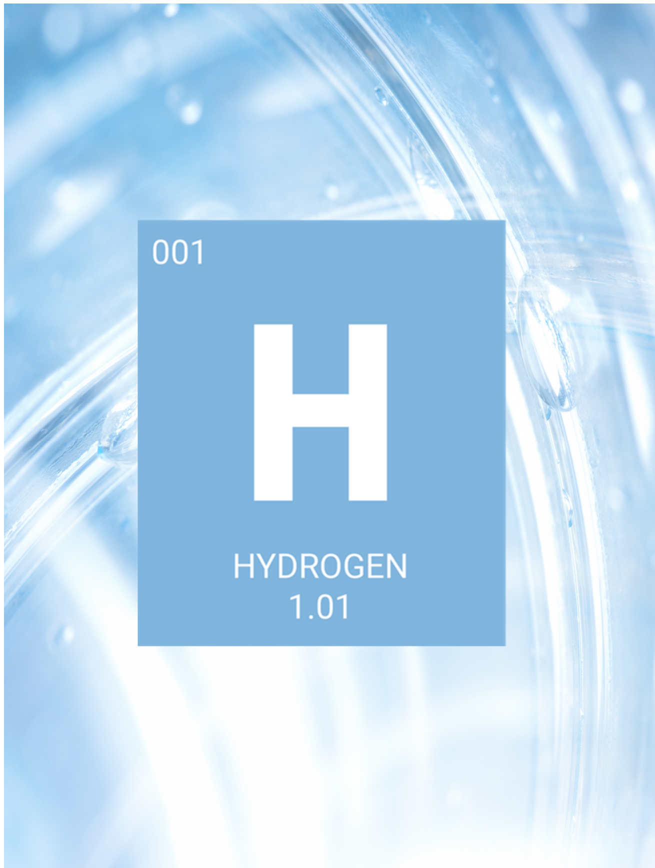


First Demonstration of a Commercial Scale Liquid Hydrogen Storage Tank Design for International Trade Applications

P.I.: Ed Holgate, Shell International Exploration and Production, Inc.
Presenter: David Creech, CB&I Storage Solutions LLC
DE EE0009387
Date: 05/07/2024
DOE Hydrogen Program
2024 Annual Merit Review and Peer Evaluation Meeting
AMR Project ID # ST241

Project Goal

This project proposes to develop a first-of-its-kind affordable very-large-scale liquid hydrogen (LH_2) storage tank for international trade applications, primarily to be installed at import and export terminals. The project aims a large-scale tank design that can be used in the range between 20,000 m^3 and 100,000 m^3 (1,400-7,100 metric tonnes of LH_2). Key success criteria for the large-scale design include:

1. Achieve a targeted LH_2 BOR (boiloff rate) of <0.1%/day

2. Achieve a CAPEX (capital investment) below 150% of LNG (liquefied natural gas) storage cost (< \$175 million target cost for 100000 m^3 LH2 tank)

3. Safety and Integrity reviewed by regulatory bodies

Overview

Timeline and Budget

- Project Start Date: 09/01/2021
- Project End Date: 08/31/2025
- Total Project Budget: $12 M
  - DOE Share: $6 M
  - Cost Share:

  $3 M from Shell, $3 M from CB&I

Barriers

- Ultra low boiling point of H_2 (20 K)
- Need to minimize boiloff product loss
- High CAPEX of LH_2 storage tank
- Technology scale-up

Partners

Project lead:

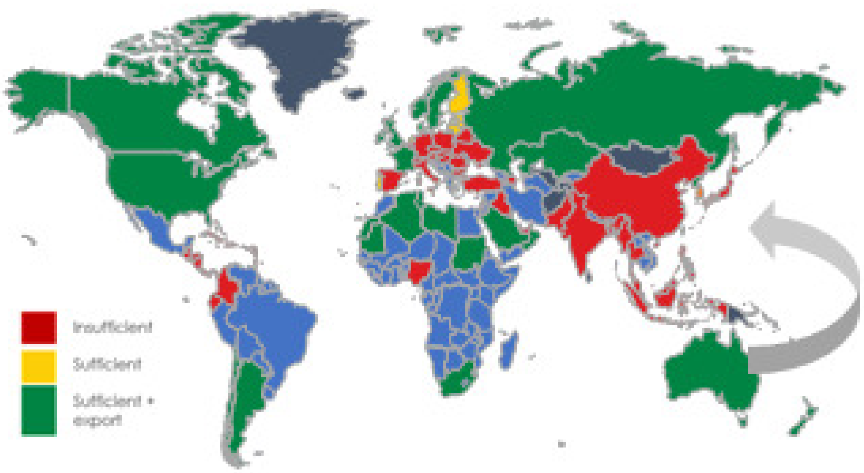
- Ed Holgate (PI, Shell International Exploration and Production, Inc.)

Partner organizations:

- CB&I Storage Solutions LLC (CB&I), MCDERMOTT
- GenH2 Corp. (GenH2)
- NASA Kennedy Space Center (NASA/KSC);
- University of Houston (UH)

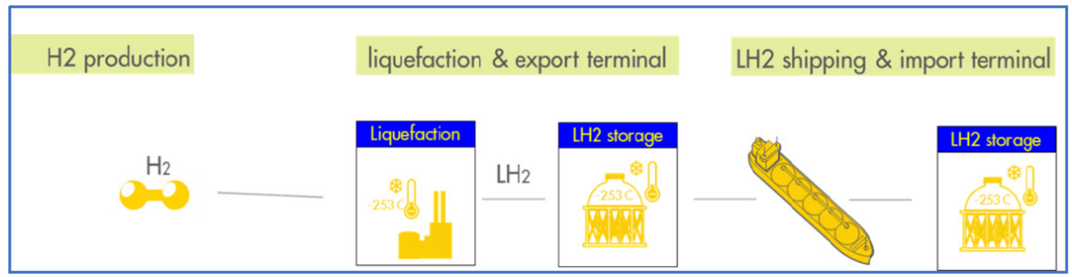
Potential Impact

H_2: Moving Energy Without Carbon



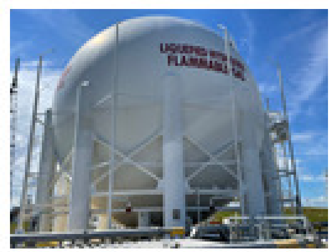
One of the three priorities in US DOE Hydrogen Program – Hydrogen Energy "Earthshots": **Low cost, efficient, safe hydrogen delivery and storage**

LH_2 Supply Chain Development

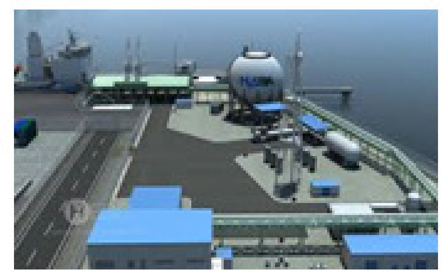


Now

Need

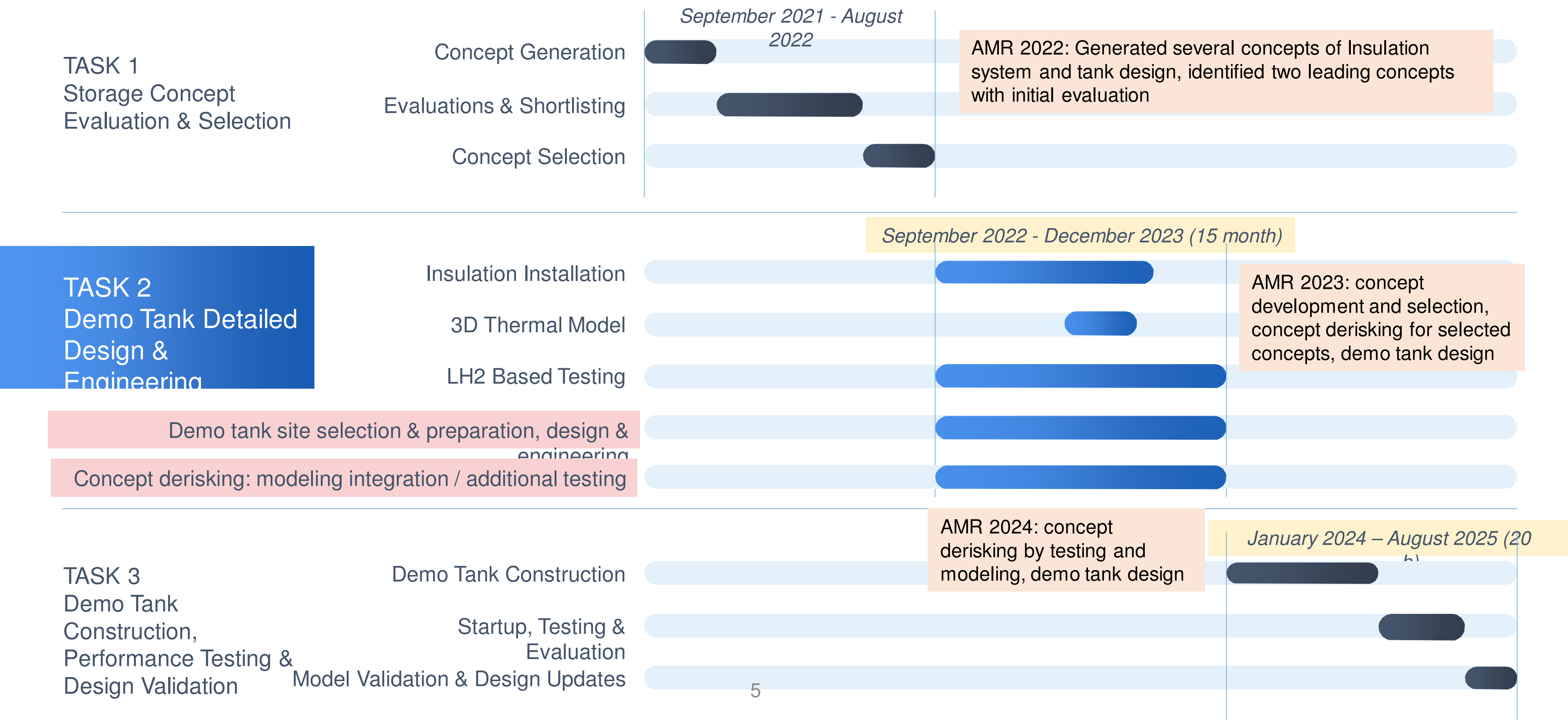


LH_2 storage tank 5,000 m^3



Receiving terminal 100,000 m^3

Updated Project Timeline



Key challenges: insulation system design – vacuum vs. non-vacuum insulation strategy

Vacuum insulation system:

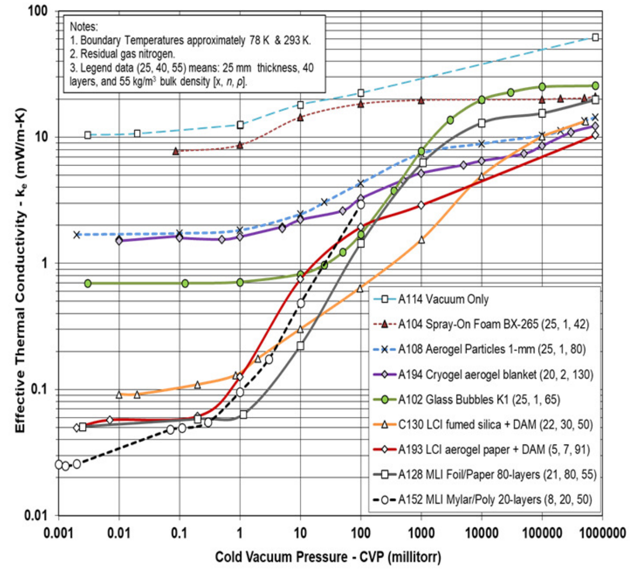
- Dominantly used for LH2 storage
- High to moderate vacuum with bulk-fill insulation material is the commonly deployed insulation strategy today for large-scale LH_2 storage.
- Dramatically reduced thermal conductivity of evacuated insulation material
- High requirement on the tank (materials, shape, vacuum shell, etc.)
- Significantly increased CAPEX of the vacuum insulated tank
- Evacuation process could take a long time
- Risk of vacuum degradation or loss for the evacuated system
- Difficult to detect the vacuum leak of the tank

Non-vacuum insulation system:

- Dominantly used for LNG storage
- Cost advantages vs. vacuum insulation system

Technical challenges:

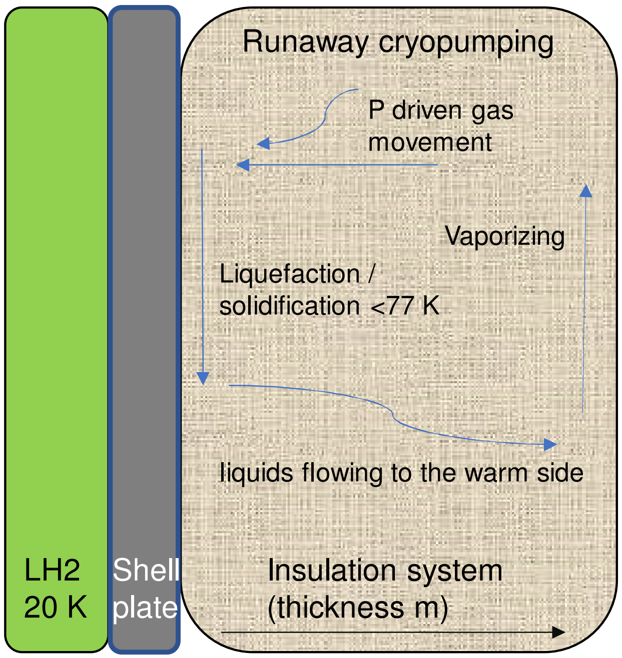
- Cryo-pumping effect
- LNG is stored at 110 K, well above the boiling point of air, air liquefaction will not happen

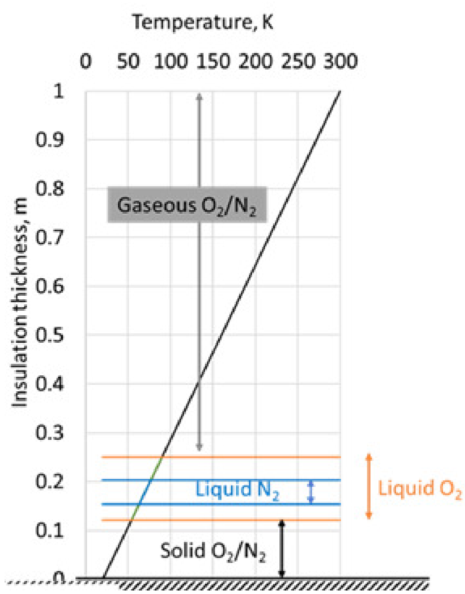


(J. Fesmire et al., cylindrical boiloff calorimeters for testing of thermal insulation systems, IOP Conf. Series: Materials Science and Engineering 101 (2015))

Key challenges: runaway cryopumping

Non-vacuum insulation system:
- Cryo-pumping / runaway cryopumping





Runaway cryopumping with liquid dripping from the bottom of the insulation material

Approach
Safety Planning and Culture

- **Safety plan** submitted to the Hydrogen Safety Panel in 2021;
- Safety feature embedded throughout the concept evaluation, selection and derisking:
  - **Technology safety review (HAZID analysis):** identified and assess potential HSE risks associated with storage tank concept design (safety risk / technical uncertainty / technical risk), compared risk differences for concept selection, and established requirements for further study and assessment in subsequent activities
  - **Codes & standards:** reviewed existing codes and standards related to large scale LH_2 storage and identified numerous gaps among the design and siting requirements
  - Concept derisking in Y2 for technical uncertainty
- Followed existing HSSE framework / review process for experiments / testing at NASA KSC / GenH2 / CB&I
- **Established HSSE workstream** to provide HSSE assurance for upcoming LH_2 related operations, particularly for LH_2 based CS900-2 system and demo tank at NASA Marshall, such as HAZOP performed on demo tank

Safety risk

Features specific to the concept that cause an elevated risk to safety during operation.

No concept-specific safety risks have been identified differentiates between the two leading concepts

Technical uncertainty

Aspects of the concept design that will be resolved withing the DOE project timeline.

E.g. uncertainty in material properties which will be reduced by experimental measurements

Technical risk

Aspects of the concept design that cannot be fully resolved withing the DOE project timeline, and therefore represent a residual risk in a first full scale project. Examples include long term phenomena and scale-up of the final product, such as foam robustness under thermal cycles.

Approach

Derisking strategy on selected concept of LH_2 storage tank

Concept selected at end of Year 1:
Identified the most promising tank configuration reaching the targeted BOR of <0.1%/day while achieving a CAPEX of < $175 million target cost for 100,000 m^3 LH_2 storage tank.

Risks identified	Risk	Uncertainty	Testing program through year 2
Cryopumping	High	High	Permeability testing Integrated thermal and mass transfer modelling
Mechanical performance	High	High	Mechanical testing FEA modeling
Convection	Medium	High	Permeability testing Convection modeling using CFD
Thermal performance	Medium	Low	LH2-based testing 3D thermal modeling

GNG decision point: The decision will be based on the results of two criteria. First, the insulation application testing performed in task 2.2 must show the chosen insulation system can be applied successfully at scale. Secondly, the results of the updated thermo- mechanical model must achieve the target BOR of less than 0.1% per day in the full-scale model.

Accomplishments and Progress

Task 2.2 Insulation application testing

Progress updates:

- Insulation materials being used on the project are similar to materials that CB&I uses on other storage products
- Commercial installation equipment is available
- CB&I concluded that this equipment can be used with little or no modification with the materials being developed on this project

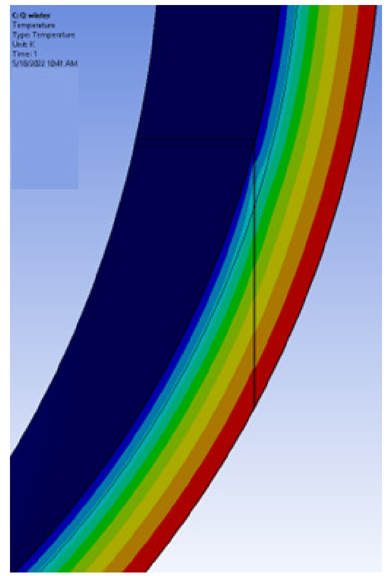
Completed Milestone 2.2.1: The necessary field equipment for insulation system installation will be specified and the required work procedures will be written.

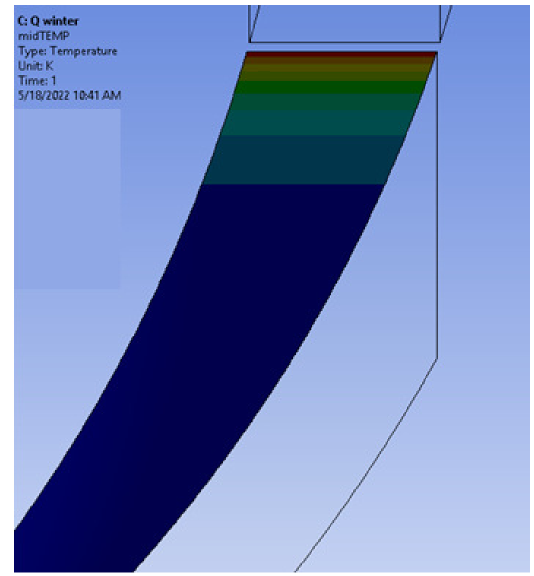
Insulation installation at industrial scale applied by CB&I

Accomplishments and Progress

Task 2.3 3D thermo-mechanical tank model

- Target = 0.1% boiloff -> Heat gain 37000 W
- Information provided by analysis
  - Temperature distribution
  - Heat flux distribution
  - Heat gain
- Criteria
  - 1a Total heat gain target is met
  - 1b Heat gain effects of penetrations are quantified and considered
  - 2 Temperature on intermediate sphere is >80K
- Approach:
  - Steady state analysis
  - Summer and winter conditions explored
  - Sensitivity analysis
- We have been using this model to:
  - Confirm hand calculations,
  - Explore global geometric changes like thicknesses, position, orientations, etc.
  - Compare various temperature dependent material models,
  - Identify mesh sensitivity,
  - Study the effect of boundary conditions (e.g. fixed temperature v. convection)
  - Isolate heat gain through penetrations (i.e. skirt)
  - Explain results – morphing studies





Completed Milestone 2.3.1: Establish the 3D thermo-mechanical tank model to predict the temperature profiles and expected BOR

Accomplishments and Progress

Task 2.4 Cryostat LH_2-based thermal performance system development

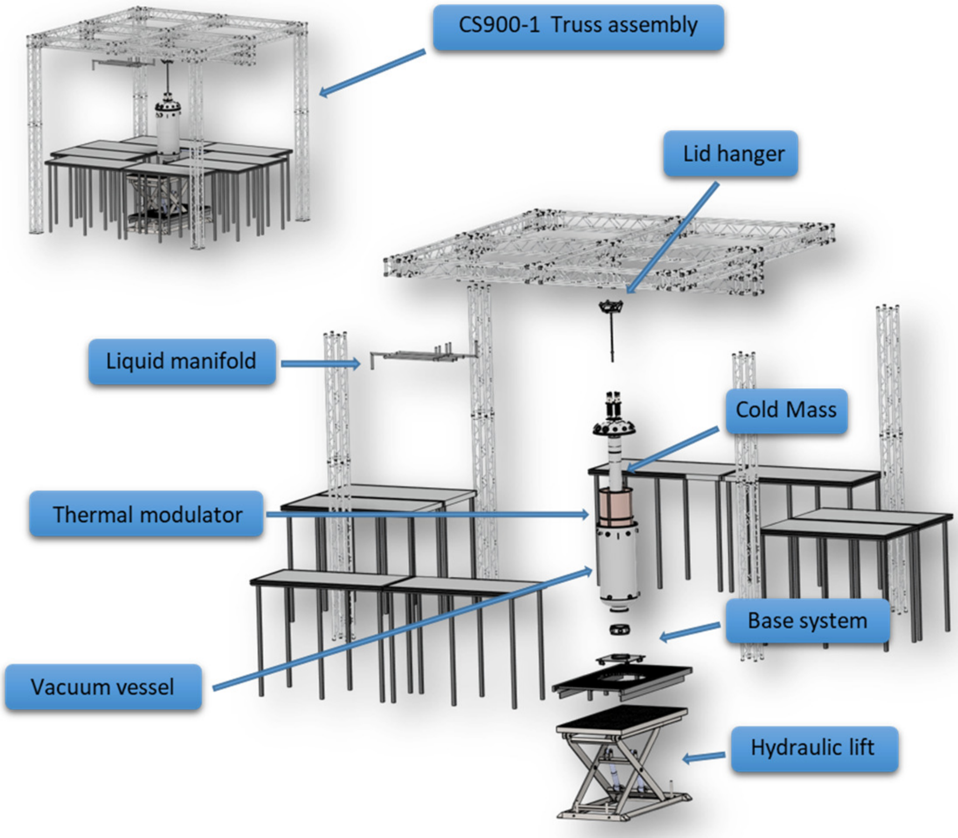
Phase I CS900-1 simulation test platform

Equipment design capable for thermal performance testing of materials and systems from 4K to 400 K

Provides verification of analytical models and confirmation of standard reference data

Progress updates:

Finished Phase I LN_2-based validation: Assembly and system build-out completed, LN_2 transfer, and cooldown test completed, and CS900-1 validation experiments finished.



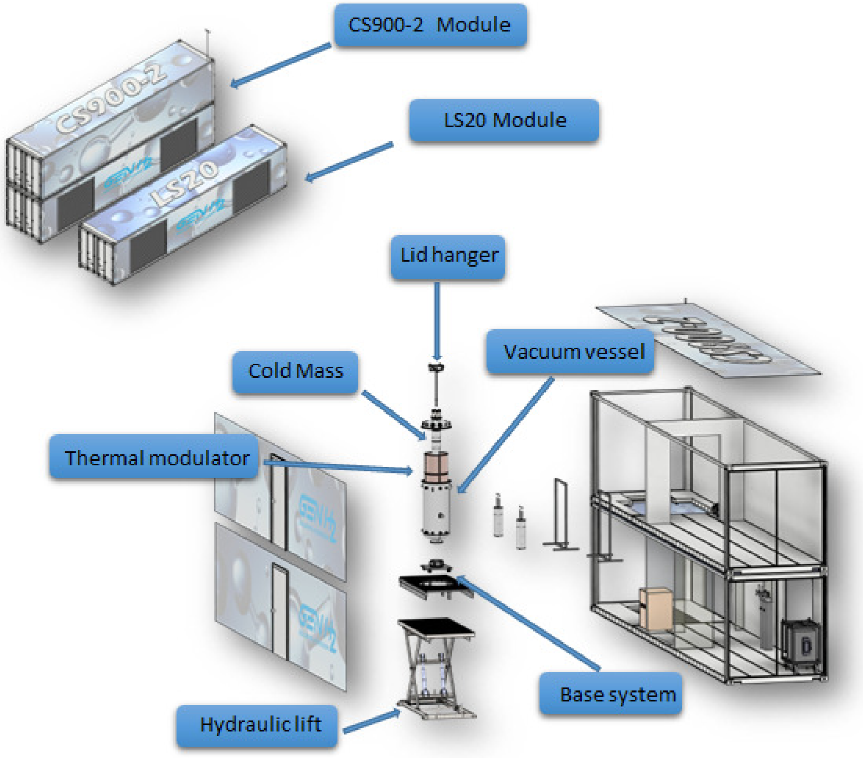
Accomplishments and Progress

Task 2.4 Cryostat LH_2-based thermal performance system development

Phase II CS900-2 LH_2-based validation:
Modular LS20-R2 system: Hydrogen liquefaction and storage unit, capable of producing 10kg of LH_2 per day, as well as controlled storage (zero boiloff) of 400L LH_2
CS900-2 simulation test platform: LH_2 boiloff test instrument with a vacuum chamber and interchangeable cold mass assemblies based on the commissioned CS900-1 LN_2 system

Progress updates:

- Completed custom designs and engineering of all supporting subsystems
- Completed all the modules and structural support fabrication and assembly
- Build-out of LS20-R2 and CS900-2 assembled and integrated into the system, to be commissioned
- LH2 testing expected in June



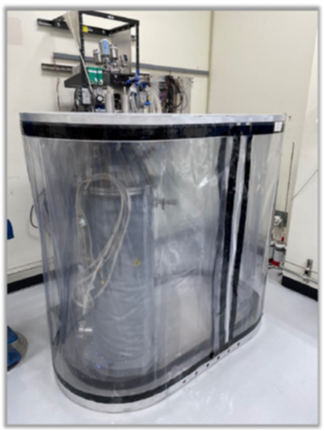
Milestone 2.4.1: Produce effective thermal conductivity and heat flux data with cold wall temperature down to 20 K using newly designed and built LH_2-based cryostat CS-900 (expect to complete by Q2 2024)

Accomplishments and Progress

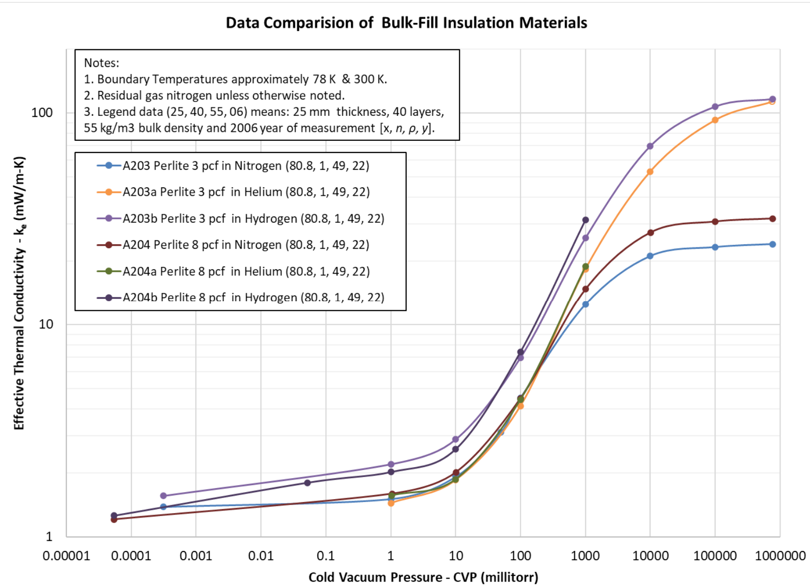
Kennedy Space Center

Task 2.5 Effective thermal conductivity measurement and modeling

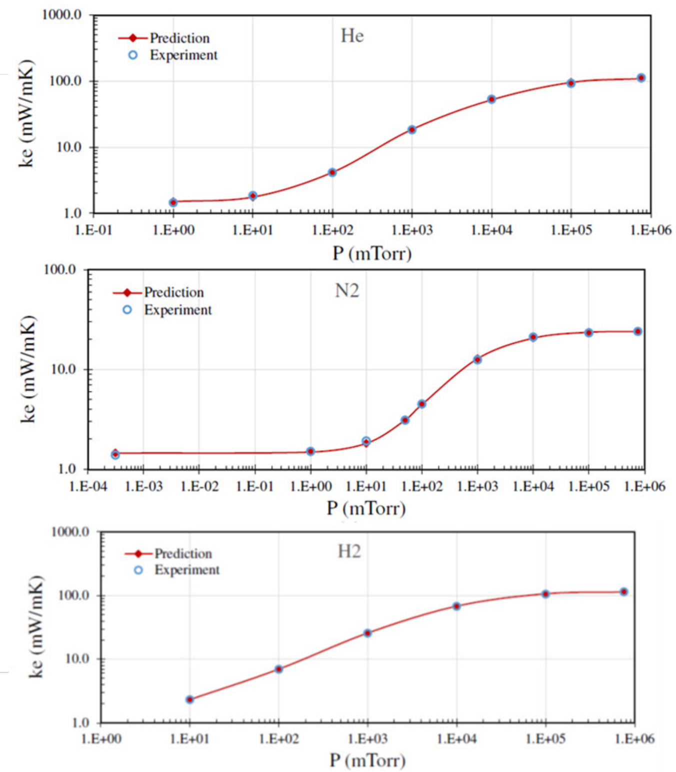
To-date, 3M K1 Glass Bubbles, low/high density-perlite have been fully characterized in nitrogen, helium, and hydrogen using the Cryostat-100 (C-100) LN_2 calorimeter.



Enclosed system of CS100 for the use of H_2 gas in the insulation space



Effective thermal conductivity of low/high density-perlite characterized in nitrogen, helium, and hydrogen background gas



Updated insulation system thermal model

Completed Milestone 2.1: The insulation system thermal model has been validated against experiments (with 77K cold wall temperature) with H_2 and He in the insulation space.

Conclusions for GNG decision point

Insulation application testing:

- Verified the installability of insulation materials from different vendors using established protocols by CB&I
- Established automatic installation equipment and protocols onto the storage tank for industrial application by CB&I
- Established installation protocol at industrial scale by CB&I

Thermo-mechanical modeling:

- A 3d finite element model has been built that captures the temperature distribution and stress state in the inner and outer sphere using the current insulation concept
- This model allows us to predict the temperature profiles in the insulation system and quantify the boil-off rate
- Modeling results demonstrated the technical feasibility of the selected tank concept
- It is ready to accept updated mechanical and material properties as well as respond to changes of dimension and added geometric complexity as the design is finalized

Passed GNG decision point: The decision will be based on the results of two criteria. First, the insulation application testing performed in task 2.2 must show the chosen insulation system can be applied successfully at scale. Secondly, the results of the updated thermo- mechanical model must achieve the target BOR of <0.1% per day in the full-scale model.

Accomplishments and Progress

Kennedy Space Center

Task 2.6 Concept derisking: Cryopumping Testing

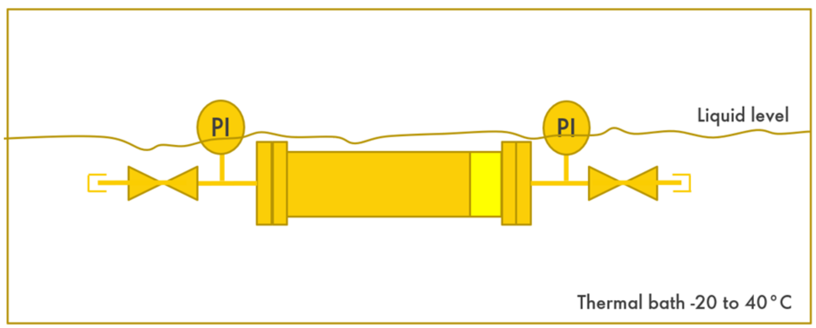
- Using cryocooler at NASA KSC to expose various insulation materials to –423F temperatures in atmospheric pressure gas
- Demonstrated presence of runaway cryopumping with unsuitable insulation materials, visible liquids dripping off bottom
- Demonstrated resistance of other insulation materials to runaway cryopumping
- Quantified mass of adsorbed gas and approximate effective conductivity of insulation systems

Runaway cryopumping with liquid dripping from the bottom of the insulation material

Accomplishments and Progress

Task 2.6 Concept derisking: Permeability measurement and cryopumping modeling

- Permeability through insulation materials measured and modelled to understand the cryopumping effect
- Permeability testing by pressure measurement of gas across the insulation material samples
- Testing from -20 °C to 75 °C for multiple samples
- Fit used to extrapolate to cryogenic temperatures
- Data used in cryopumping models to find the maximum allowable permeability of insulation materials



Conclusion:
Identified materials that prevent runaway cryopumping

Accomplishments and Progress

Marshall Space Flight Center

Task 2.6 Concept derisking: mechanical properties testing

NASA Marshall (MSFC) Hydrogen Test Facility Mechanical Testing

- Mechanical testing at MSFC was conducted with the specimen submerged in a cryostat filled with liquid hydrogen on a servo-hydraulic load frame
- A five-minute soak at test temperature was performed prior to testing
- Results included thermal expansion and mechanical properties
- The resulting material properties are used in finite element analysis by CB&I to evaluate the mechanical performance of the insulation materials

Completed Milestone 2.6.1 Obtain the properties data of insulation materials from external testing at 20 K

HTF Test Cell at MSFC

Accomplishments and Progress

Marshall Space
Flight Center

Task 2.7 Demo tank detailed design and engineering

Location at NASA Marshall Space Flight Center

Benefits:

- To MSFC: integrated into MSFC's existing LH2 testing facility and supplement their existing onsite storage;
- To Project: leveraged MSFC's rich experiences on LH2 handling and operation, reinforced the collaboration;
- To DOE: established connections with MSFC and LH2 testing facilities

Progress:

- NASA completed IAA with DOE in October 2023 for additional funds to develop the site location
- Space Act Agreement between NASA and CB&I established
- Base line project schedule extended 6-8 months; Overall budget will not change
- Coarse HAZOP completed on Nov 14/15 at MSFC
- Cleared all vegetation from site in September 2023
- Completed site survey in October 2023
- Geotechnical report completed in January 2024
- Site is expected to be available for construction in April 2024

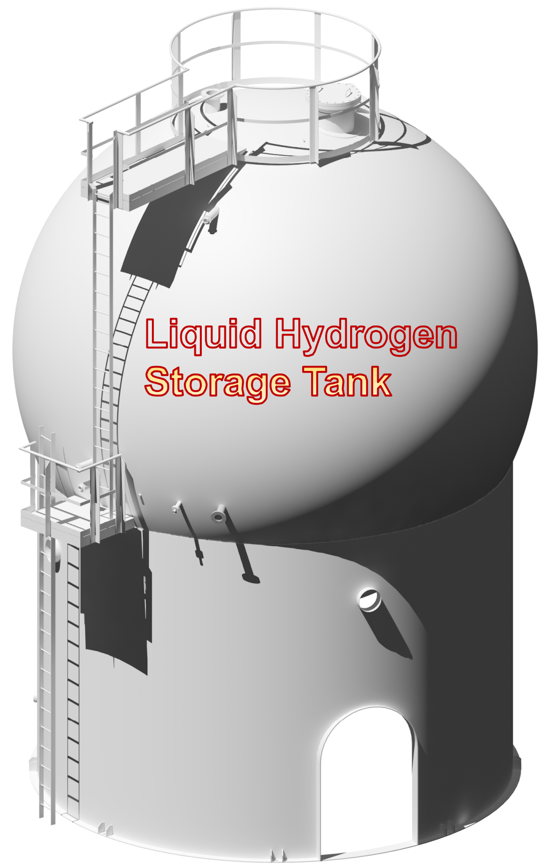
View Looking West from HTF Building in August 2023

Ongoing site preparation in November 2023

Accomplishments and Progress

Task 2.7 Demo tank detailed design and engineering

- CB&I completed the mechanical design of the demo tank
- P&ID finalized in August 2023.
- Completed Fabrication / Construction Execution Plan
- Established instrumentation plan
- CB&I Standard Testing Program for demo tank quality control
- CB&I is currently reviewing quotes from suppliers for manual valves and pressure relief valves
- CB&I updated cost estimation for demo tank
- CB&I began procurement of plate and long-lead time items
- CB&I plans to begin fabrication in Q1 2024 and construction to follow in Q2 2024



Milestones Summary

Milestone #	Project Milestones	Task Completion Date (Project Quarter)		Progress summary
		Original Planned	% Complete	
M1 / M2.5.1	The insulation system thermal model has been validated against experiments (with 77K cold wall temperature) with H_2 and H_e in the insulation space.	Q1 Y2	100%	Updated the previously developed effective thermal conductivity (Ke) model using the new measured data from LN2-based experiments, see Task 2.5 for more details
M2 / M2.2.1	The necessary field equipment for insulation system installation will be specified and the required work procedures will be written.	Q2 Y2	100%	Standard industrial insulation installation equipment and application procedures Established installation procedures for materials
M3 / M2.3.1	Establish the 3D thermo-mechanical tank model to predict the temperature profiles and expected BOR	Q2 Y2	100%	The 3D thermal model was established and will be updated after demo tank testing
M4 / M2.4.1	Obtain thermal conductivity data with cold wall temperature down to 20 K using new-built LH_2-based cryostat CS-900	Q3 Y2	95%	Completed LN2 validation Completed the integration of the H2 equipment enclosure and CS900-2 system
M2.6.1	Obtain the properties data of insulation materials from external testing at 20 K	Q4 Y2	100%	Received the mechanical properties testing results from NASA Marshall and WSU
M5 / M2.6.1 / G2	The decision will be based on the results of two criteria. First, the insulation application testing performed in task 2.2 must show the chosen insulation system can be applied successfully at scale. Secondly, the results of the updated thermo- mechanical model must achieve the target BOR of 0.01-0.1% per day in the full-scale model.	Q5 Y2	100%	Tank design based on the target BOR The constructability of the Insulation system performed and verified.

Responses to Previous Year Reviewers' Comments

- No comments from reviewers from 2023 AMR meeting

Collaboration and Coordination

	Partner	Scope of the work
Tasks in Y1	Shell (lead)	Project lead, project management & reporting, concept development (generation, integration, and selection), risk analysis, technology safety review
	NASA	LN_2 based experiments
	GenH2	LH_2 testing center and LH_2 based cryostat development
	CB&I	Mechanical and structural analysis, 3D tank thermal model, cost analysis, codes & standards
	UH	Insulation property modeling
Tasks in Y2	Shell (lead)	Project lead, project management & reporting, concept derisking
	NASA	Experimental support
	GenH2	LH_2 based experiments
	CB&I	Insulation installation testing, demo tank design
	UH	Thermal modeling support
Tasks in Y3	Shell (lead)	Project lead, project management & reporting
	NASA	Experimental support
	GenH2	LH_2 based experiments
	CB&I, MSFC	Demo tank construction & testing
	UH	Thermal modeling support

Remaining Challenges and Barriers

- Challenges: for the demonstration tank, the schedule is likely to be impacted by the uncertainty in site preparation to meet the safety requirement, materials supply chain with long lead time, extended testing period, etc.
- Mitigation: early planning and early ordering

Proposed Future Work in FY2024

- **LH_2-based thermal conductivity measurement:**
  - To establish all the protocols and commission the LH2 based CS-900 system; to measure thermal conductivity data of selected insulation material with cold wall temperature down to 20 K
- **Demo tank: Procurement / construction / commissioning / testing**
  - To complete the site preparation of MSFC and start foundation construction in April 2024
  - To complete material / equipment procurement in Q2 2024
  - To start the tank fabrication and construction in Q2 2024 and finish the construction in Q3 2024
  - To carry out the tank commissioning & start-up in Q4 2024
  - To kick off performance testing in Q4 2024

Summary

- **Relevance:** to develop a first-of-its-kind affordable large-scale LH_2 storage tank design (20,000 -100,000 m^3) for international trade applications, primarily to be installed at import and export terminals
- **Approach:** concept derisking via testing and modeling; demonstration tank activities
- **Technical accomplishments:**
  - Concept derisking: insulation material mechanical performances evaluated using FEA based on the results of mechanical properties measurement from MSFC;
  - Concept derisking: established integrated thermal and mass transfer model to evaluate the cryopumping effects at operating conditions (key inputs obtained from material properties measurements by NASA KSC and Shell)
  - LH2 based effective thermal conductivity measurement: completed the LN2-based CS900-1 system assembly and commissioning and performed the testing for validation; finished the LH2-based CS900-2 system components with infrastructure support and expected to start the testing in Q2 2024
  - Concept derisking: Establish the 3D thermo-mechanical tank model to predict the temperature profiles and expected boil-off rate
  - Identified MSFC as demo tank location with the support from DOE for site preparation via IAA (between DOE and NASA MSFC), established the SAA between CB&I and NASA MSFC for demo tank construction, and established a five-phase integrated schedule for the upcoming demo tank activities including site preparation, tank construction, commissioning, project testing period, and normal operation by NASA Marshall after the project.
  - Completed demo tank detailed design and engineering including the mechanical design, P&ID, instrumentation plan, fabrication execution plan, construction execution plan, updated cost estimation, etc.
  - Established the methods and protocols for insulation system installation at large scale
- **Future work:**
  - Effective conductivity measurement using newly-built LH_2-based cryostat CS-900
  - Demo tank activities: site preparation, construction, commissioning and performance testing