DOE/NASA Advances in Liquid Hydrogen Storage Workshop

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Overview of the New LH_2 Sphere at NASA Kennedy Space Center

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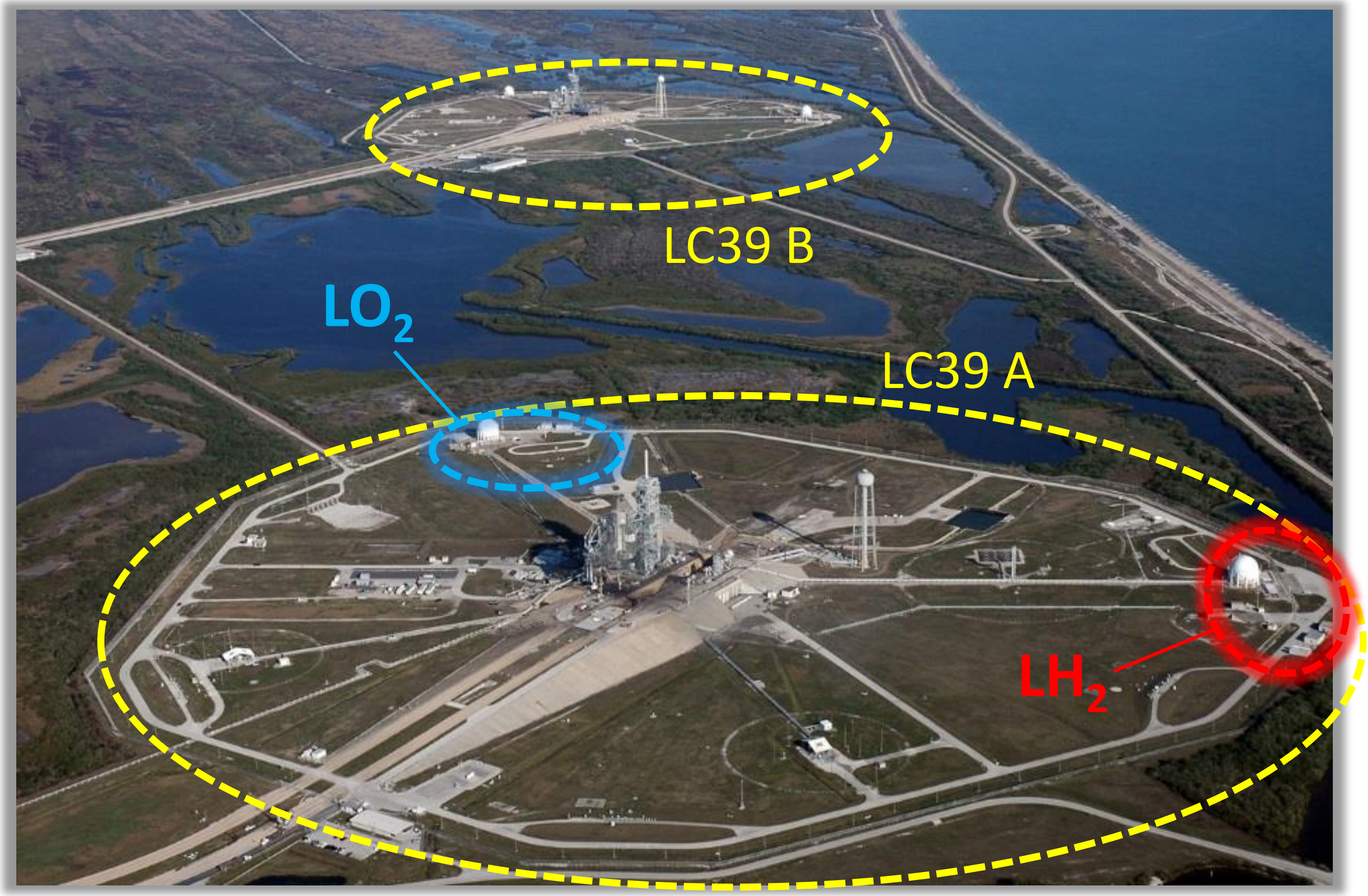
Highlights

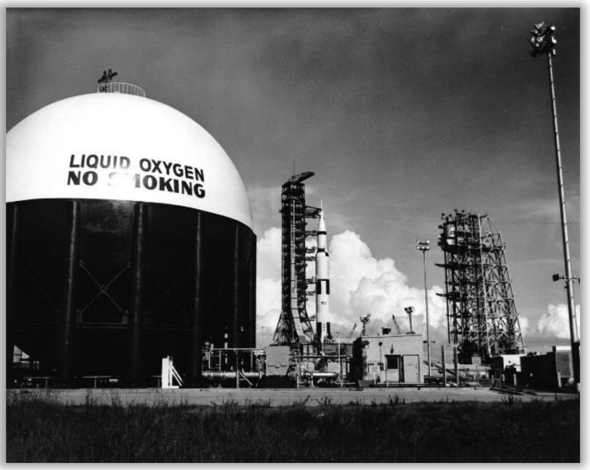
- World's largest LH_2 storage tanks constructed in mid-1960s at NASA Kennedy Space Center in Florida by Chicago Bridge & Iron
  - These vacuum-perlite insulated tanks, still in service, are 3,200 m^3 capacity (ea.)
- In 2019, CB&I Storage Solutions (CB&I) began construction of additional 4,700 m^3 LH_2 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
- Constructed 1963-1965 by Chicago Bridge & Iron Co.
- **Designed for Normal Boiling Point (NBP) storage**

<u>Saturn V</u>

Weight = 6.2 Mlbs

Thrust =7.5 Mlbs

<u>Total On-Board Cryo Prop.</u>

LO_2 = 454Kgal, LH_2 = 335kgal

1965 CRYO STORAGE TANK SPECIFICATIONS

Liquid Oxygen (2 ea.)

- 900,000 gal (3,407 m^3) 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)

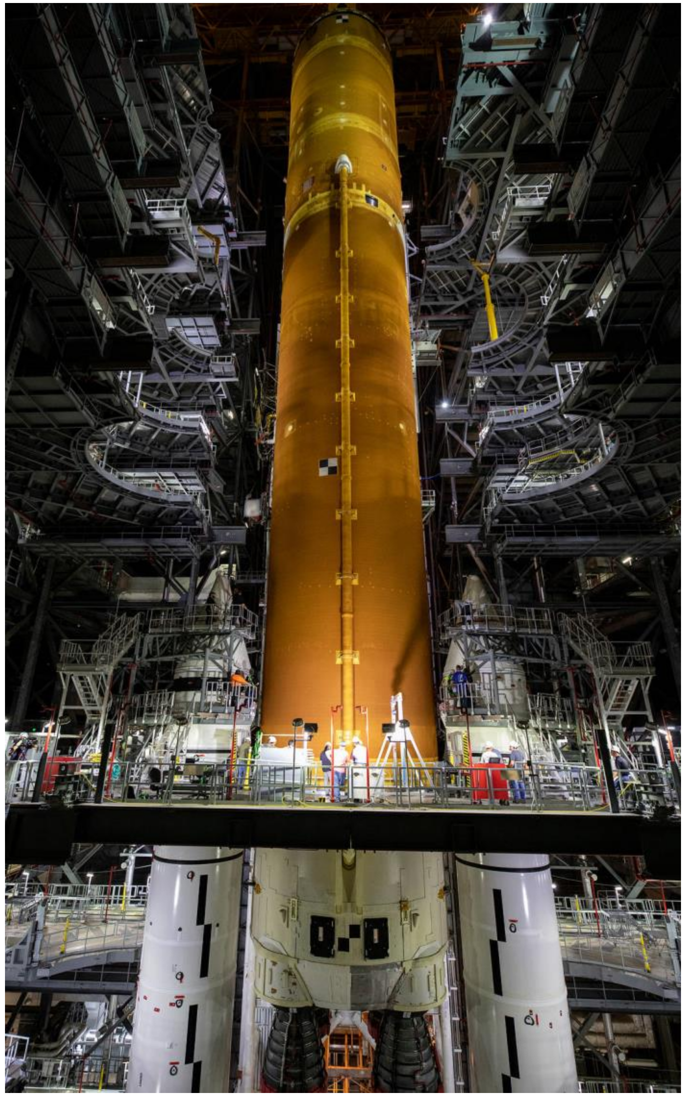
Liquid Hydrogen (2 ea.)

- 850,000 gal (3,218 m^3) 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 LH_2 tanks in the world....for now!

1955 – 1965 – 2021 and Beyond

- Head start provided by the Atomic Energy Commission around 1955 for LH_2 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_2 storage tanks (and still in service today)
- NASA's new Space Launch System (SLS) heavy lift rocket for the Artemis program includes an LH_2 flight tank holding 2,033 m^3 of LH_2 in its 8.4-m dia. by 40-m height



SLS Assembly in VAB at KSC

INTRODUCTION

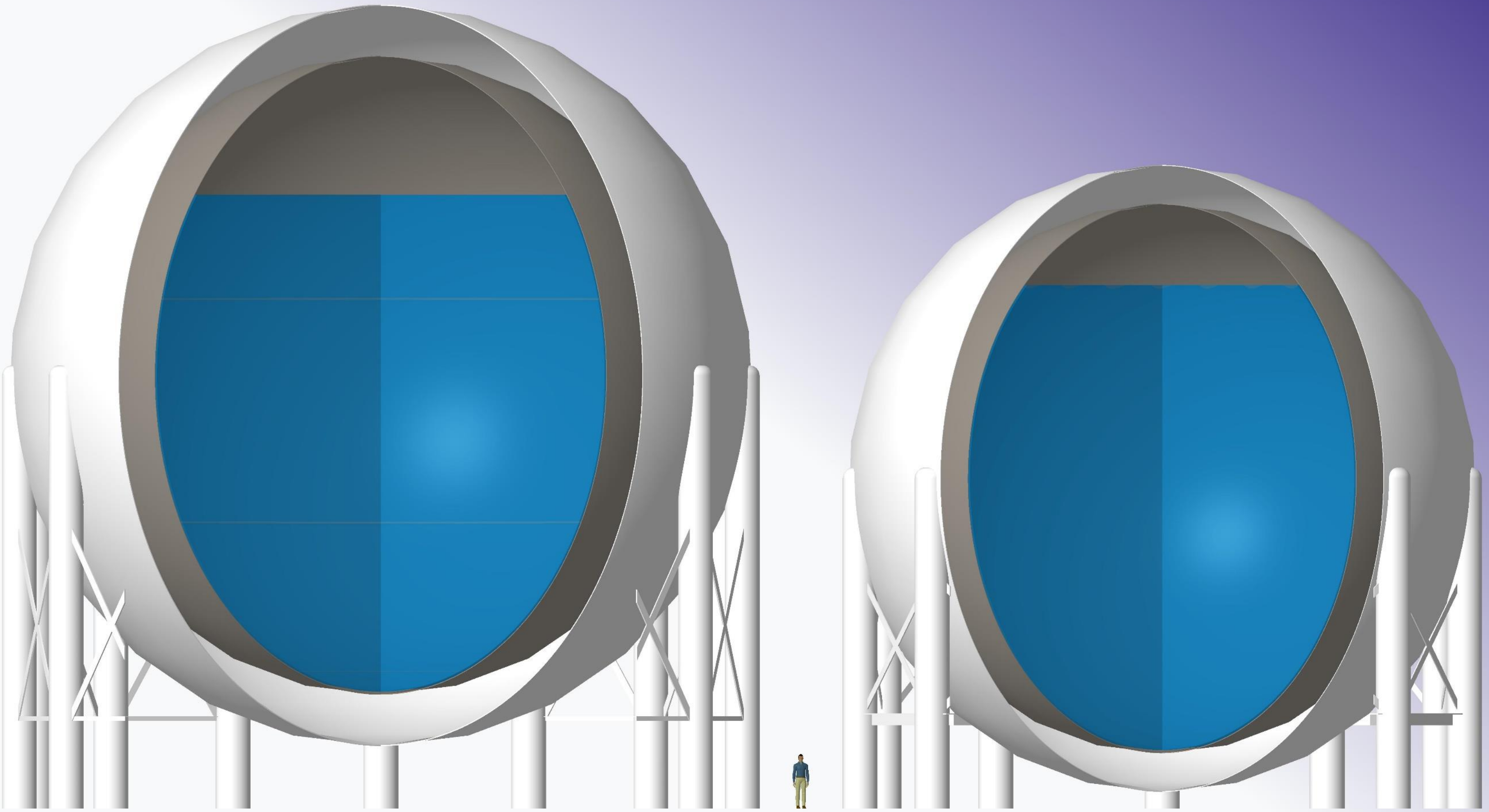
- In 2018, construction began on an additional LH_2 storage tank at Launch Complex 39B
- This new tank will give an additional storage capacity of 4,732 m^3
- Total on-site storage capacity of about 8,000 m^3

NASA Kennedy Space Center's Launch Complex 39

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

Apollo-era 3,200-m^3 LH_2 storage tank

New 4,700-m^3 LH_2 storage tank



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

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

Tank specifications

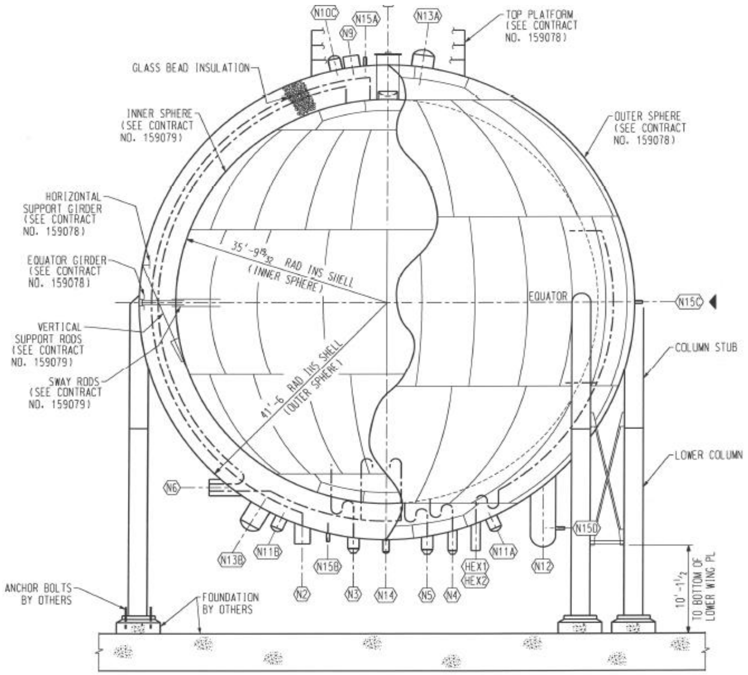
- Detailed design and construction by CB&I Storage Tank Solutions as part of the PMI contract for the launch facility improvements
- ASME BPV Code Section XIII, Div 2 and ASME B31.3 for piping
- Usable capacity = 4,732 m^3 (1,250,000 gal) w/ min. ullage volume 10%
- Max. boiloff or NER of 0.048% (600 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)

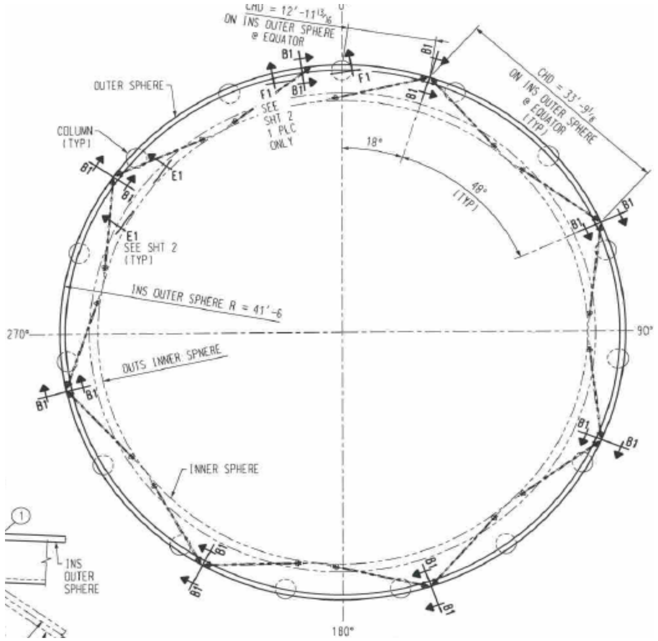
Tank Configuration

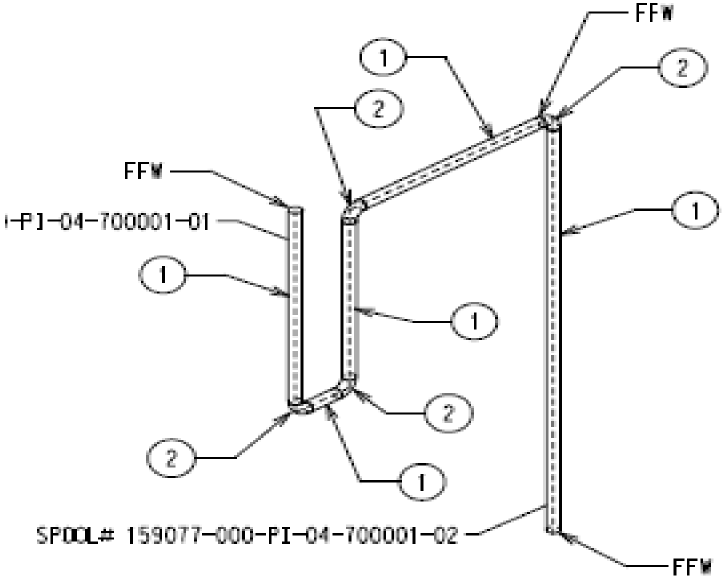
- The 25.3-m outer diameter spherical tank has 15 support legs welded to the equator and stands at an overall height of 28.0 m
- Tank is supplied from a tanker manifold and ambient air vaporizers for pressurization
- Tank includes a vent stack on top for normal boiloff gas and is connected to a dedicated 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



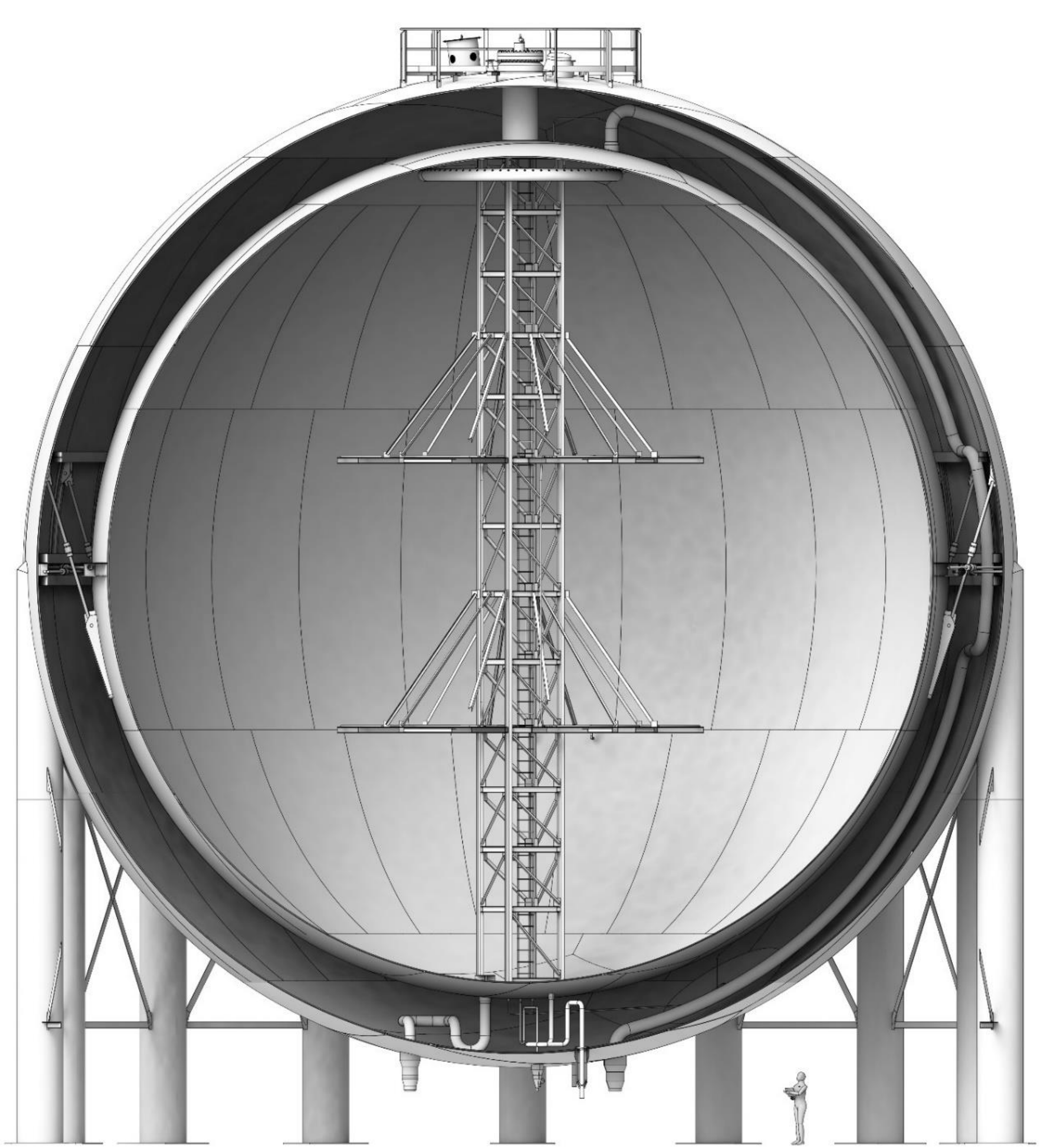




Three key ingredients of LH_2 tank thermal performance: evacuated insulation (left); structural supports (middle); and piping penetrations (right)

LH_2 Storage Tank

- Usable capacity = 4,732 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)



New Technologies

- 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_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

Passive-only – no active control

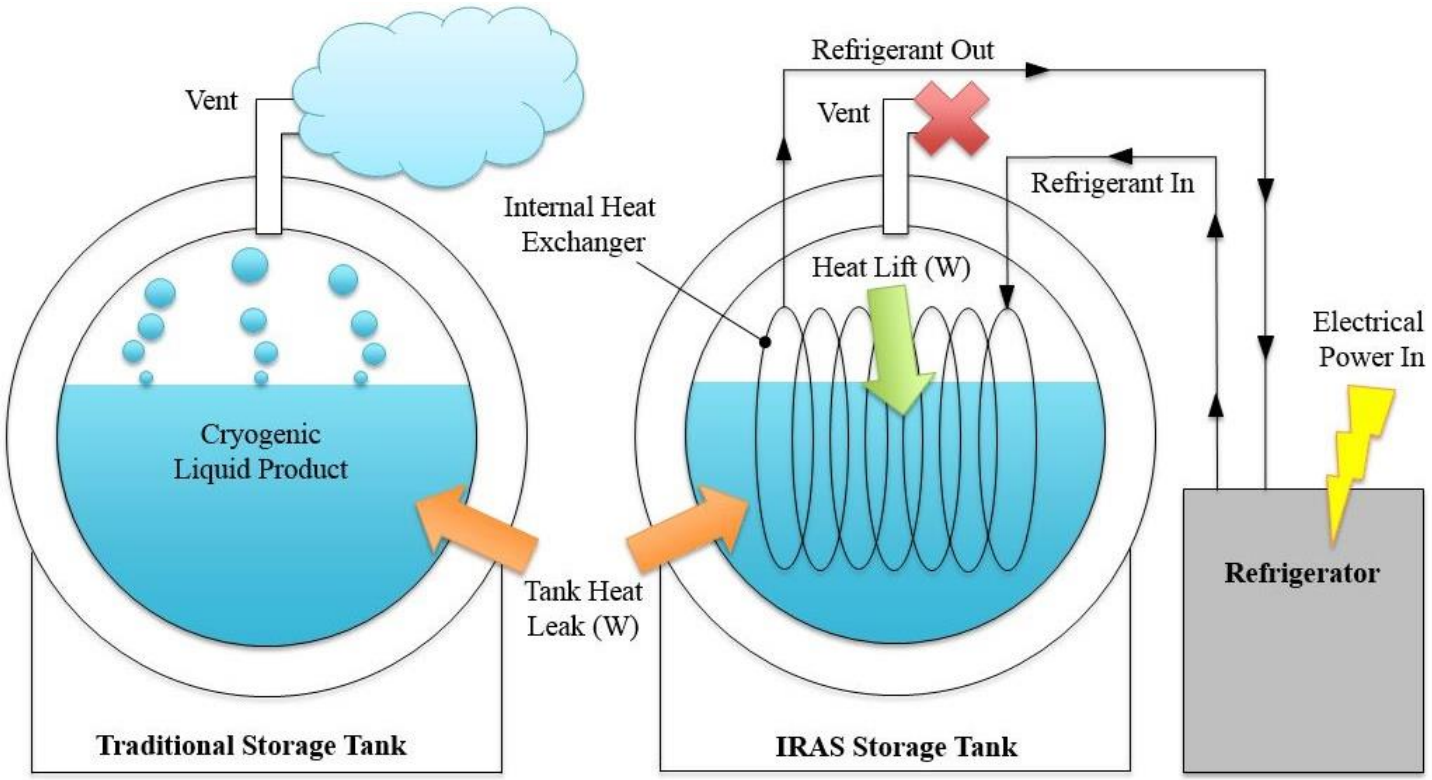
[Image: National Museum of American History]

Part I

Integrated Refrigeration and Storage (IRAS) Heat Exchanger

IRAS HEAT Exchanger Concept

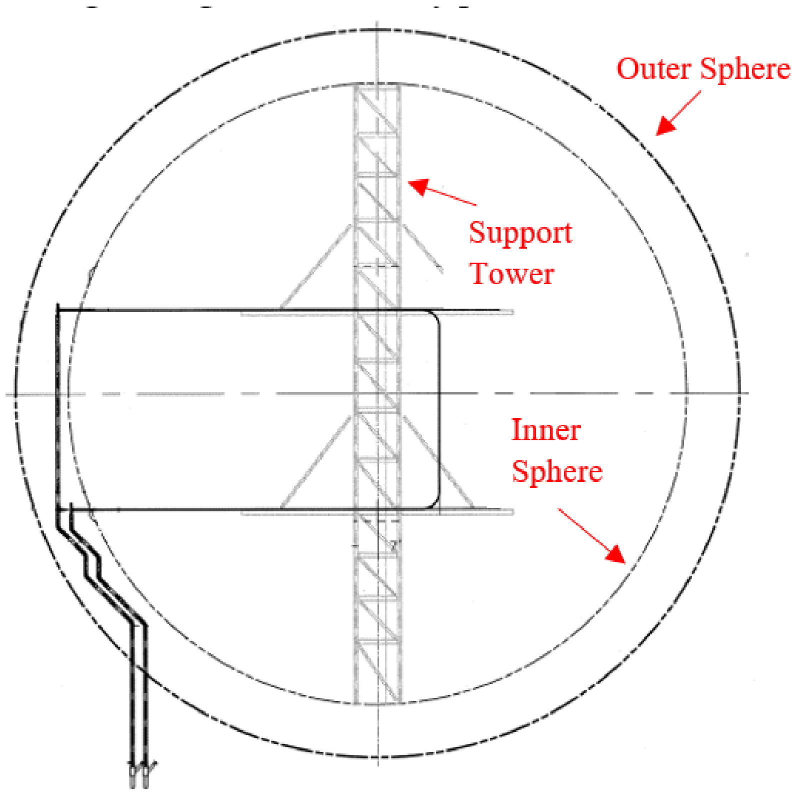
- Traditional storage tank - no control. Heat energy from ambient stores within the liquid, ullage pressure rises, relief valve opens to vent.
- IRAS tank – full control. Pressure and temperature are controlled by taking up the heat through the internal heat exchanger. No venting of boiloff gas.

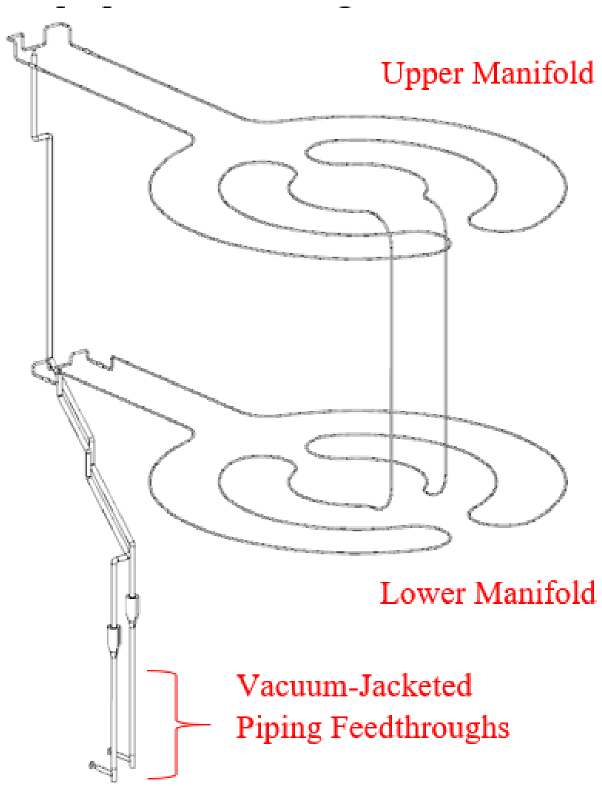


IRAS HEAT Exchanger Design

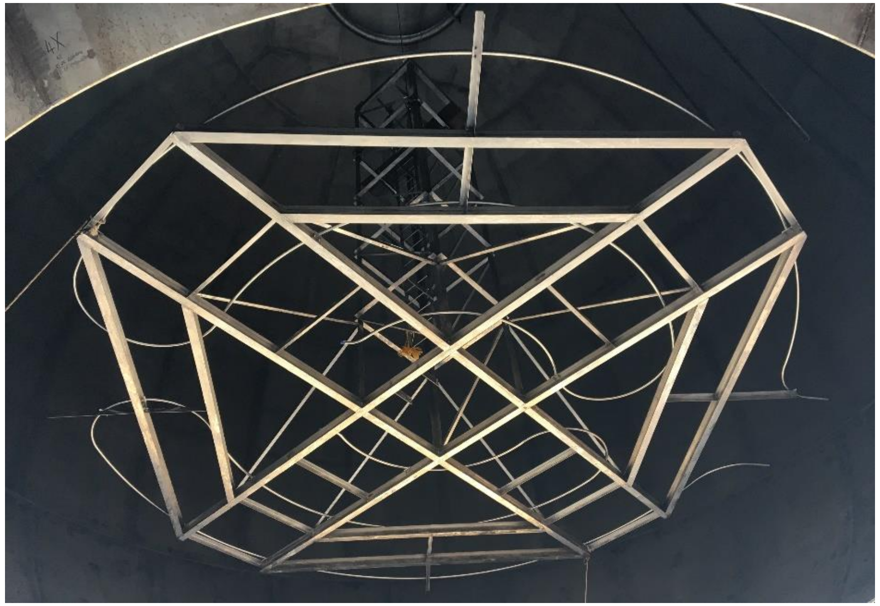
- Upper and lower heat exchanger (HX) manifolds
  - Positioned at the 25% and 75% fill level elevations
  - Constructed of fully welded 38-mm (1.5-inch OD) 316L stainless steel tubing
- Total coil length = 43 m, for a heat exchange area of ~5.2 m^2
- Helium refrigerant will be fed to the coils via 51-mm (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

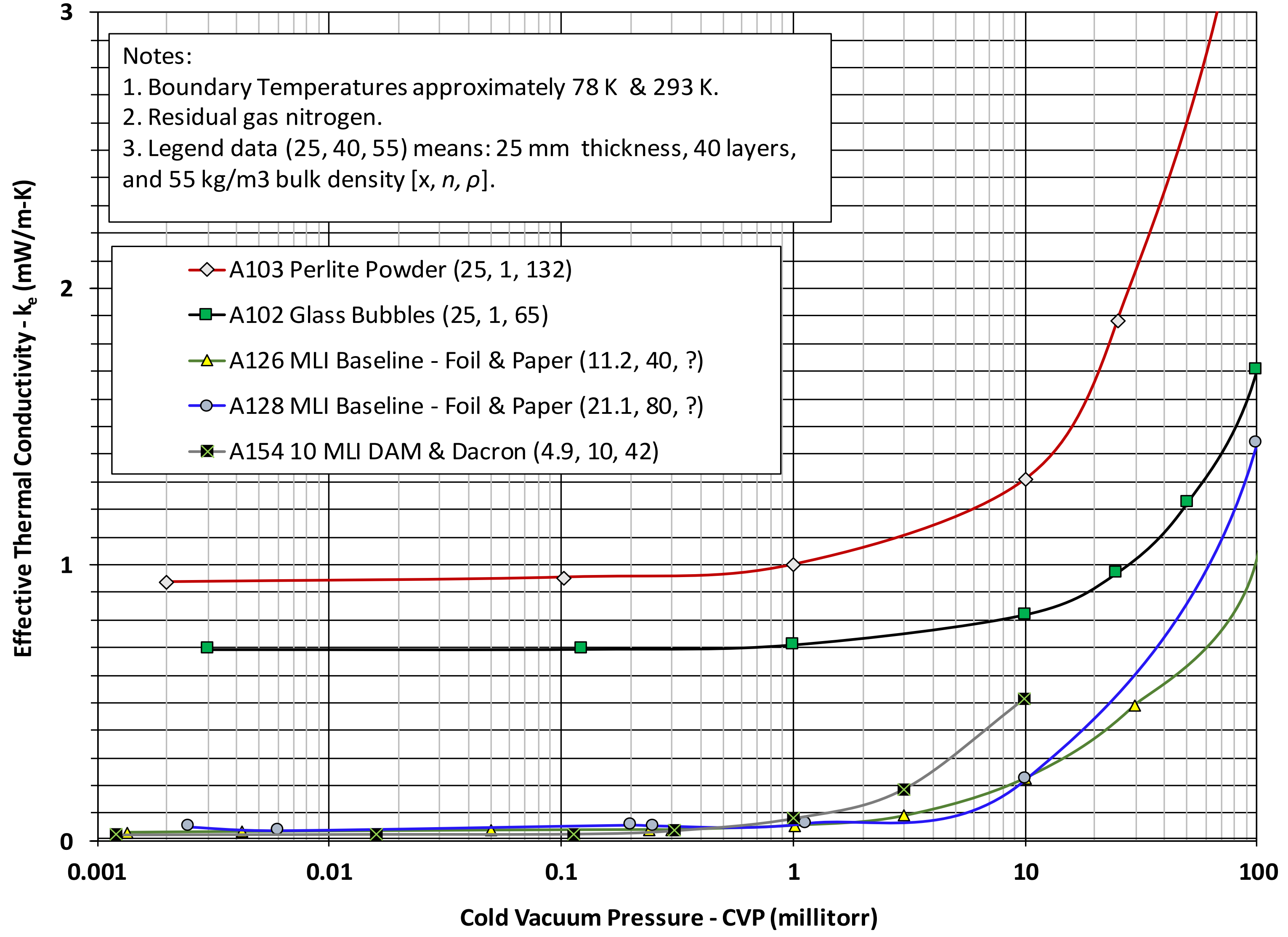
Glass Bubbles – Development Timeline

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)
2005	Field demonstration of 6000-gallon LN_2 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 LH_2 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 LH_2 storage tank for NASA/KSC Launch Complex 39B
2021	Completion of new 1,250,000-gallon LH_2 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_2

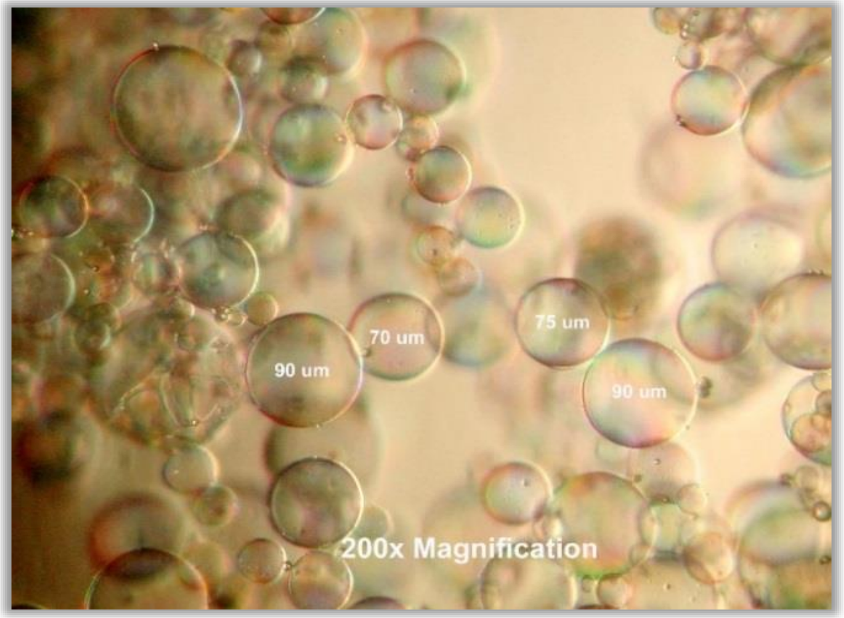
Glass Bubbles – Selected Publications

1. 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 cryogenic-vacuum 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

Common Questions about Glass Bubbles

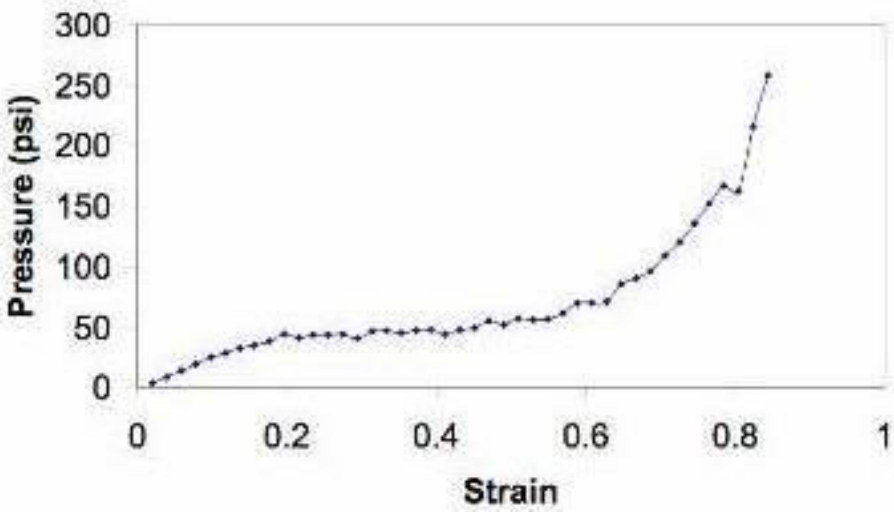
Do bubbles break?

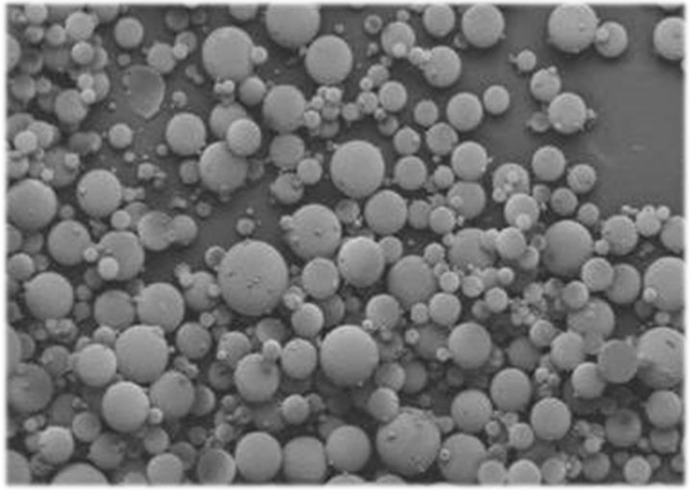
No.

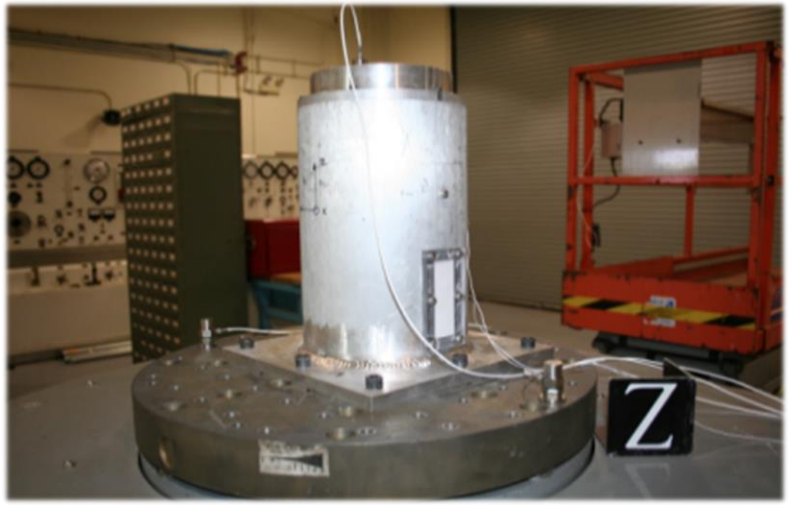
Is evacuation a problem?

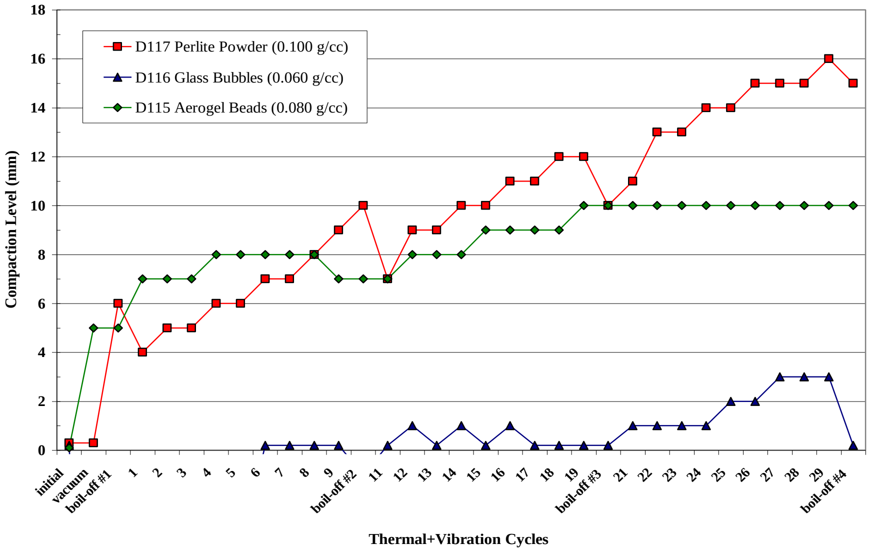
No.

Mechanical Testing of 3M K1 Glass Bubbles



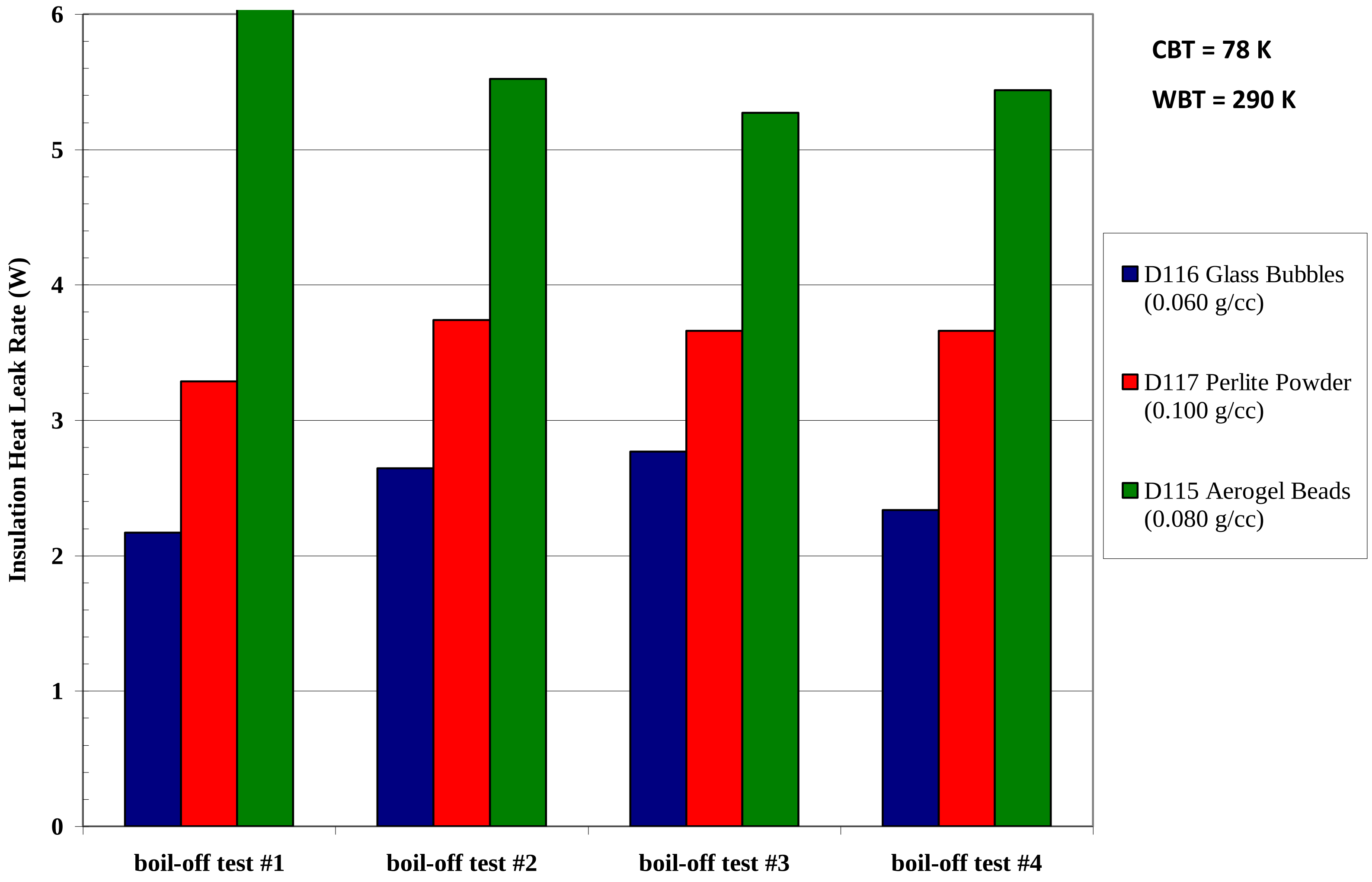






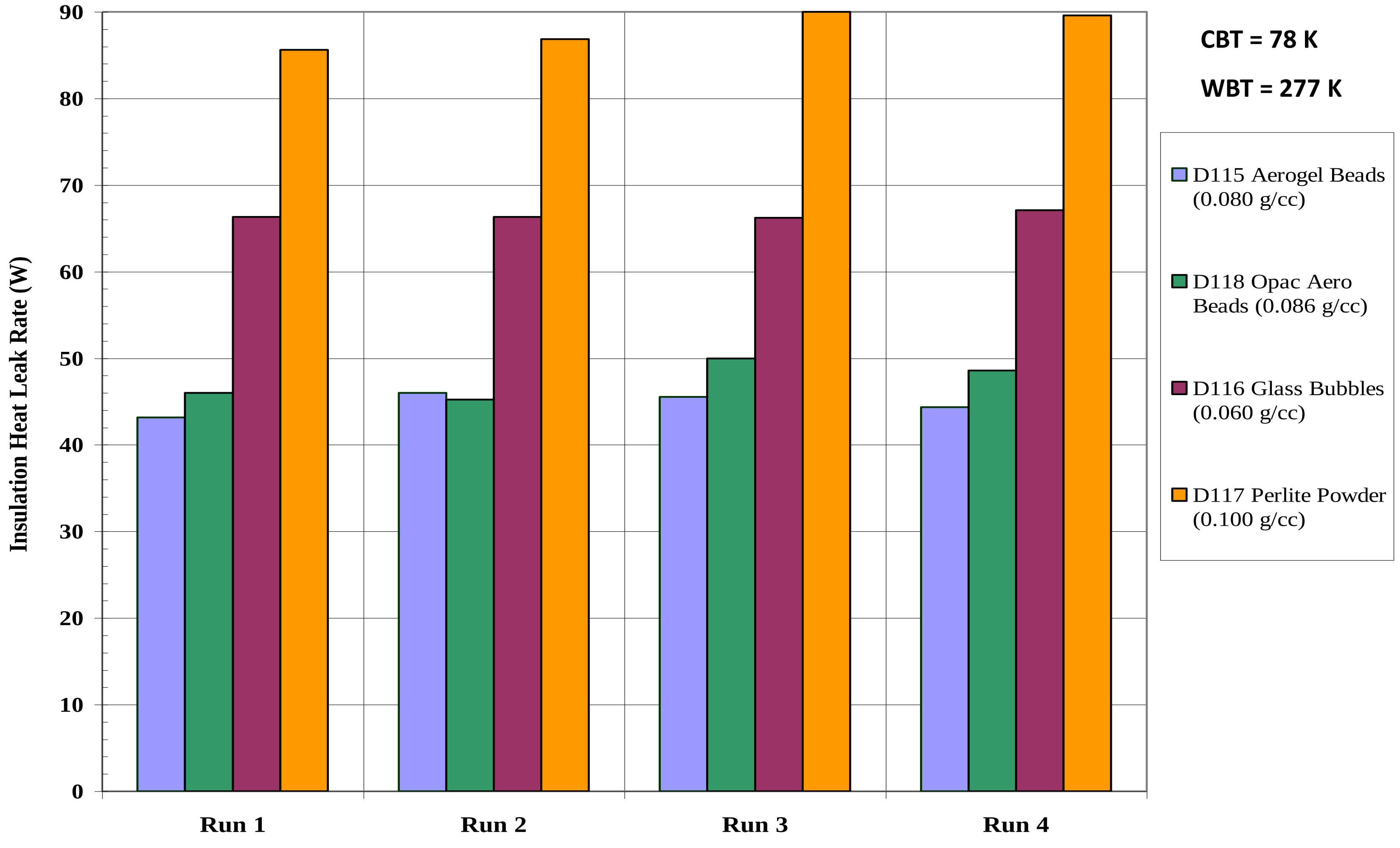
Experimental 10-liter Dewar Test Apparatus

THERMAL TEST RESULTS: "HIGH VACUUM" SUMMARY



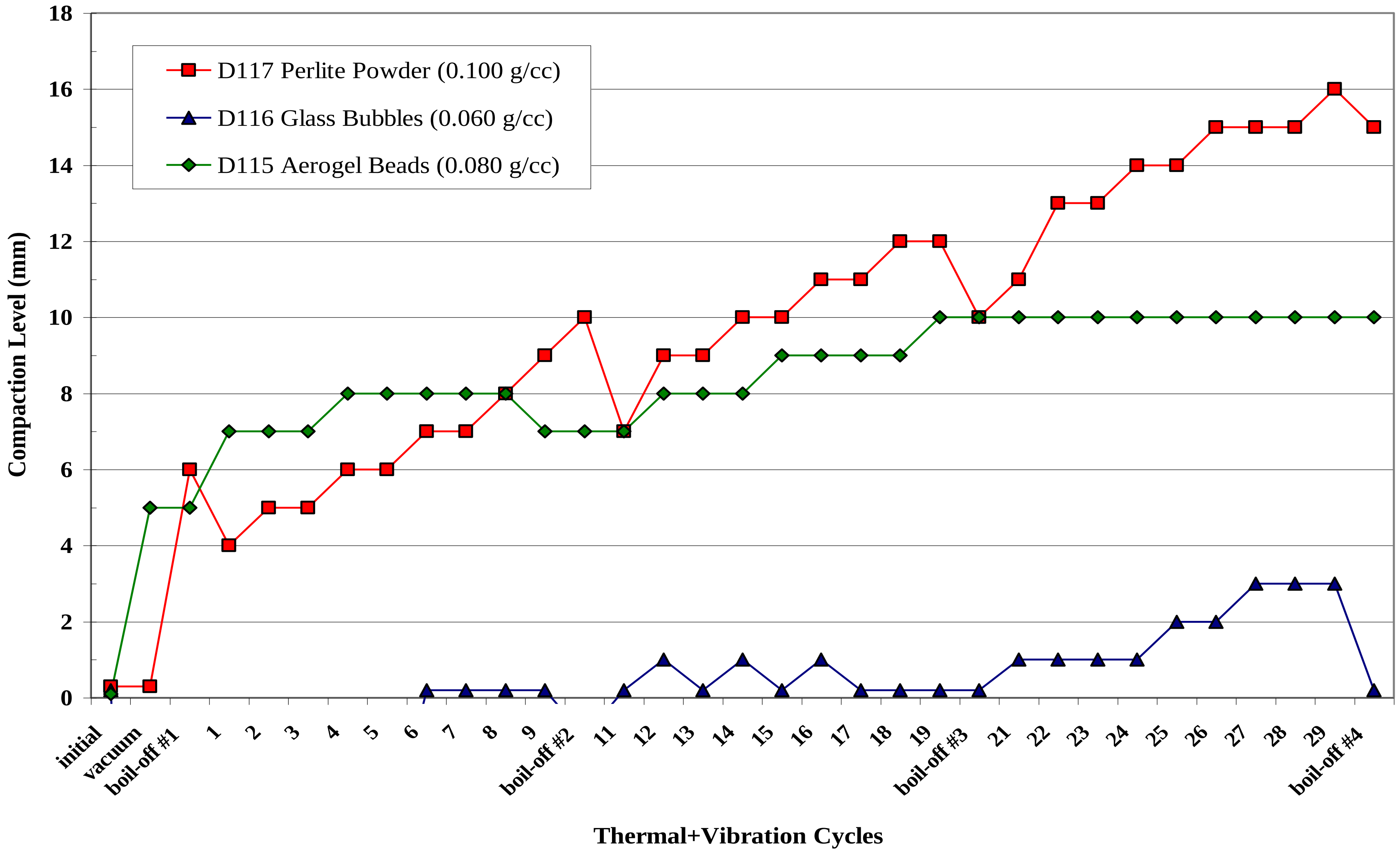
10-liter Dewar Testing

THERMAL TEST RESULTS: “NO VACUUM” SUMMARY

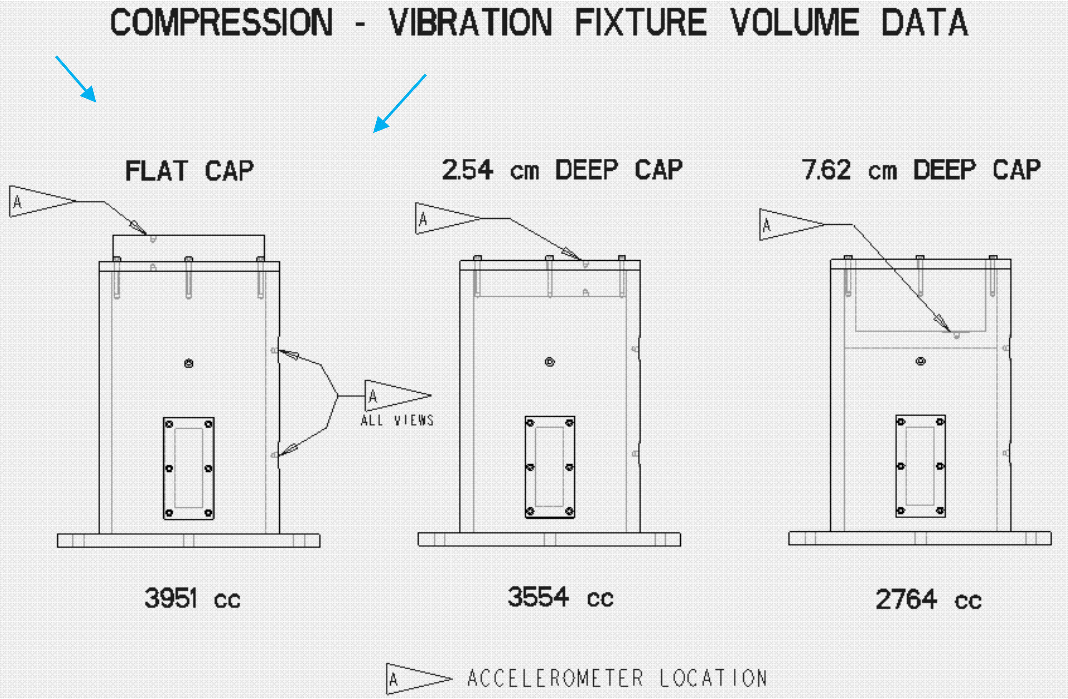


10-liter Dewar Testing

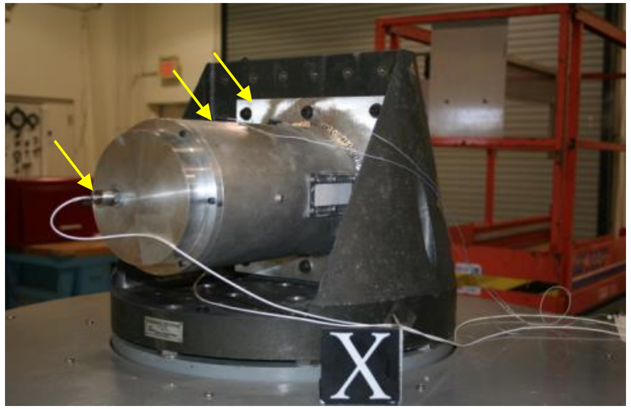
COMPACTION LEVELS FOR THERMAL CYCLING + VIBRATION

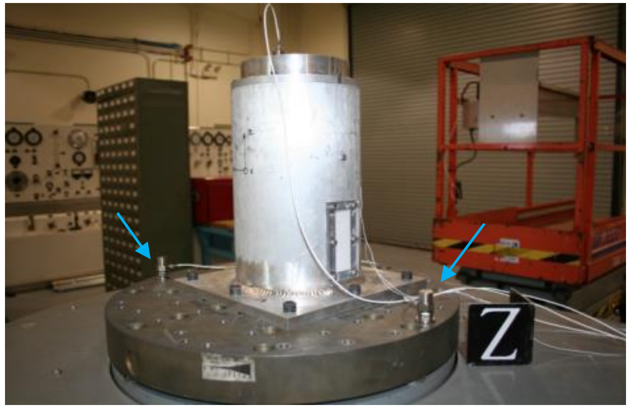


Vibration Testing of Bulk Fill Insulation Materials



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





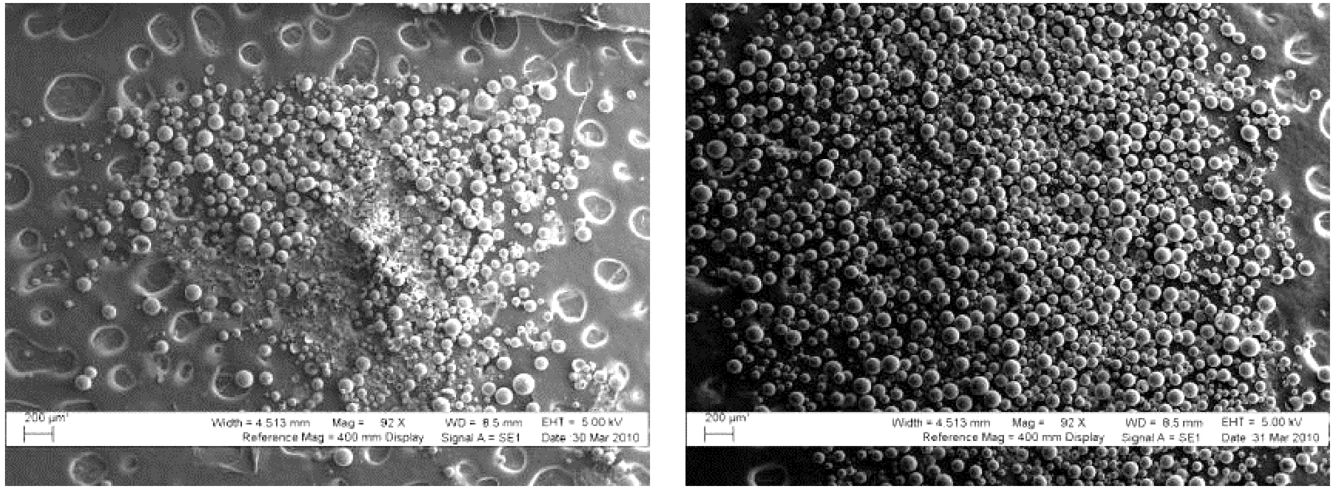
Lateral (X,Y) vibration test fixture with arrows pointing to response accelerometers (left photo) and vertical (Z) vibration test fixture with arrows pointing to control accelerometers (right).

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

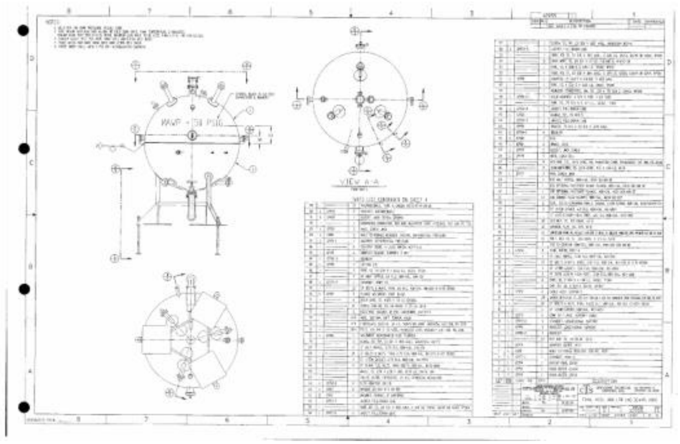
K1 Glass Bubbles after X-axis vibration, 4% void (left) and after Z-axis vibration, 2.5% void (right). Photographs of typical results.

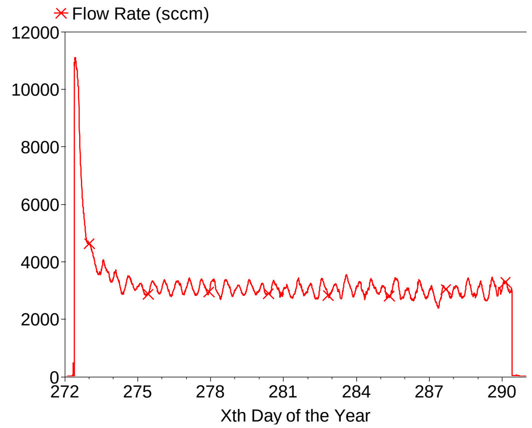
High Density Perlite exhibited compaction in the range of 13-17% after X-axis vibration (left) and Z-axis vibration (right). Photographs of typical results.

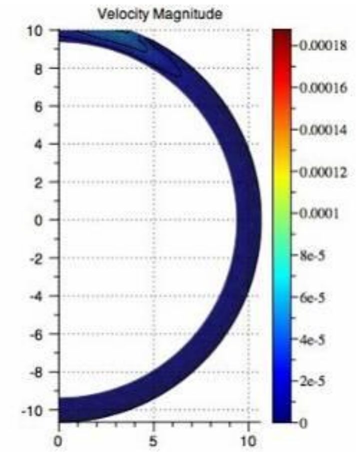


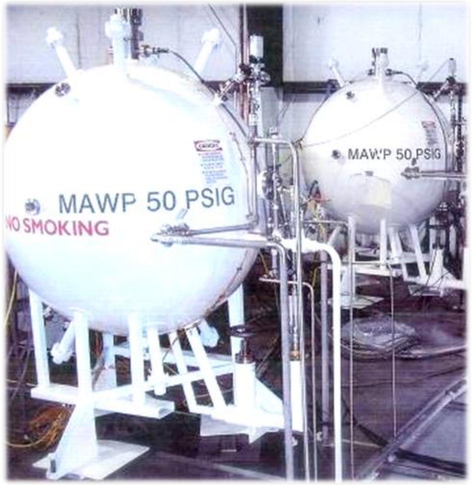
Glass Bubbles in the VTF before and after X / Z Random Shaker vibration: Glass Bubbles showed little degradation based on several samples. Typical micrographs 92X magnification.

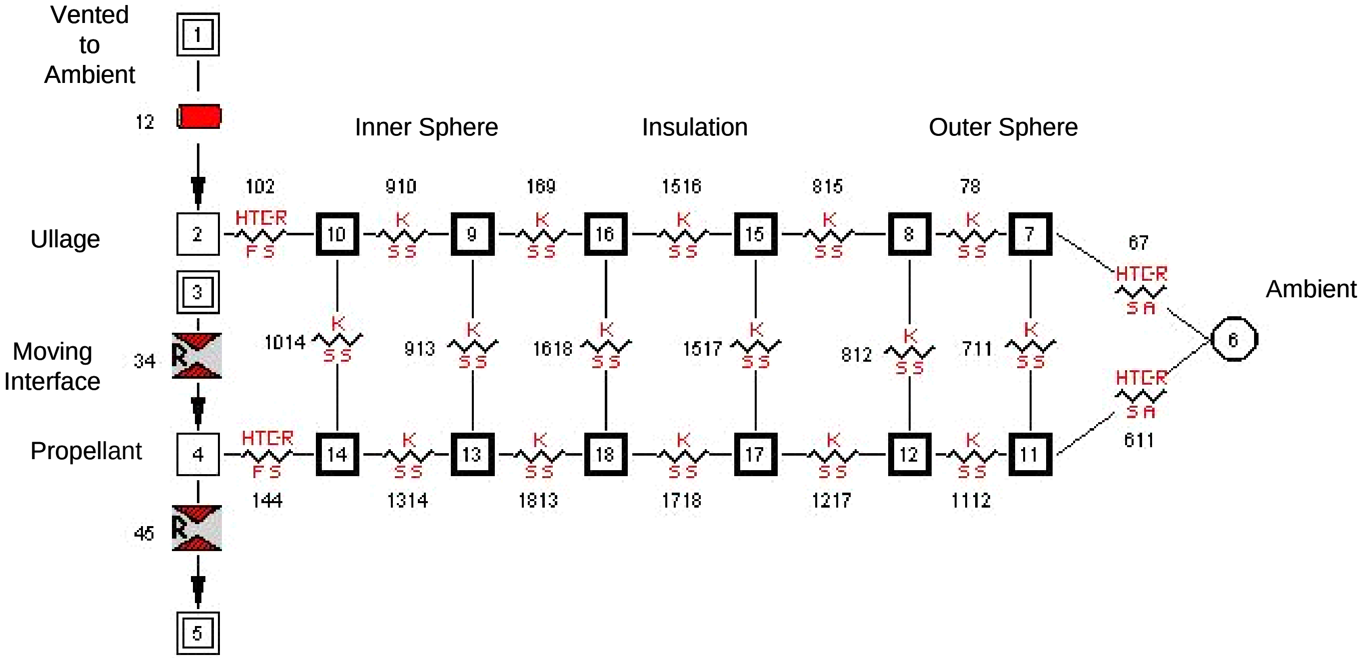
1000-liter Spherical Cryostat Testing











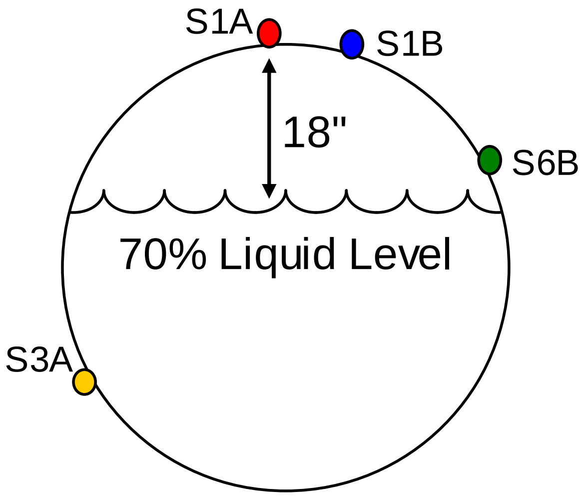
1000-liter Spherical Cryostat Testing

1/15th scale version of LC-39 LH_2 storage tank

Glass Bubbles
and
Perlite Powder

LH_2 and LN_2

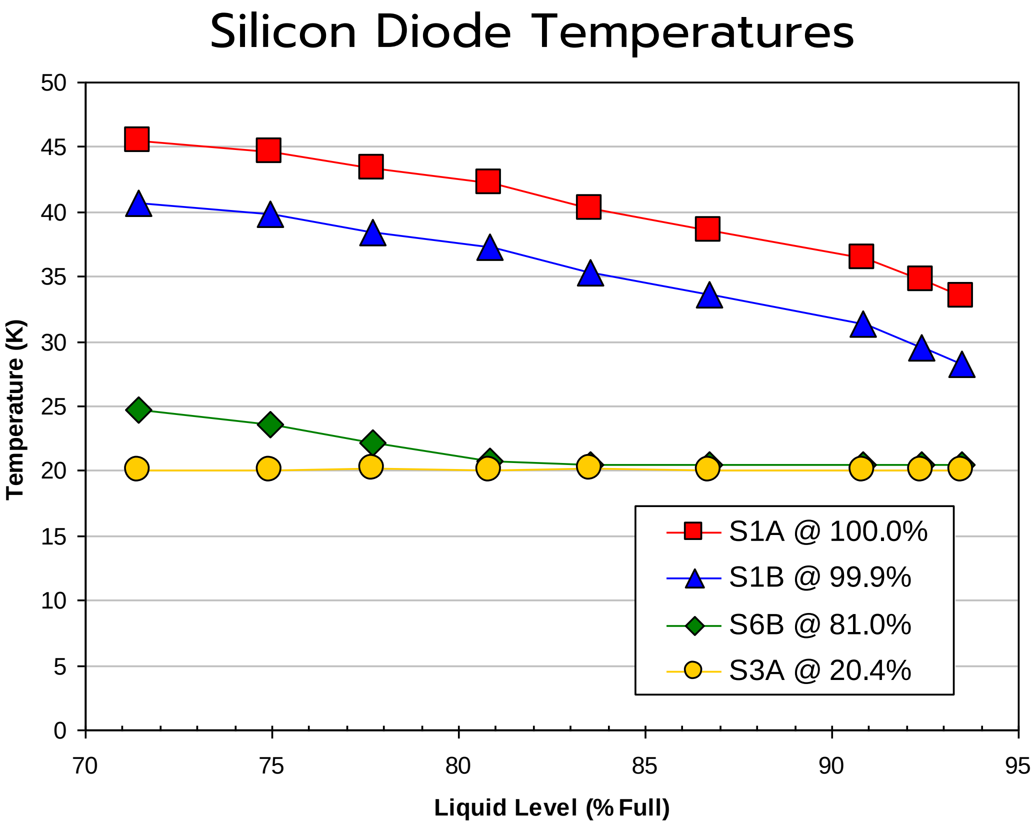
1000-liter Spherical Cryostat Testing



Internal Tank Wall Temperature Measurements

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

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

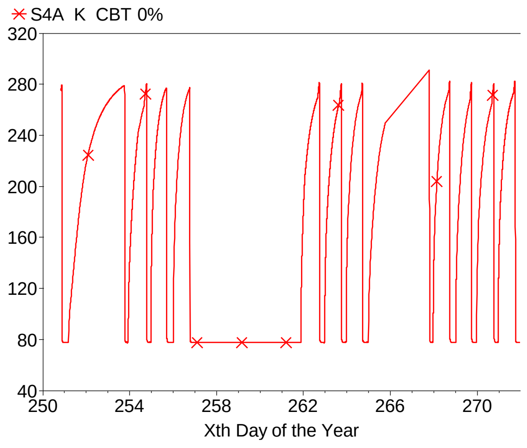


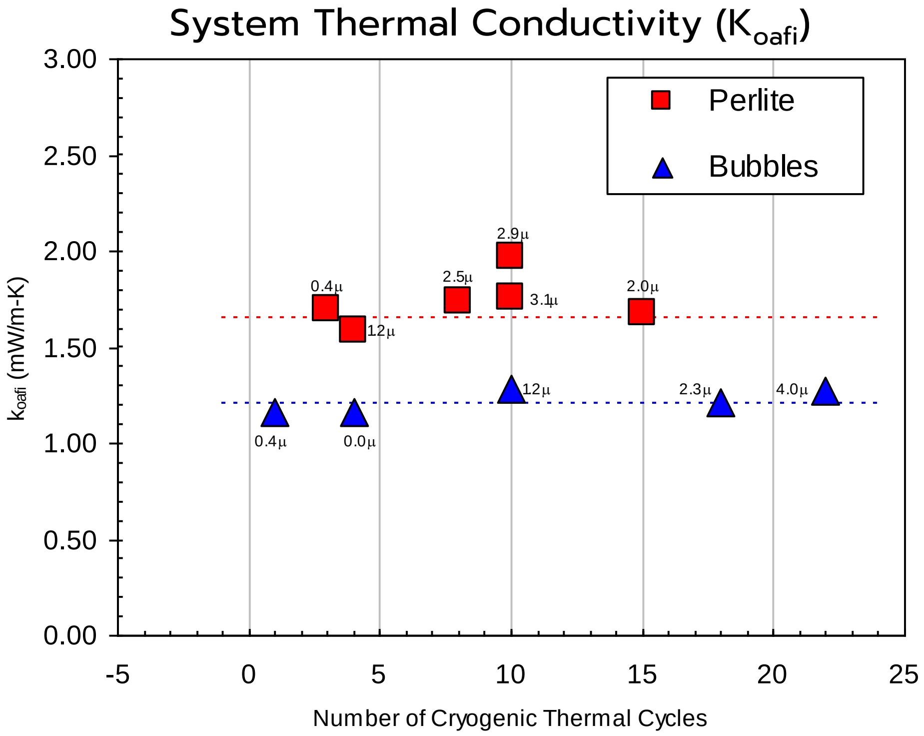
1000-liter Spherical Cryostat Testing

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

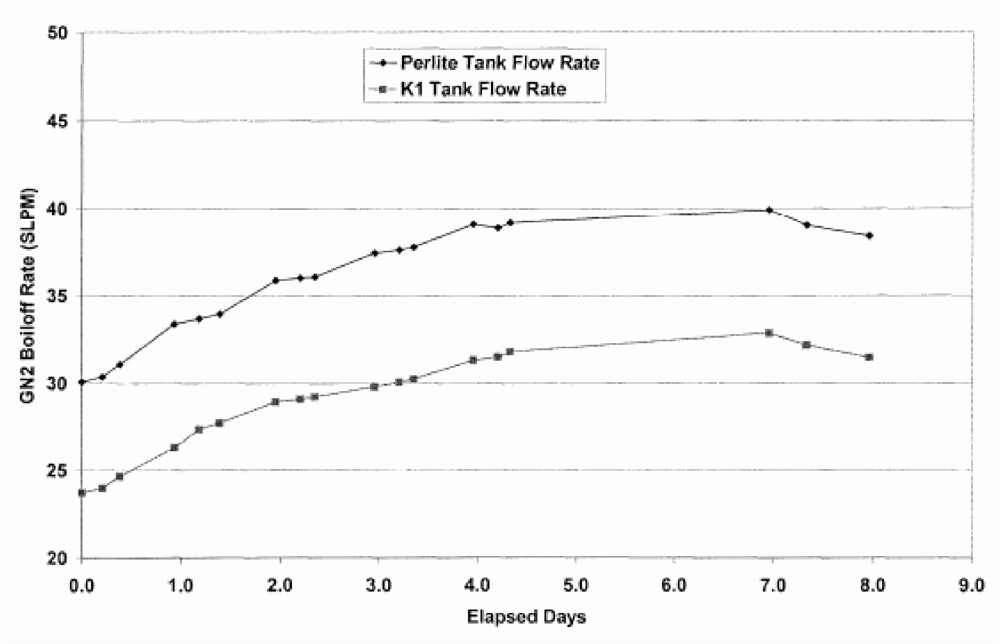
Inner Tank Temperature





Demonstration Testing with 23-m^3 Vertical Cylindrical Tank

- K1 Glass Bubbles versus Perlite Powder
- Two identical LN_2 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

Cryogenics Test Laboratory
Kennedy Space Center

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)	

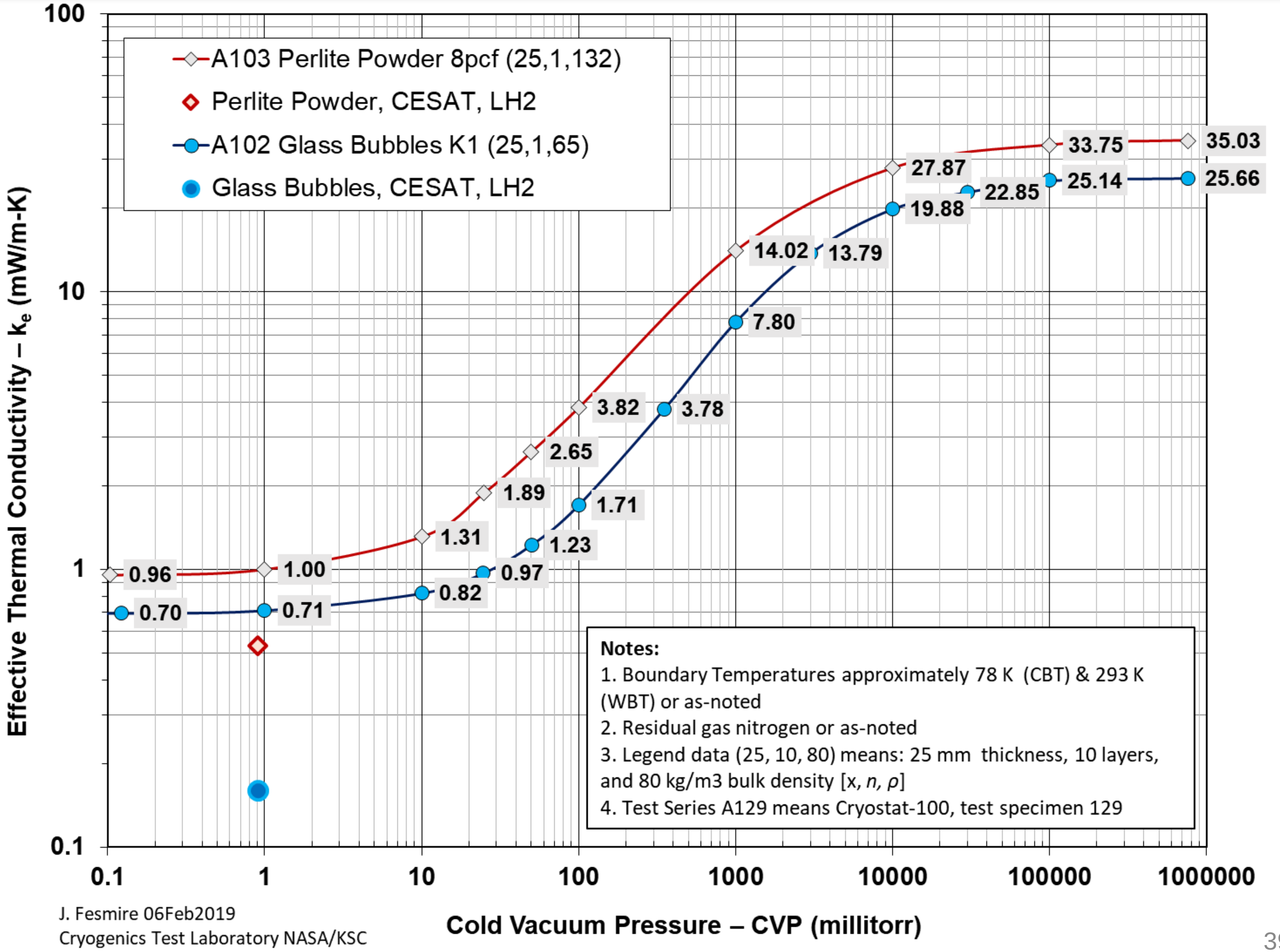
Effective Thermal Conductivity Test Data

3M K1 Glass Bubbles (65 kg/m³)

versus

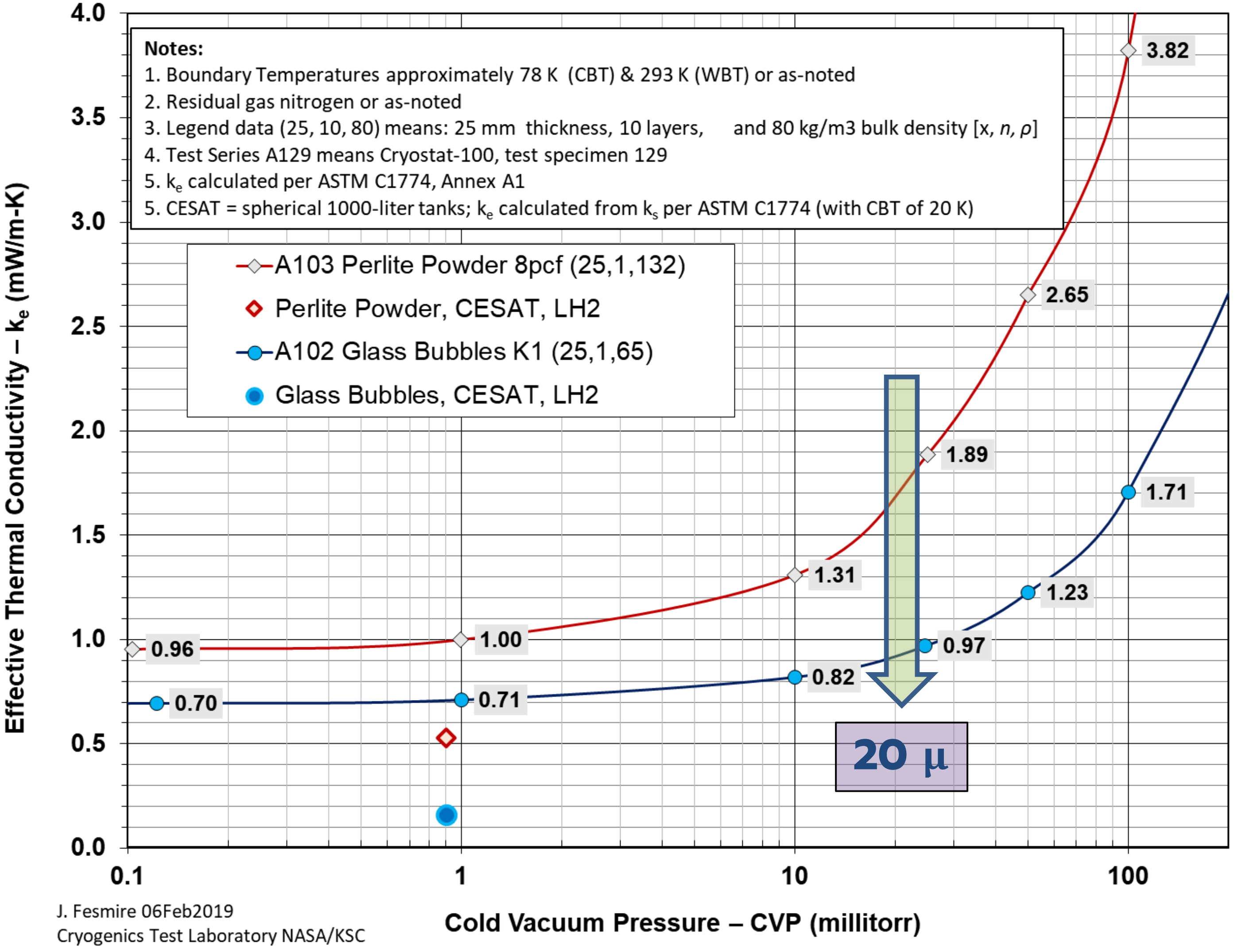
Perlite Powder (132 kg/m³)

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



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^3 (50,000-gal) VJ LH_2 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

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

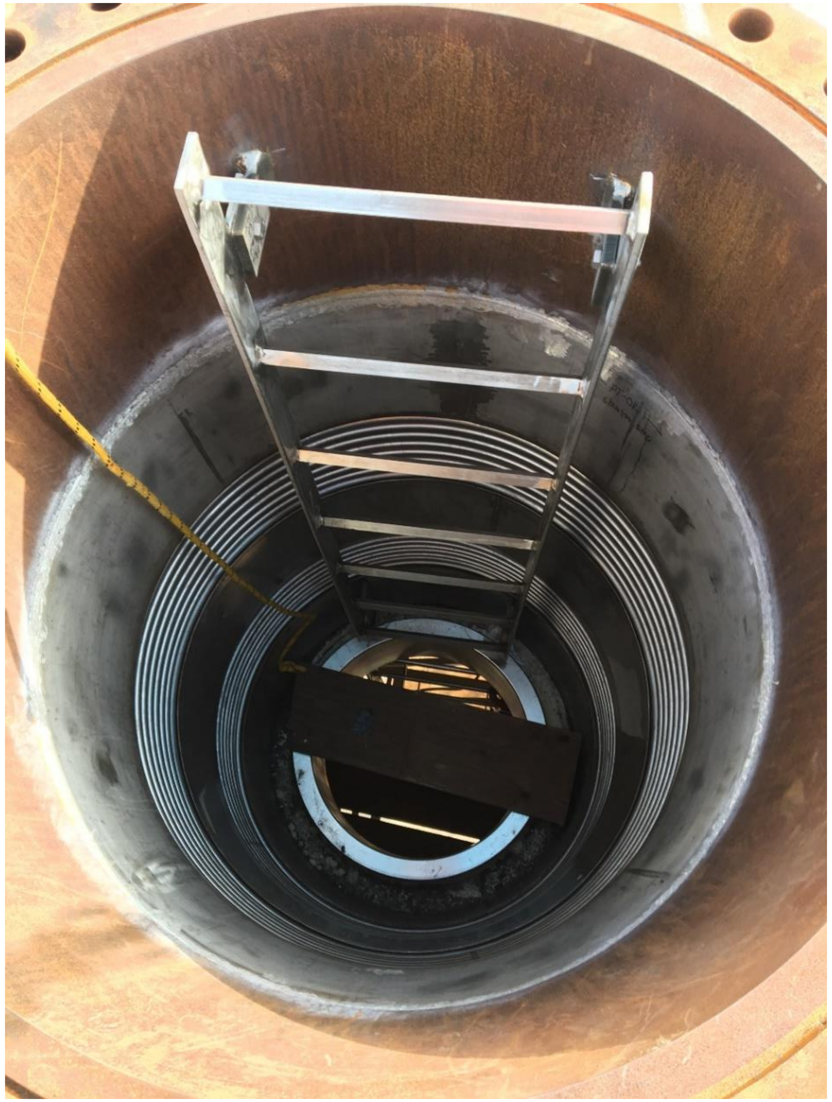
Tank Construction

- 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)


A1817
RAM

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

AIAA
Shaping the Future of Aerospace

ANSI
American National Standards Institute

ASHRAE®

ASME
SETTING THE STANDARD

ASTM INTERNATIONAL

British Cryogenics Council

CGA
Compressed Gas Association
The Standard For Safety Since 1913

CSA Group®

energy API

ISO®

NFPA®

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

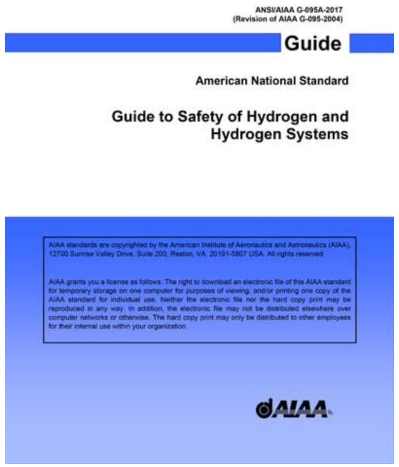
IMO
INTERNATIONAL MARITIME ORGANIZATION

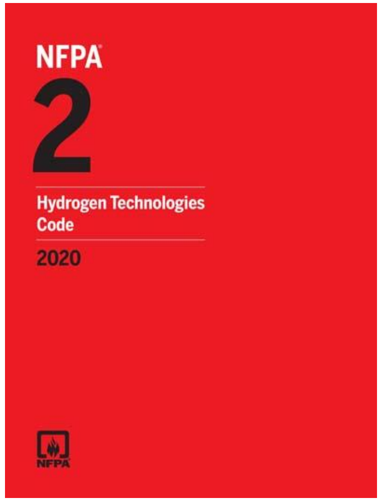
csa
Cryogenic Society of America, Inc.

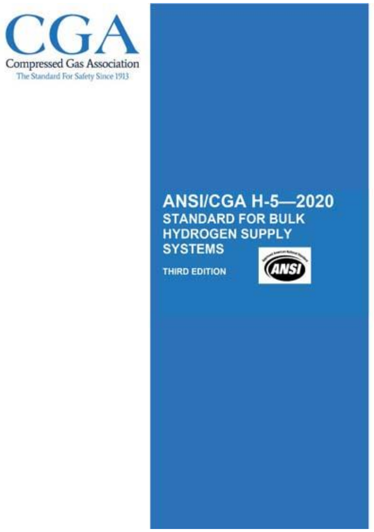
EIGA

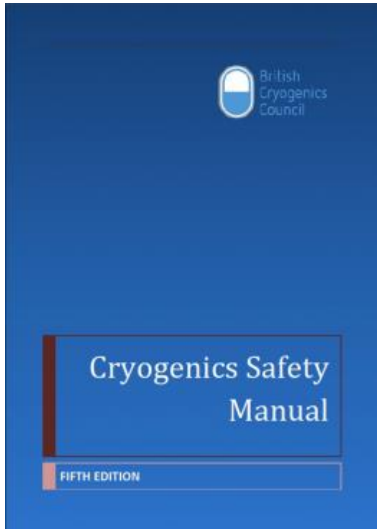
Main Documents for LH_2

- 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, 5th Edition – 2018









Thank you

for your attention

Questions?

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