ENERGY EFFICIENT LARGE-SCALE STORAGE OF LIQUID HYDROGEN

2021 Cryogenic Engineering Conference and
International Cryogenic Materials Conference (CEC-ICMC)

July 20, 2021

James E. Fesmire
NASA Kennedy Space Center
Cryogenics Test Laboratory
KSC, FL 32899 USA

Adam M. Swanger
NASA Kennedy Space Center
Cryogenics Test Laboratory
KSC, FL 32899 USA

Andy Jacobson
CB&I Storage Solutions
14105 S. Route 59
Plainfield, IL 60544 USA

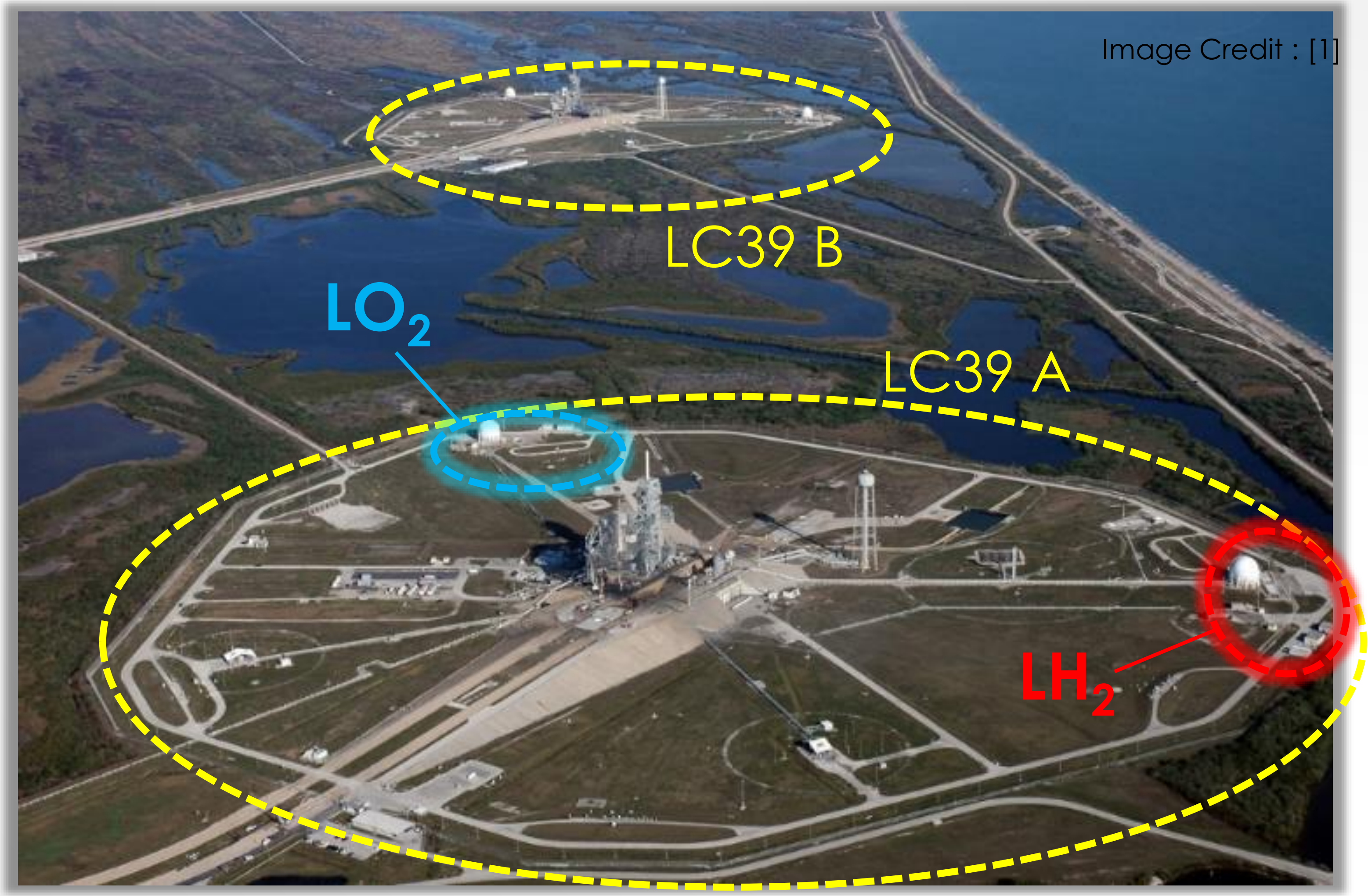
Bill Notardonato
Eta Space
485 Gus Hipp Blvd
Rockledge, FL 32955 USA

HIGHLIGHTS

- World's largest LH_2 storage tanks constructed in mid-1960s at NASA/KSC
- These vacuum-perlite insulated tanks, still in service today, are 3,200 m^3 capacity (ea.)
- In 2018, construction began on an 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 8.4-m diameter by 40-m height
- Two new energy-efficient technologies are included: glass bubbles insulation system and an Integrated Refrigeration and Storage (IRAS) heat exchanger for **passive + active** thermal control:
  - Evacuated glass bubbles insulation system has been shown to reduce LH_2 boiloff by 46% versus perlite in field demonstrations
  - Controlled storage via IRAS, when fully implemented, will provide full control of ullage pressure, zero boiloff, and even production of densified LH_2

INTRODUCTION

- LC-39A & B built in 1960's for Apollo moon program
- Identical layout
- Both used throughout Apollo and Space Shuttle Programs
- Cryogenic storage systems sized for Apollo missions (Saturn V vehicle)



LC39 CRYOGENIC STORAGE – APOLLO ERA

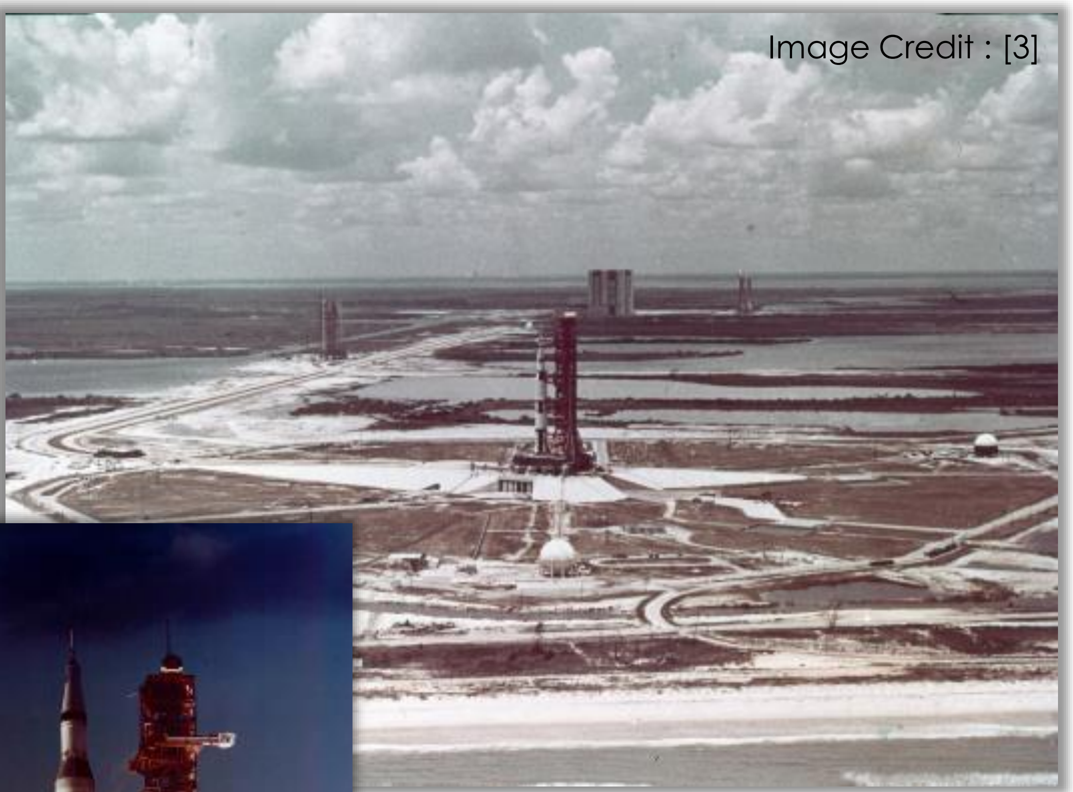


Image Credit : [3]

Image Credit : [2]

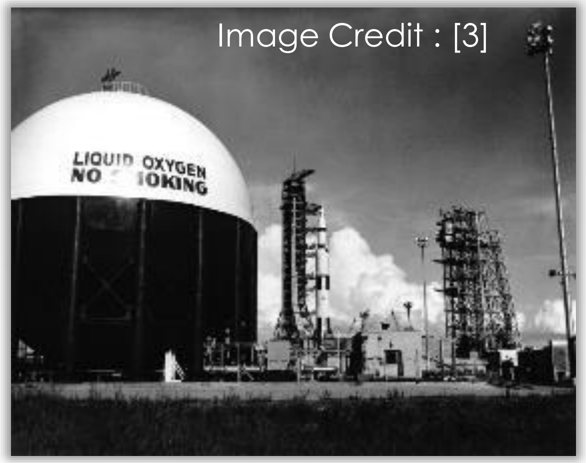


Image Credit : [3]

Image Credit : [3]

Saturn V

Weight = 6.2 Mlbs

Thrust =7.5 Mlbs

Total On-Board Cryo Prop.

LO_2 = 454Kgal, **LH_2 = 335kgal**

- 4 site-built tanks for LO_2 & LH_2
- Constructed 1963-1965 by Chicago Bridge & Iron Co.
- **Designed for Normal Boiling Point (NBP) storage**

1965 CRYO STORAGE TANK SPECIFICATIONS

Images Credit: Author

Liquid Oxygen

- 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

- 850,000 gal (3,218 m^3) useable volume
- ~69 ft. (21 m) outer diameter; MAWP = 90 psig (6.2 bar)
- Vacuum-jacketed w/perlite bulk-fill insulation (~4 ft. thick)
- Normal Evaporation Rate = 0.0625% (530 gal/day)
- Largest LH_2 tanks in the world….for now!

ETA SPACE MCDERMOTT CB&I STORAGE SOLUTIONS CryogenicsTestLab KENNEDY SPACE CENTER

INTRODUCTION

- Head start provided by the Atomic Energy Commission in the 1950s
- NASA went from a two m^3 LH2 storage tank to a pair of 3,200 m^3 tanks by 1965
- Built by Chicago Bridge & Iron Storage under the Catalytic Construction Co. contract, 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 m^3 of LH2 in its 8.4-m diameter by 40-m height

SLS Assembly in VAB at KSC

INTRODUCTION

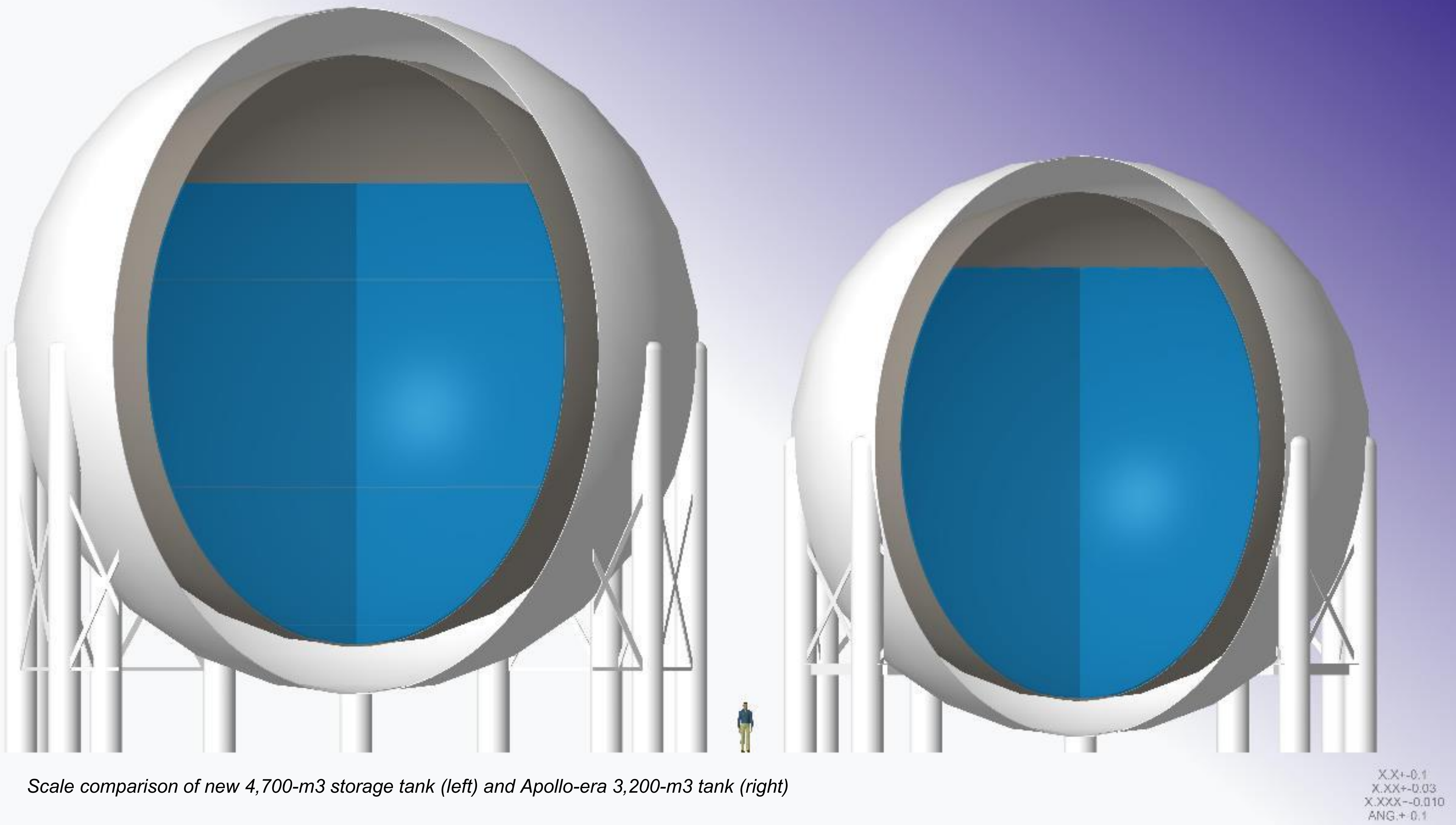
- In 2018, construction began on an additional storage tank at Launch Complex 39B
- This new tank will give an additional storage capacity of 4,732 m^3
- Total on-site storage capacity of roughly 8,000 m^3

NASA Kennedy Space Center's Launch Complex 39

NEW PAD-B LH_2 STORAGE VESSEL

- 1,250,000 gal (4,732 m^3) usable volume - 47% larger than Apollo-era tank
- ~79 ft. (24 m) outer diameter; MAWP = 90 psig (6.2 bar)
- Spec NER = 0.048% (600 gal/day; 2,271 L/day)

ETA SPACE MCDERMOTT CB&I STORAGE SOLUTIONS CryogenicsTestLab KENNEDY SPACE CENTER



Scale comparison of new 4,700-m3 storage tank (left) and Apollo-era 3,200-m3 tank (right)

TANK SPECIFICATIONS

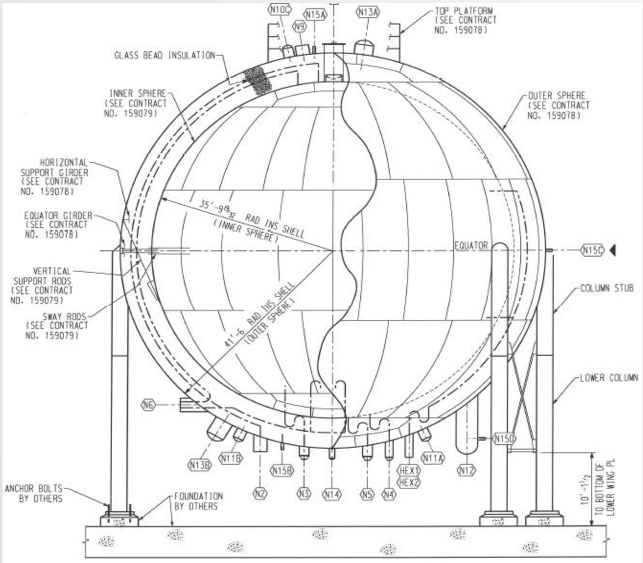
- Detailed design by CB&I Storage Tank Solutions as part of the PMI contract for the launch facility improvements
- ASME BPV Code Section XIII, Div 1 and ASME B31.3 for the connecting piping
- Usable capacity = 4,732 m^3 (1,250,000 gal) w/ min. ullage volume 10%
- Max. boiloff or NER of 0.048% (600 gal/day, 2,271 L/day)
- Min. Design Metal Temperature (MMDT) = 4.3 K (-452 °F)
- Pressure rating = full vacuum to 6.6 barg (95 psig)

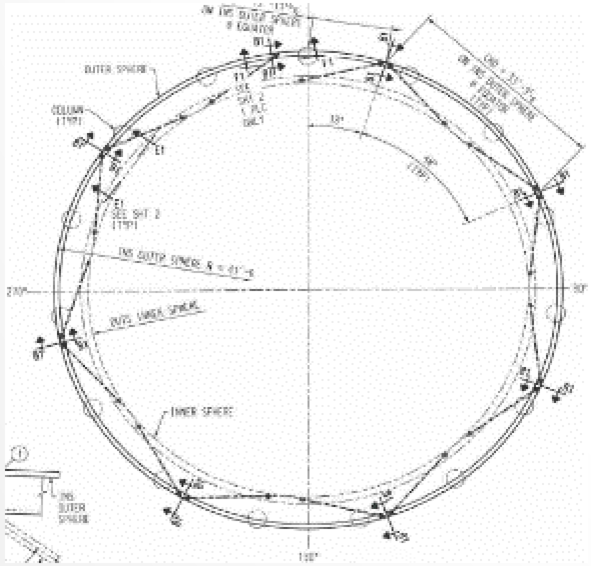
TANK CONFIGURATION

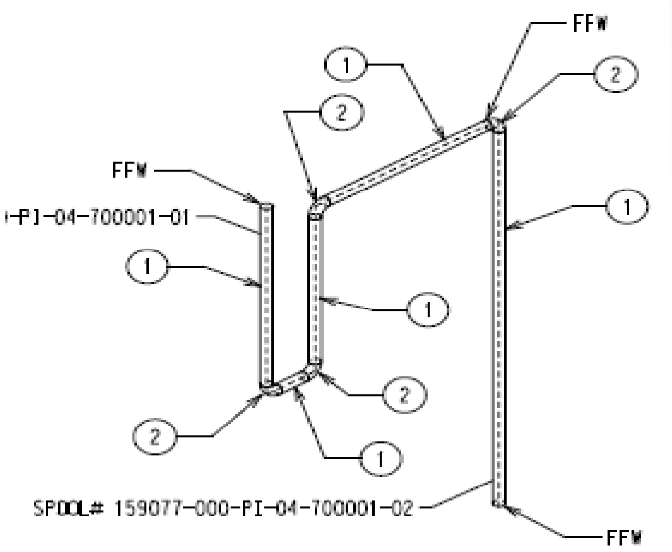
- The 24.0-m outer diameter spherical tank has 12 support legs welded to the equator and stands at an overall height of 28.0 m
- Tank is supplied from a tanker manifold and an ambient air vaporizer for pressurization
- Tank includes a vent stack on top for normal boiloff gas and is connected to a dedicated facility flare stack of 0.3-m diameter
- Other standard piping nozzles include a 300-mm diameter vacuum-jacketed liquid withdrawal line

TANK DESIGN

Total heat load (Q) being transmitted to the inner vessel is determined by the combination of the thermal insulation system (evacuated), the structural supports system, and the piping penetrations







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

NEW TECHNOLOGIES

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

Passive + Active = Full Thermal Control

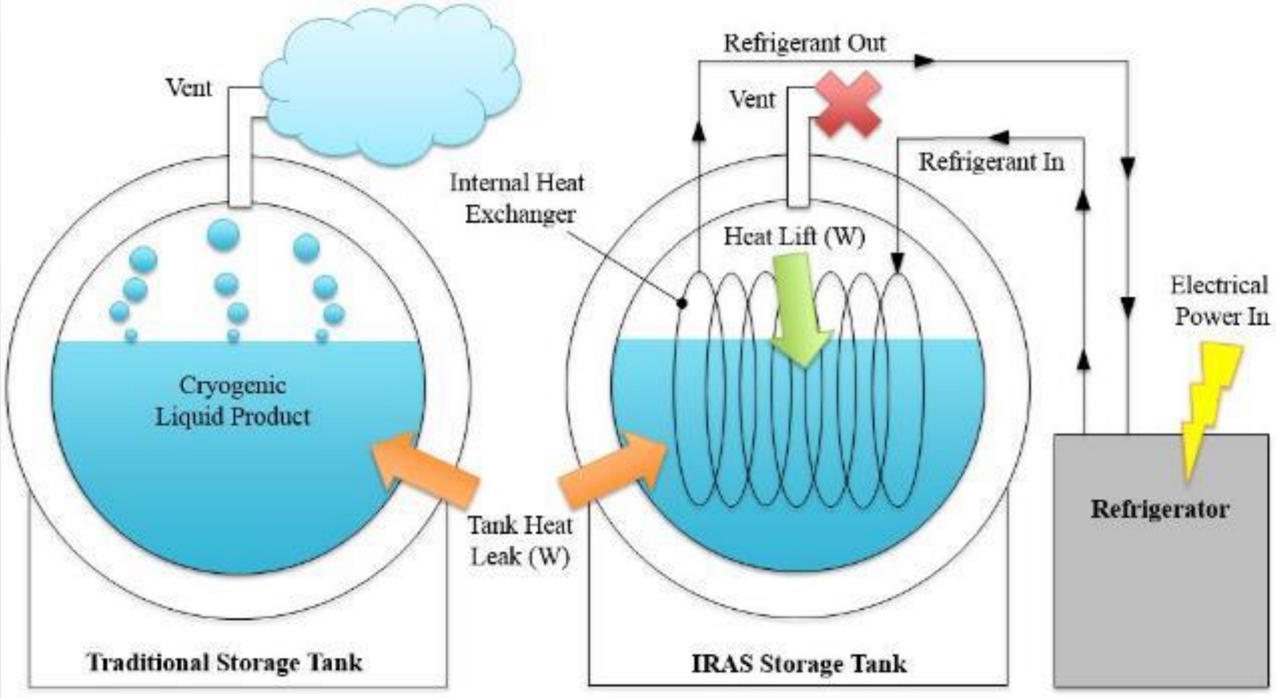
NEW TECHNOLOGIES

- Two new energy-efficient technologies to provide large-scale liquid hydrogen storage and control capability
- Passive thermal control: an evacuated glass bubbles-based insulation system is implemented in lieu of evacuated perlite powder which has been the mainstay in large-scale tanks for the last 80 years
- Active thermal control: internal heat exchanger is implemented for the future addition of an Integrated Refrigeration and Storage (IRAS) system for complete controlled storage capability

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

IRAS HEAT EXCHANGER CONCEPT

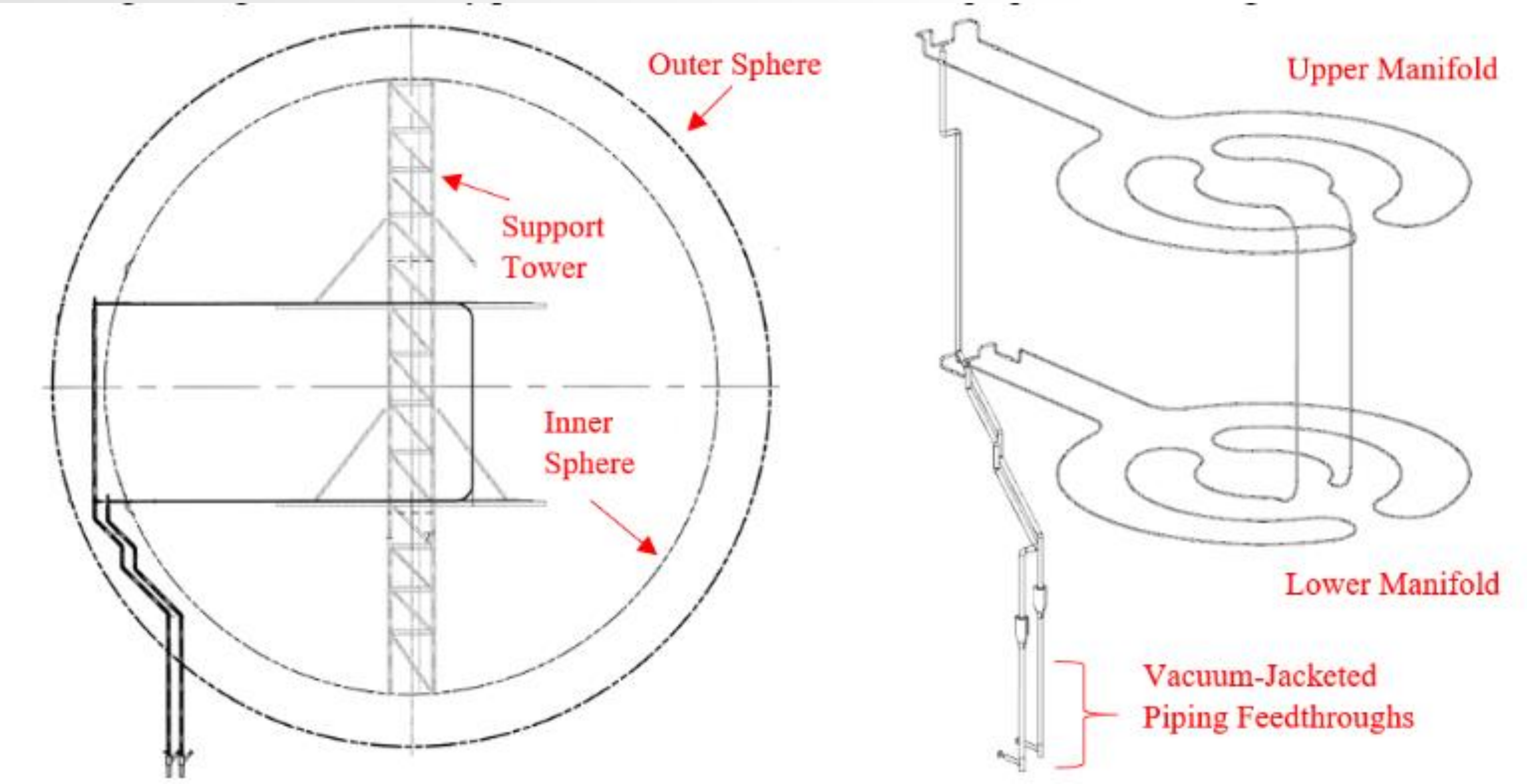
- Traditional storage tank - no control. Heat energy from ambient stores within the liquid, ullage pressure rises, relief valve opens to vent.
- IRAS tank – full control. Pressure and temperature are controlled by taking up the heat through the internal heat exchanger. No venting of boiloff gas.



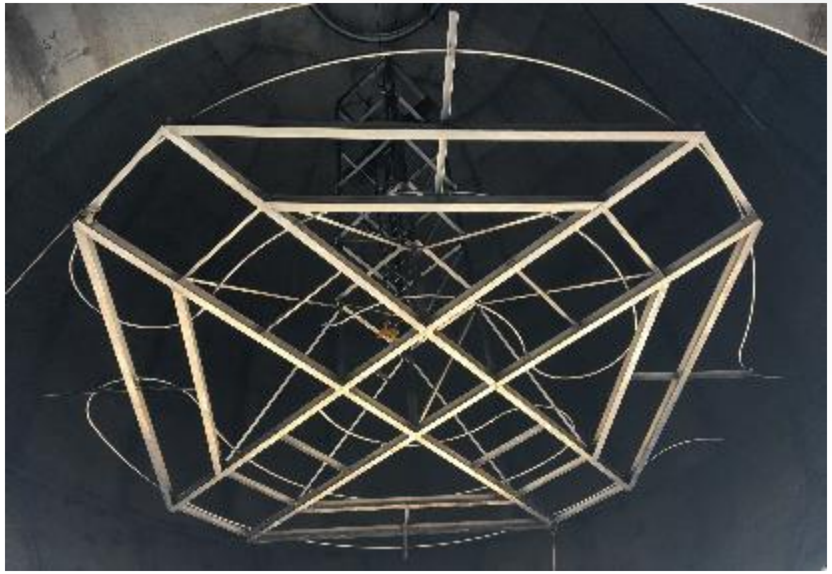
IRAS HEAT EXCHANGER DESIGN

- Upper and lower manifolds positioned at the 25% and 75% fill level elevations and are constructed of fully welded 38-mm (1.5-inch) 316L stainless steel tubing
- Total coil length = 43 m, for a heat exchange area of roughly 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 vacuum annulus (lower portion)
- Bayonet connections and isolation valves are provided for the inlet and outlet flexible VJ lines to connect to the future refrigeration system

IRAS HEAT EXCHANGER DESIGN



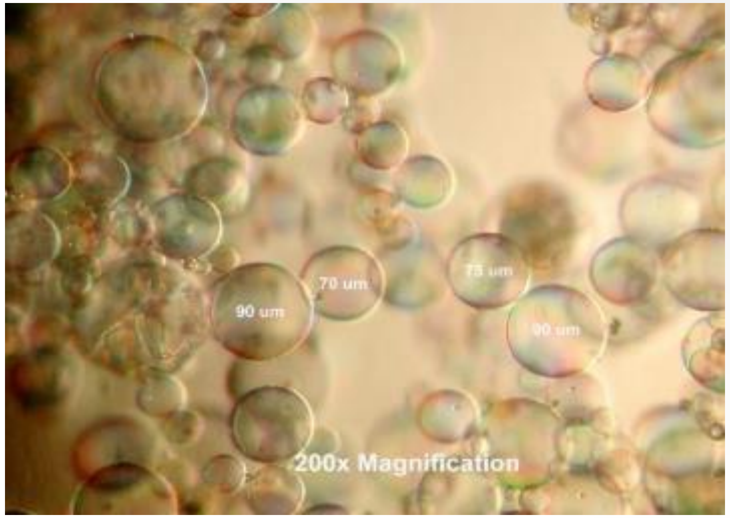
Heat exchanger configuration inside the sphere (left); 3D view of refrigerant feedlines and manifold (right)



Top manifold and support frame being lifted into place

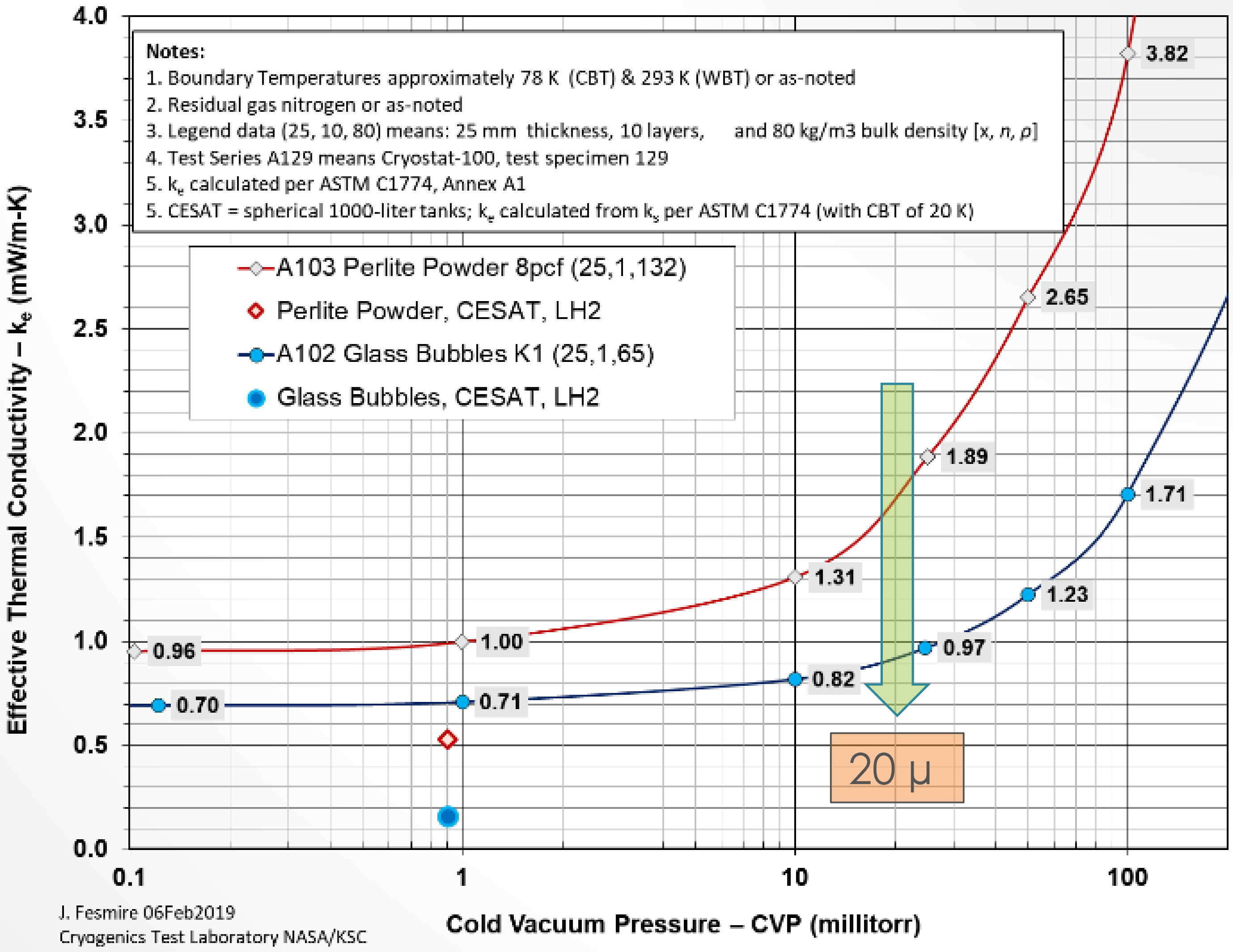
GLASS BUBBLES INSULATION SYSTEM

- Type K1 glass bubbles by 3M - filling the entire annular space
- Nominal 60-micron diameter hollow microspheres of borosilicate glass have a bulk settled density of approximately 65 kg/m^3 (top photo)
- Material tanker offloading/installation for demonstration testing at Stennis Space Center in 2008 (bottom photo)



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 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



ETA SPACE MCDERMOTT CB&I STORAGE SOLUTIONS CryogenicsTestLab KENNEDY SPACE CENTER

TANK CONSTRUCTION

- Began in late 2018
- Planned for completion in late 2021
- 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 late summer 2021 followed by purging and evacuation of the annular space

NASA Kennedy Space Center's Launch Complex 39B

Top Access Port

HX Support Structure being lifted up (looking up inside inner vessel)


A1817

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 LH2 storage tank nearing completion
- Incorporated are new technologies for simplified operations and long-term energy savings
- IRAS to enable any combination of the following capabilities: complete ullage pressure control, zero boiloff, zero-loss transfer, and densification
  - Study is underway for the refrigeration system design, specification, and planning
- Adoption of the glass bubbles insulation system for about 50% less boiloff rate
  - Potential for use the global logistics chain 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)
- Project (DoE/Industry) in work along the line of how to design and construct mega-scale tanks

THANK YOU

for your attention

Questions?

James E. Fesmire

James.e.fesmire@nasa.gov

1.321.747.7657