## **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-m<sup>3</sup> (50,000gal) VJ LH<sub>2</sub> sphere at Stennis Space Center gave an average boiloff reduction of 46% over three thermal cycles in six years



Last Question about Glass Bubbles

Are bubbles better?

Yes.

Bubbles are better.

# Storage System Construction at Launch Complex 39B

- 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



- 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









#### Top Access Port



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<sup>3</sup> LH<sub>2</sub> 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<sub>2</sub> storage and transfer
  - From large-scale (up to 10,000 m<sup>3</sup> capacity ) to mega-scale (up to 100,000 m<sup>3</sup> capacity)

- 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<sub>2</sub>

- Starting places for technical guidance and reference on systems, process, and safety
- Here are the main ones:
  - ANSI/AIAA G-095A Guide to Safety of Hydrogen and Hydrogen Systems – 2017
  - ANSI/CGA H-5 Standard for Bulk Hydrogen Supply Systems – 2020
  - NFPA-2 Hydrogen Technologies Code 2020
  - British Cryogenics Council Cryogenics Safety Manual, 5<sup>th</sup> Edition – 2018



# Thank you

for your attention

#### **Questions?**

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