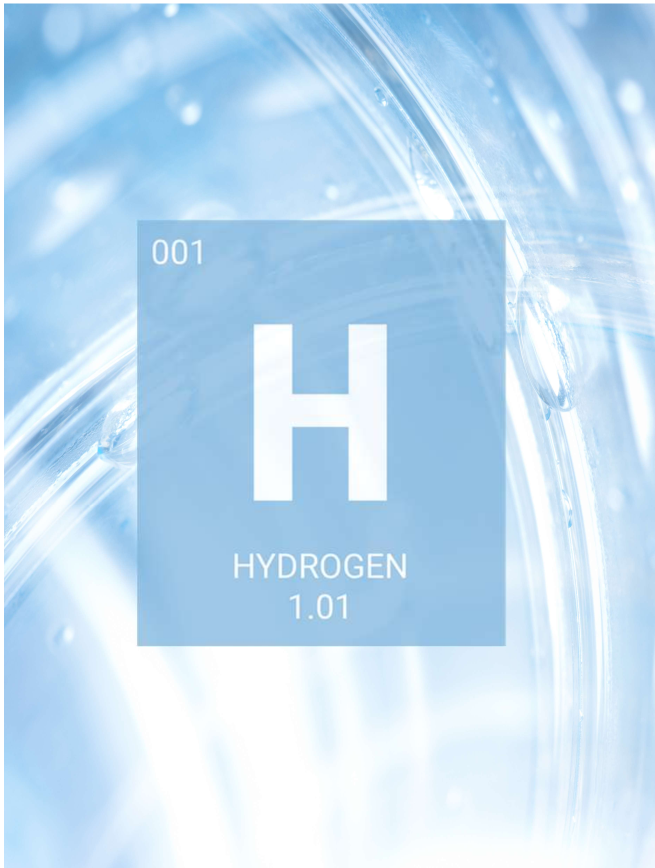

First Demonstration of a Commercial Scale Liquid H2 Storage Tank Design for International Trade Applications

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DE-EE0009387
Date: 04/25/2022
DOE Hydrogen Program
2022 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: 08/31/2024
- Total Project Budget: $12 M
  - DOE Share: $6 M
  - Cost Share:

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

Partners

Project lead:

- 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)

Relevance

- One of the three priorities in US DOE Hydrogen Program – Hydrogen Energy “Earthshots”:

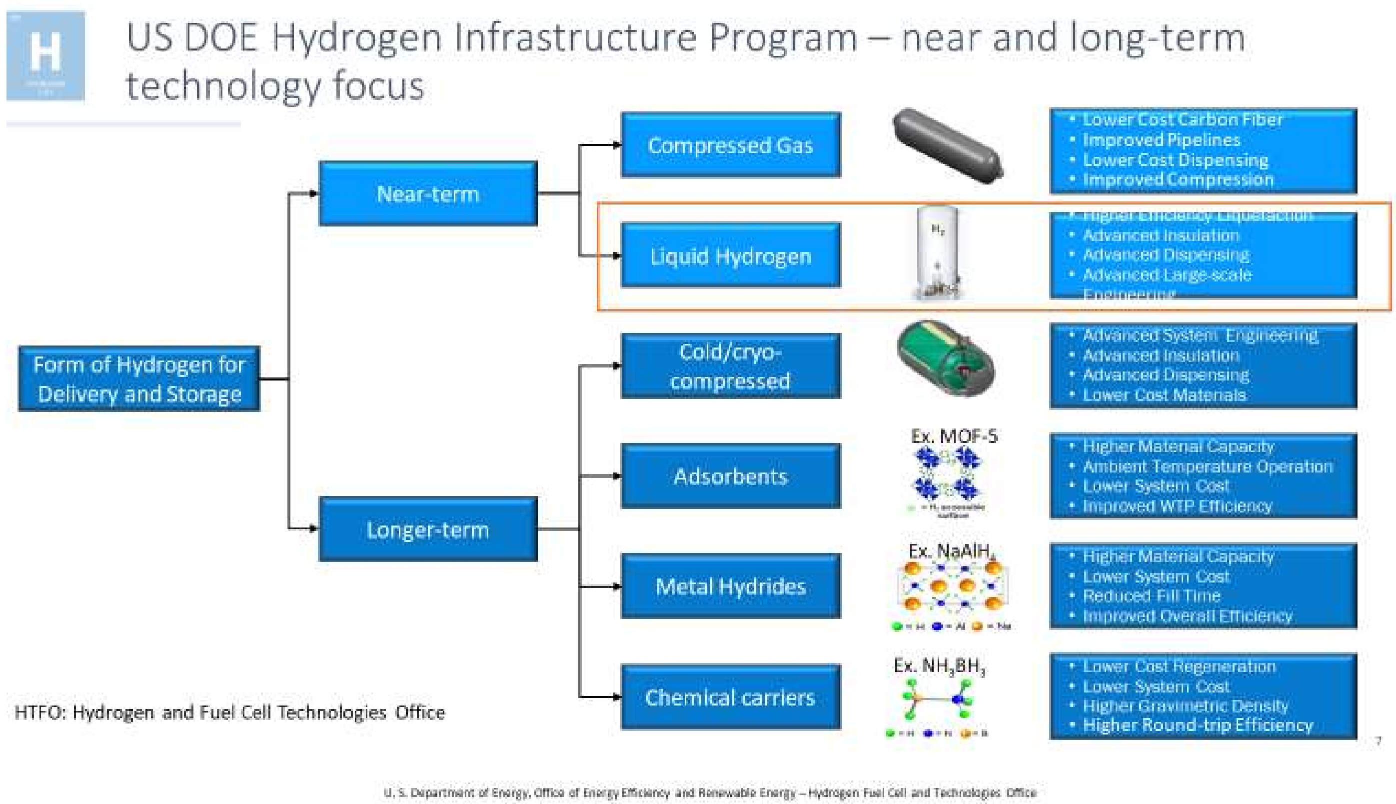
1. Low cost, clean hydrogen production: $2/kg by 2025, and *<u>$1/kg by 2030</u>*

2. **Low cost, efficient, safe hydrogen delivery and storage**

3. End use applications to achieve scale and sustainability, enable emissions reduction and address environmental justice priorities

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

- Liquid hydrogen storage: near-term technology focus



Potential Impact

Hydrogen Supply Chain Development

Now

LH_2 storage tank 5,000 m^3

Need

Receiving terminal 100,000 m^3

Moving Energy Without Carbon

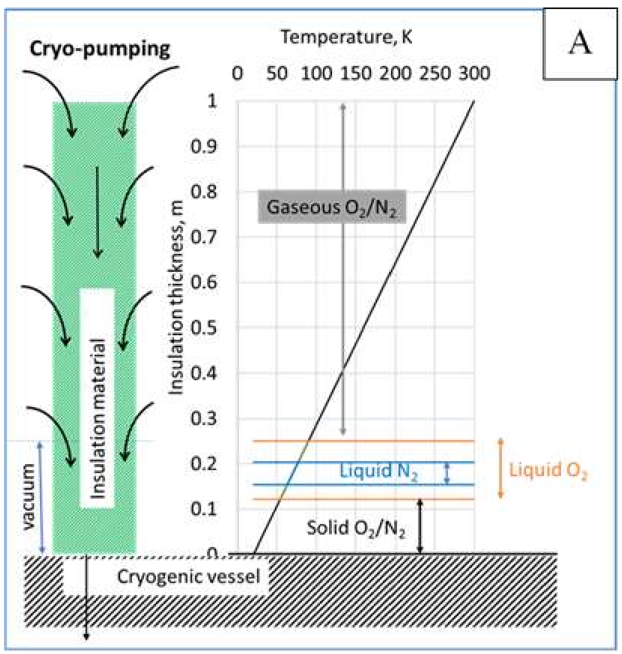
Key challenge:

- Ultra-low boiling point of H_2 (20 K)
- Need to minimize boil-off product loss
- Hydrogen cost at delivery point
- Technology scale-up

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

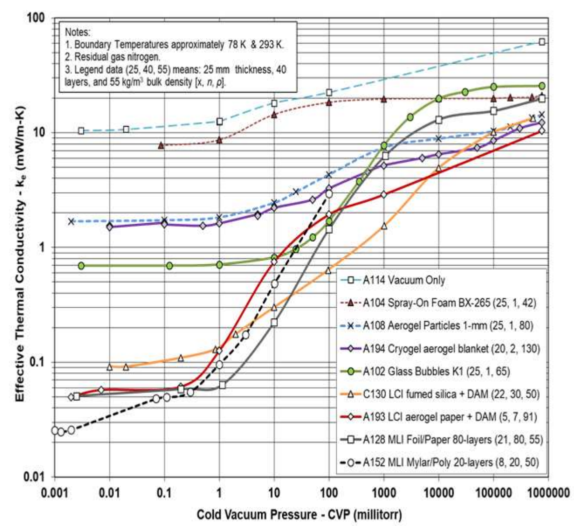
Non-vacuum insulation system:

- Cryo-pumping effect
- LNG is stored at 110 K, well above the boiling point of air, air liquefaction will not happen
- Use of He or H_2 with high Ke



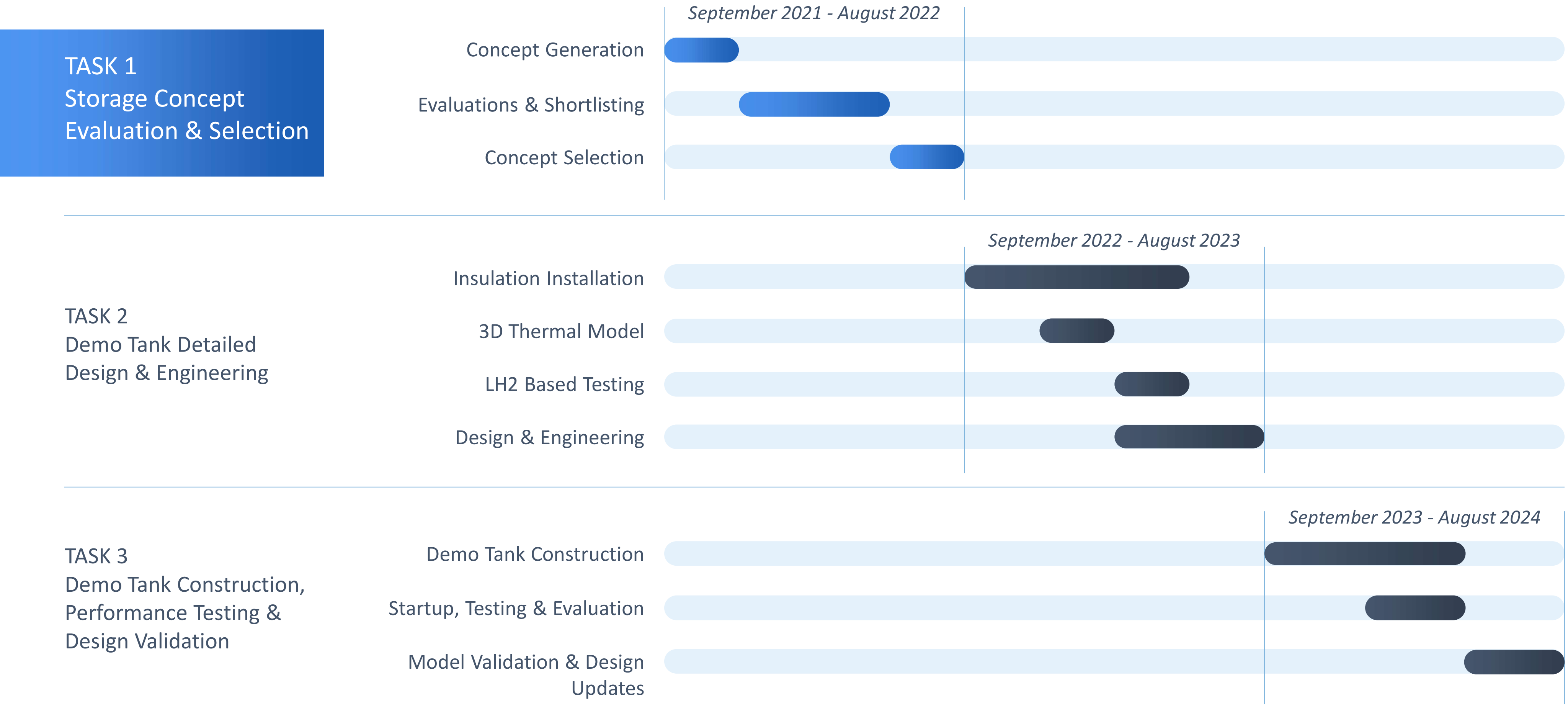
Vacuum insulation system:

- 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

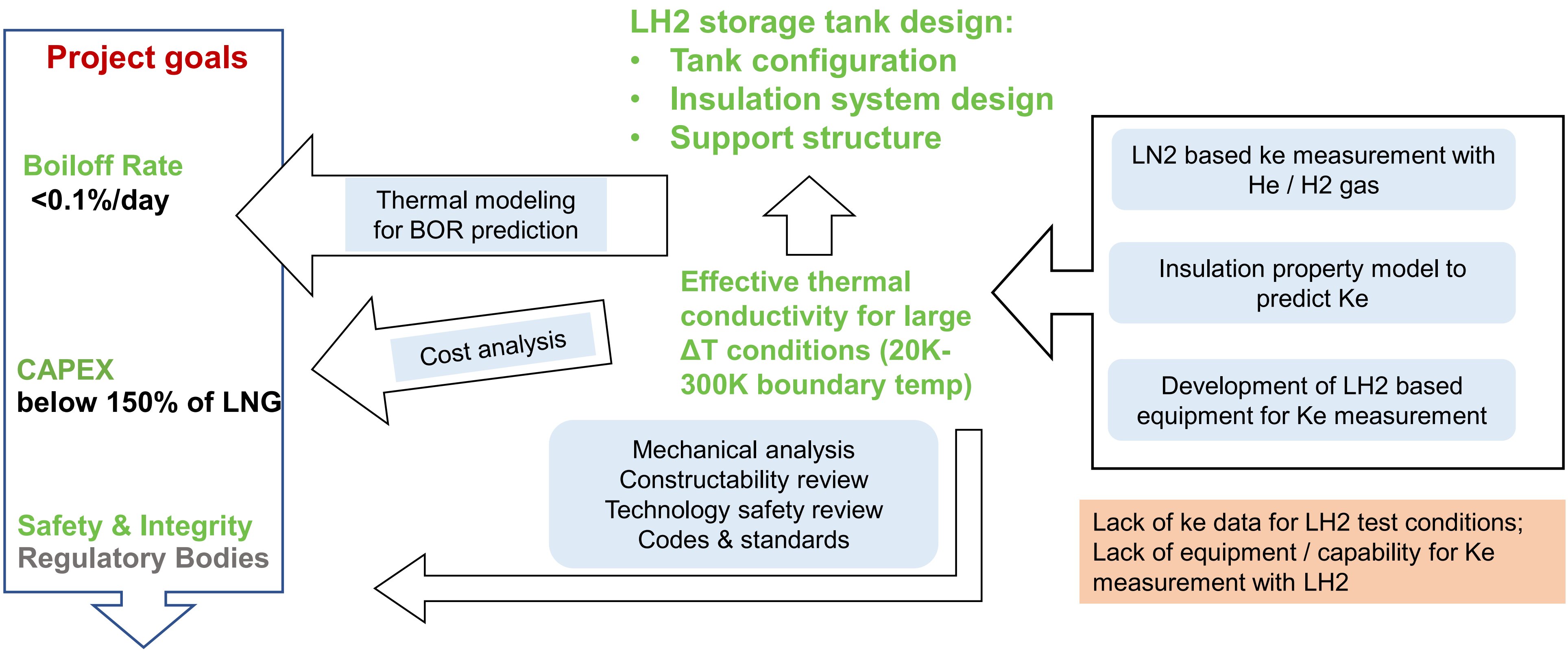


(J. Fesmire et al., cylindrical boiloff calorimeters for testing of thermal insulation systems, IOP Conf. Series: Materials Science and Engineering 101 (2015))

Project Timeline



Approach
Concept Evaluation and Selection



Concept selection:
Go/No-Go DP: To identify 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 m3 LH2 storage tank.

Accomplishments and Progress

Task 1.1 Concept generation

- Tank variations:

Tank configuration	Inner tank support	Insulation system design	
Spherical tank Flat bottom tank Cylindrical tank	Suspension design Load bearing insulation etc.	• Vacuum (Vac) • Non-vacuum (NV) • Vac+NV.	• Bulk-fill material • Rigid Insulation • Blankets

- Concept generation:

Tank volume: 100,000 m^3, BOR targeted at 0.1%, Thermal conductivity from literature (LN2 based experiments);

→ Established preliminary thermal model

Milestone 1: Generated several concepts of Insulation system and tank design

→ Preliminary evaluation criteria for concept shortlisting
- Safety in design
- Constructability
- High-level cost
- Supply chain availability
- Risks and uncertainties

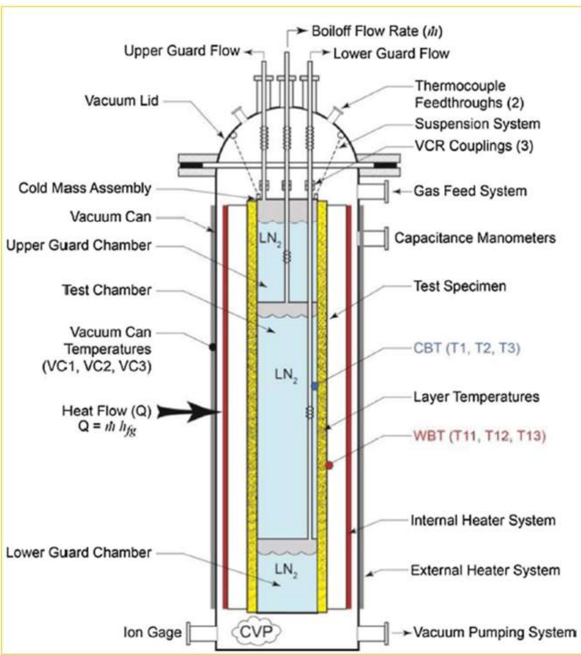
→ Identified two leading concepts for further development

Task 1.2 Concept development / evaluation

- Effective thermal conductivity measurement on Slide 10-12
- Thermal modeling on Slide 13
- HAZID analysis on Slide 14
- Future work: cost estimation, structure design, mechanical analysis, insulation material application testing, risk impact assessment, etc.

Approach
LN2 based Thermal Conductivity Measurements

- CS-100 modification: increased insulation sample thickness; software updates
- Development of the equipment / methods for the Ke measurements using H_2 background gas: completed the detailed design of facility modifications required for the test and the schematic of the setup



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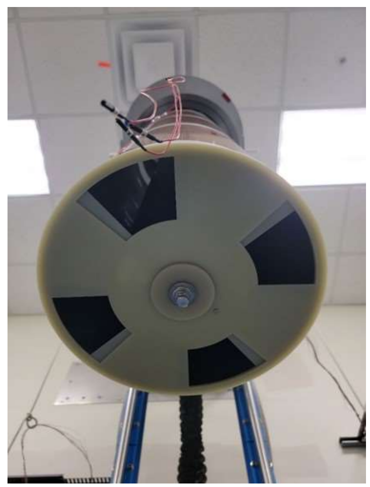
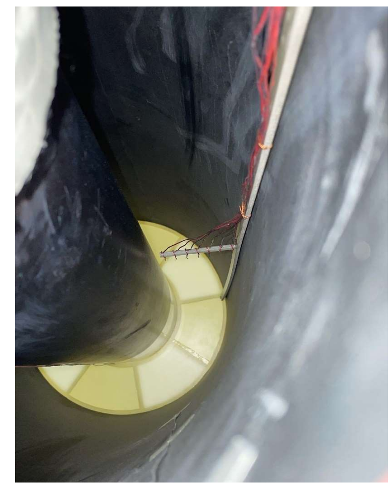


Modified bulk fill insulation base plate

Large diameter heater sleeve ~3” insulation thickness



Cold head in sleeve w/temperature rake

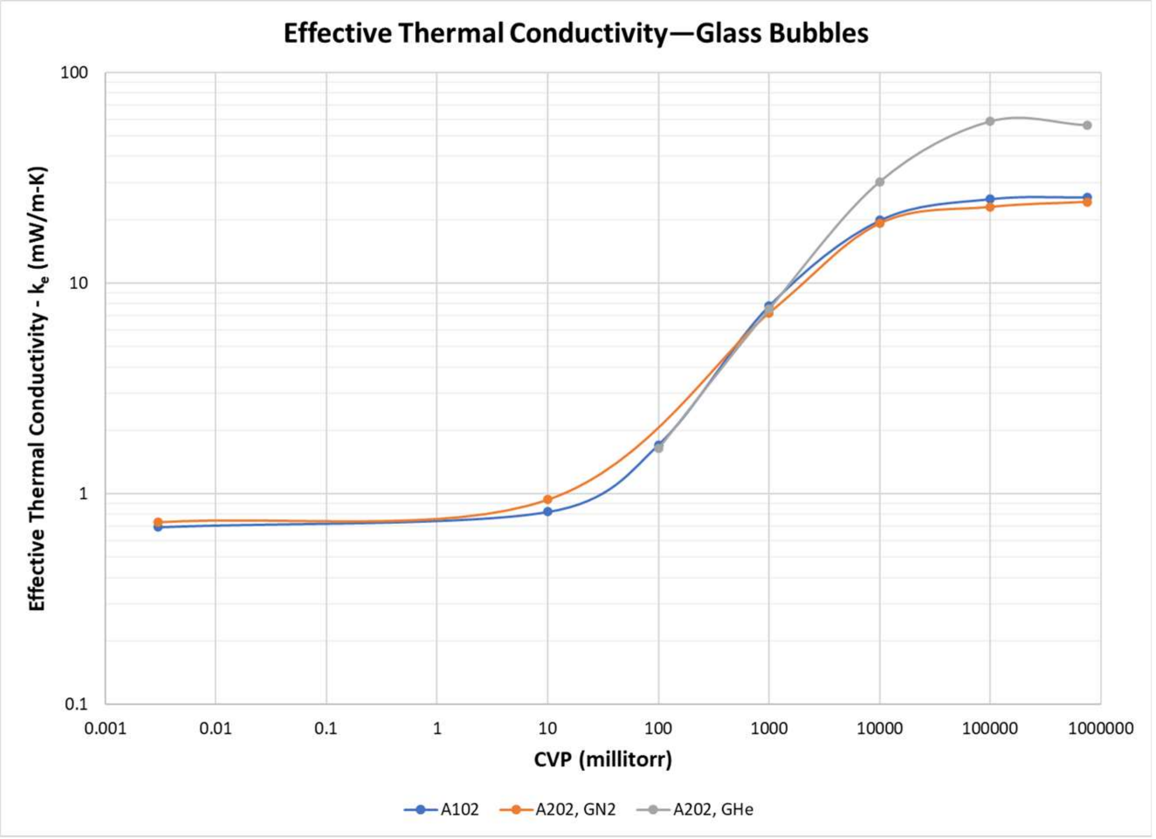
Accomplishments and Progress

Ke of Glass Bubble in Nitrogen and Helium background gas

Effective thermal conductivity comparison at different pressures

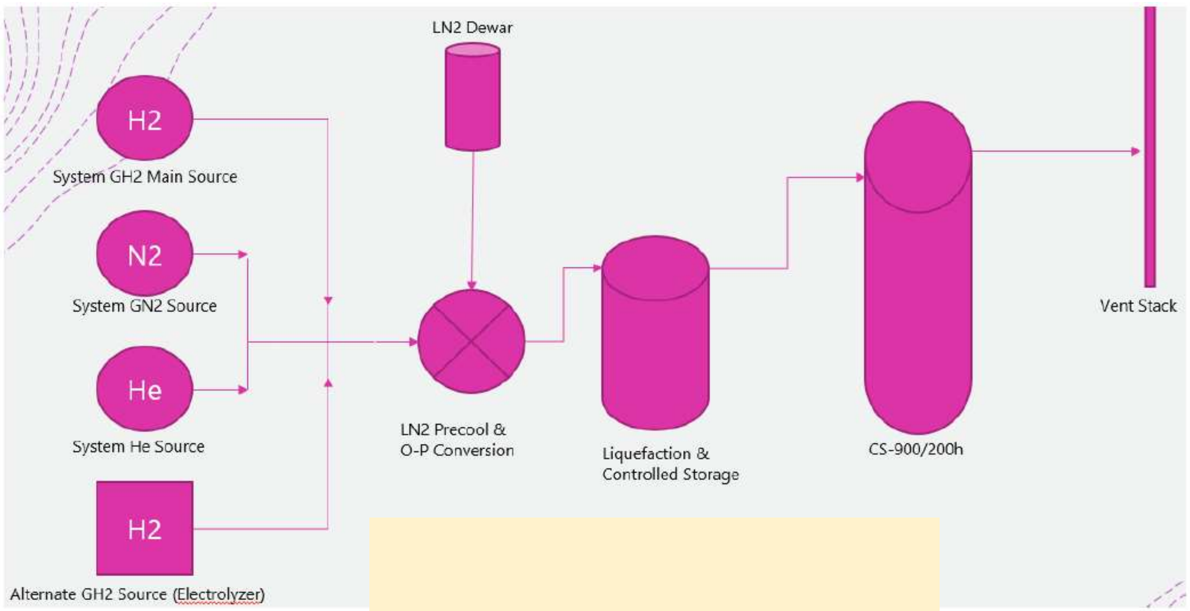
	Effective Thermal Conductivity (mW/m-K)		
	Nitrogen		Helium
CVP (millitorr)	A102	A202	A202
HV	0.70	0.73	---
10	0.82	0.94	---
100	1.71	---	1.64
1000	7.80	7.21	7.54
10000	19.9	19.2	30.4
100000	25.1	23.0	58.8
760000	25.7	24.3	56.3

Notes: 1) Cryostat CS-100 of Cryogenics Test Laboratory at NASA/KSC; 2) ASTM C1774, Annex A1; 3) For 78 K and 293 K boundary temperatures; 4) 3M K1 Glass Bubbles at approximately 70 kg/m3; 5) Data set A102 produced in 2006.



Approach
LH2 testing center and LH2 based cryostat development

LH2 facilities process flow diagram



Storage tank 400-liter (refrigerated)

Key timeline

- Macroflash (ASTM C1774-A4) final commissioning – April
- Cryostat CS-900 fabrication/design in process – start setup in July
- Lab-scale liquefaction system (MicroBear) procurement complete – start setup in June
- Facilities permitting – target July
- LH_2 small-batch production – target August
- Cryostat CS-900 (ASTM C1774-A1/A2) initial comparative test with LH_2 – target September

Macroflash

First-of-its-kind LH2 based cryostat CS-900

Approach and Progress
Thermal Modeling and BOR prediction

Synergy with LNG Technology

- ❖ Knowledge transfer
- ❖ Key differences:
  - ❖ Focus on non-vacuum Insulation concept
  - ❖ Temperature all the way to 20K

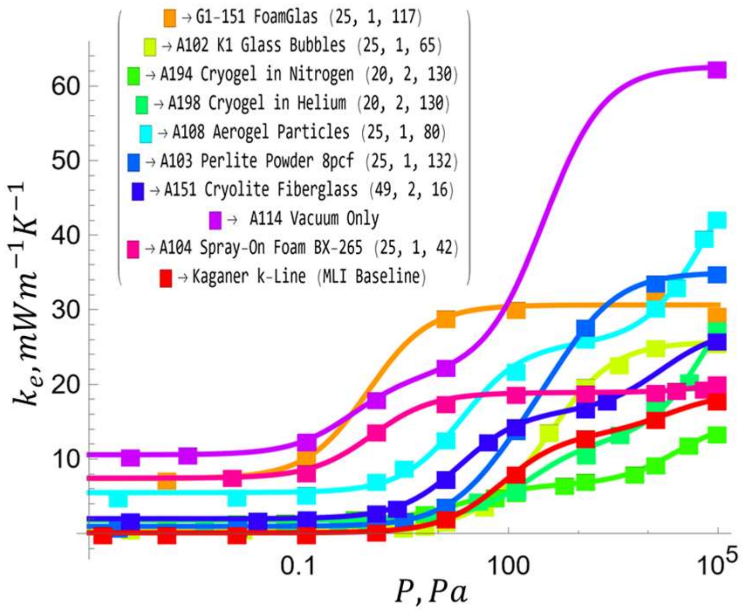
Physics-based modeling

- Insulation Property model (T, P, gas, material characteristics)
- Dynamics in the insulation system and within tank (Heat/mass transport, natural convection)

$$k_e = AT^B + CT^3 + \frac{DT^E P}{FT + P}.$$

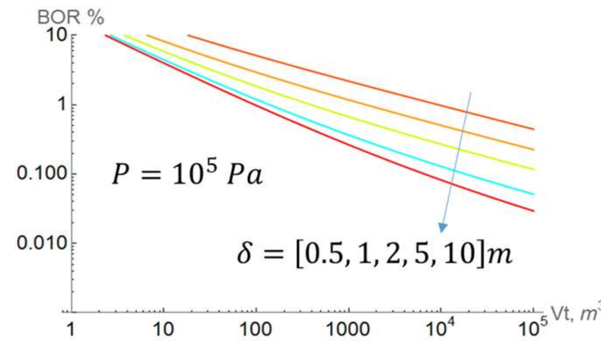
- Solids conductive contributions
- Solids radiative contributions
- Gas contributions

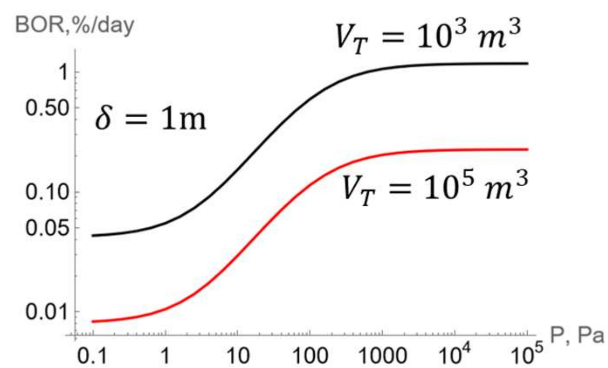
Thermal insulation system property model



- ✓ ***Insulation model developed and refined***
- ✓ ***External publication in preparation***

BOR prediction





Approach, Accomplishments and Progress

Technology safety review

What

- High-level hazard Identification technique
- Team-based, relies on knowledge, experience, brainstorm, and engineering judgment
- Effect-driven; presupposes a failure can occur
- Solution-oriented

Why

- Identify and assess potential HSE risks associated with hydrogen production
- Qualitatively compare risk differences to inform decision-making
- Establish requirements for further study and assessment in subsequent activities

How

- Brainstorm of failure scenarios for leading concepts
- Estimate scenario consequences, likelihood, and potential controls approaches
- Capture recommendations to be actioned during concept select
- Sense for concept risk differential

Snapshot of HAZID analysis on two leading concepts

Scenario Description	Concept 1 Risks / Differences	Concept 2 Risks / Differences	Controls / Other Comments	Relative Risk	Concept 1 Actions	Concept 2 Actions
External: External fire impacting storage vessel	Applicable - 1 Additional intermediate tank may provide additional protection against	Applicable - 2 Foam cannot withstand high temperatures		1	Define external impact design scenarios and requirements	Define external impact design scenarios and requirements
External: Impact from external Vapor cloud explosion or detonation (terrorist attack or other chemical process e.g. fertilzer)	Applicable Note: Risk differences for all external risks captured in external fire line item	Applicable		0		
External: Impact from external projectiles (e.g. drone strike, debris in storm)	Applicable	Applicable		0		
External: Earthquake leading to tank damage	Applicable	Applicable	Seismic design conditions will be applied	0		

- Brainstorm failure scenarios for both concepts
- Assign risk level for each concept
- Actions captured
- Informs (not determines) decision-making
- Actions transferred to project Risk Register
- Tracked as part of project register and action review

Approach, Accomplishments and Progress
Codes & standards

Current Status

- Review is on going
- Review has been limited to NFPA 2
- Applicable NFPA 2 Chapters:
  - Chapter 4 General Fire Safety Requirements
  - Chapter 6 General Hydrogen Requirements
  - Chapter 8 Liquefied Hydrogen

Existing Gaps

- Vessel design requirements (i.e. requiring VJ vessels)
- Vessel sizes exceed the upper limits for siting requirements
- Chapter 9 "Explosion Protection"- Currently reserved for future updates but does not currently have any requirements

Timeframe for Completion

- Q3 Project Year/ June 2022

Milestone table

Year 1 Milestone

September 2021 - August 2022

Milestone #	Project Milestones	Task Completion Date (Project Quarter)	
		Original Planned	Percent Complete
M1.1.1	Generate technically feasible concepts for large-scale LH_2 storage tank, aiming 20,000 - 100,000 m^3 storage volume and BOR of <0.1% per day	Q1 Y1	100%
M1.2.1	Carry out Hazard Identification Review for LH_2 tank concepts	Q2 Y1	100%
M1.2.2	Establish the small-batch LH_2 production and obtain the permits for testing facilities.	Q3 Y1	45%
M1.3.1 / G1	The most promising tank configuration should reach the targeted BOR of <0.1% per day while achieving a CAPEX of < $175 million target costfor 100,000 m^3 LH_2 storage tank.	Q4 Y1	10%

Year 2/3 Milestone

Milestone #	Project Milestones	Task Completion Date
M2.5.1	The insulation system thermal model validation with H_2 and H_e gas in the insulation space	Q1 Y2
M2.2.1	Development of equipment and procedure for insulation system installation	Q2 Y2
M2.3.1	Establishment of 3D thermal-mechanical tank model	Q2 Y2
M2.4.1	Obtain the ke from new-built LH_2-based cryostat CS-900	Q3 Y2
M2.6.1/ G2	Verification of tank constructability, cost and BOR based on the updated design	Q4 Y2
M3.1.1	Material procurement and demo tank construction based on Q1 plan	Q1 Y3
M3.1.1	Demo tank construction progresses according to Q2 plan	Q2 Y3
M3.2.1	Demo tank commissioning and filled with LH· for the first time	Q3 Y3
EOP	Demonstrate and validate the design via testing	Q4 Y3

Responses to Previous Year Reviewers' Comments

- The project has not been previously reviewed at 2021 AMR.

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
	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	Demo tank construction & testing
	UH	Thermal modeling support

Remaining Challenges and Barriers

- Challenges: for LH_2 testing facilities and equipment, the progress is likely to be impacted by the uncertainty in equipment supply chain. Due to COVID impact and inflation, both the prices and lead time for the equipment have both increased since the initial budget submission.
- Mitigation: cost tracking and early planning

- Challenges: increased cost of demonstration tank due to inflation and increased material cost
- Mitigation: cost tracking and early ordering

Proposed Future Work in FY2022

- **Concept evaluation and selection:**
  - LN_2-based experiments: To complete CS-100 testing with different insulation materials in N_2, H_e, and H_2 background gases.
  - Thermal modeling: To refine the model for insulation material thermal conductivity and calculate the BOR
  - Cost analysis: To estimate the cost for the tank concepts and cost review in End June
  - Thermo-mechanical analysis: To continue the mechanical design and structure analysis of the two leading concepts under different scenarios for sensitivity analysis and complete the tank design review in End June
  - Codes & standards: To finish the overview of applicable regulations, codes and standards and identify potential gaps from existing ones
  - LH_2 testing facilities and equipment: To continue the purchasing on various components for LH_2 facility and associated equipment and establish the LH_2 lab-scale capability
  - Insulation installation testing
  - Risk impact assessment and concept selection

- LH_2 based experiments (Year 2 task)
- 3D thermal modeling (Year 2 task)
- Demonstration tank detailed design and engineering (Year 2 task)

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 development (generation, evaluation and selection); demonstration tank design, engineering, construction and testing
- **Technical accomplishments:**
  - Generated several tank concepts based on variations in tank configuration, insulation materials, vacuum/nonvacuum insulation, etc. and identified two leading concepts based on both economical and practical perspectives for further evaluation and development
  - Completed technology safety review for qualitative relative risk comparison between concepts, and aid in concept selection decision
  - Finished the K_e measurement of glass bubble in N_2 and H_e background gas, developed the equipment / methods for the experiments using H_2 background gas
  - Established physics-based correlation to predict the effective thermal conductivity of various insulation materials, developed the model to predict the convective contribution to the insulation performance
  - In progress: development of Liquid Hydrogen Center and design of the Cryostat CS-900 for the LH_2 testing
- **Future work:**
  - To identify the most promising concepts via cost analysis, thermal-mechanical analysis, design review, risk impact analysis, etc.

TECHNICAL BACKUP AND ADDITIONAL INFORMATION

Technology Transfer Activities

- Currently no technology transfer activities

Special Recognitions and Awards

- None

Publications and Presentations

- Forthcoming