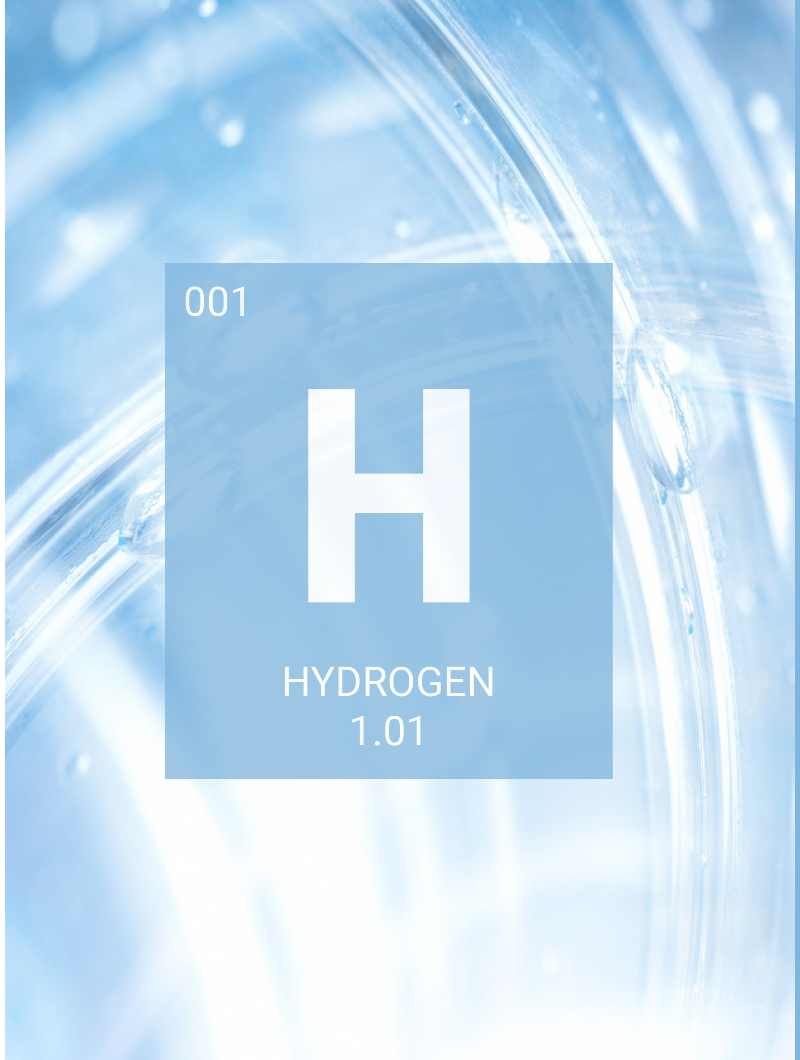

First Demonstration of a Commercial Scale Liquid Hydrogen Storage Tank Design for International Trade Applications

P.I.: Ed Holgate
Presenter: Kun Zhang
Shell International Exploration and Production, Inc.

DE-EE0009387
Date: 04/07/2023
DOE Hydrogen Program
2023 Annual Merit Review and Peer Evaluation Meeting
AMR Project ID # ST241

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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

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:

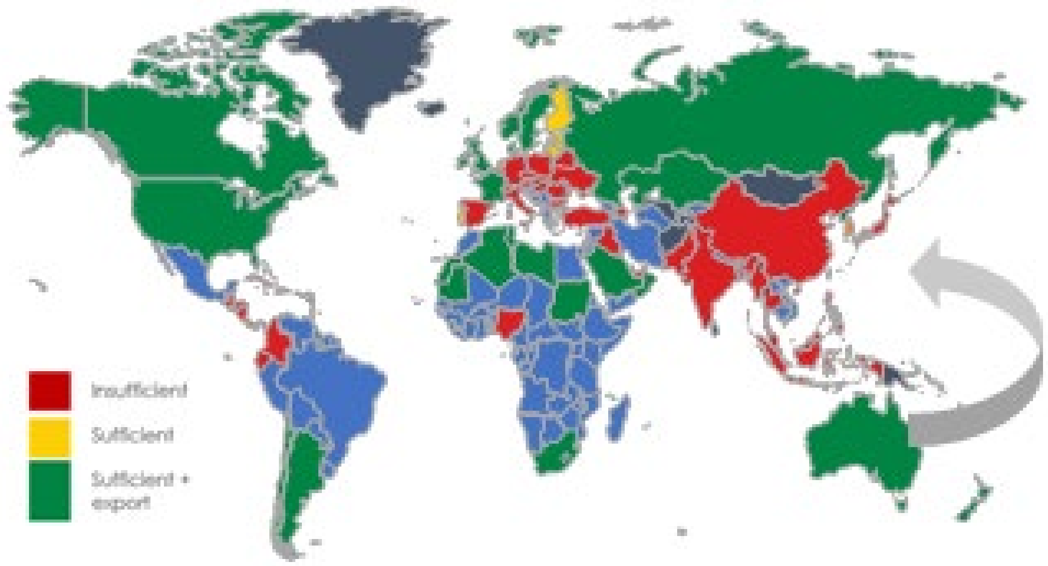
- Shell International Exploration and Production, Inc.

Partner organizations:

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

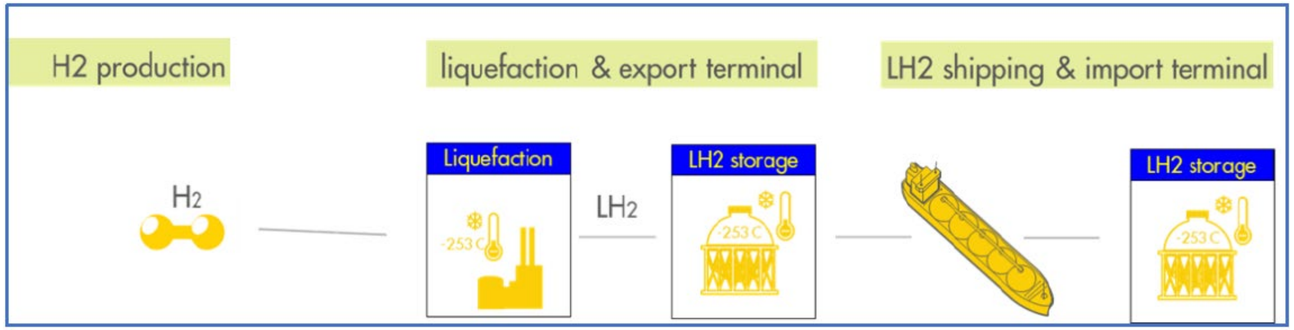
Potential Impact

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

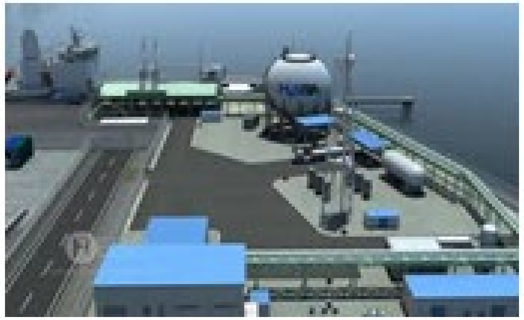


Now

LH_2 storage tank 5,000 m^3

20X

Need

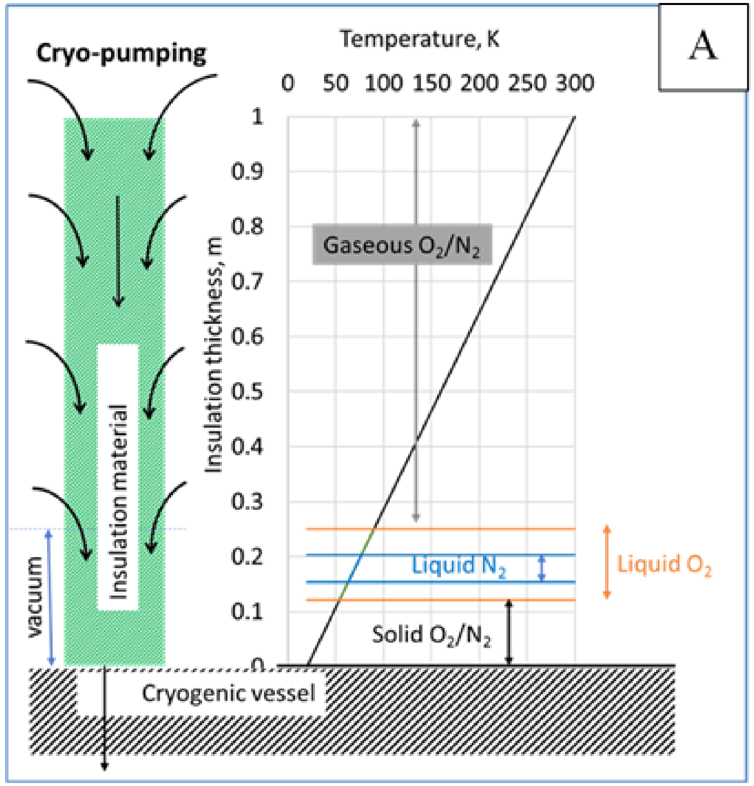


Receiving terminal 100,000 m^3

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

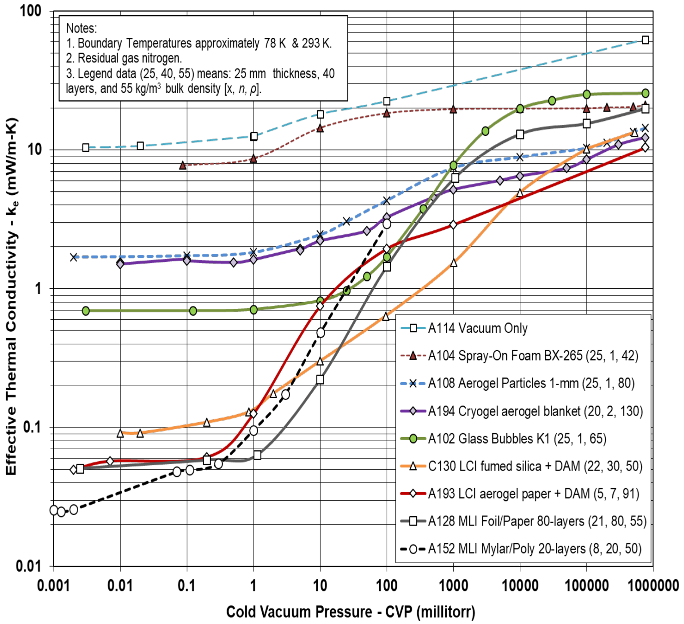
Non-vacuum insulation system:

- 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 & Status

TASK 1
Storage Concept Evaluation & Selection

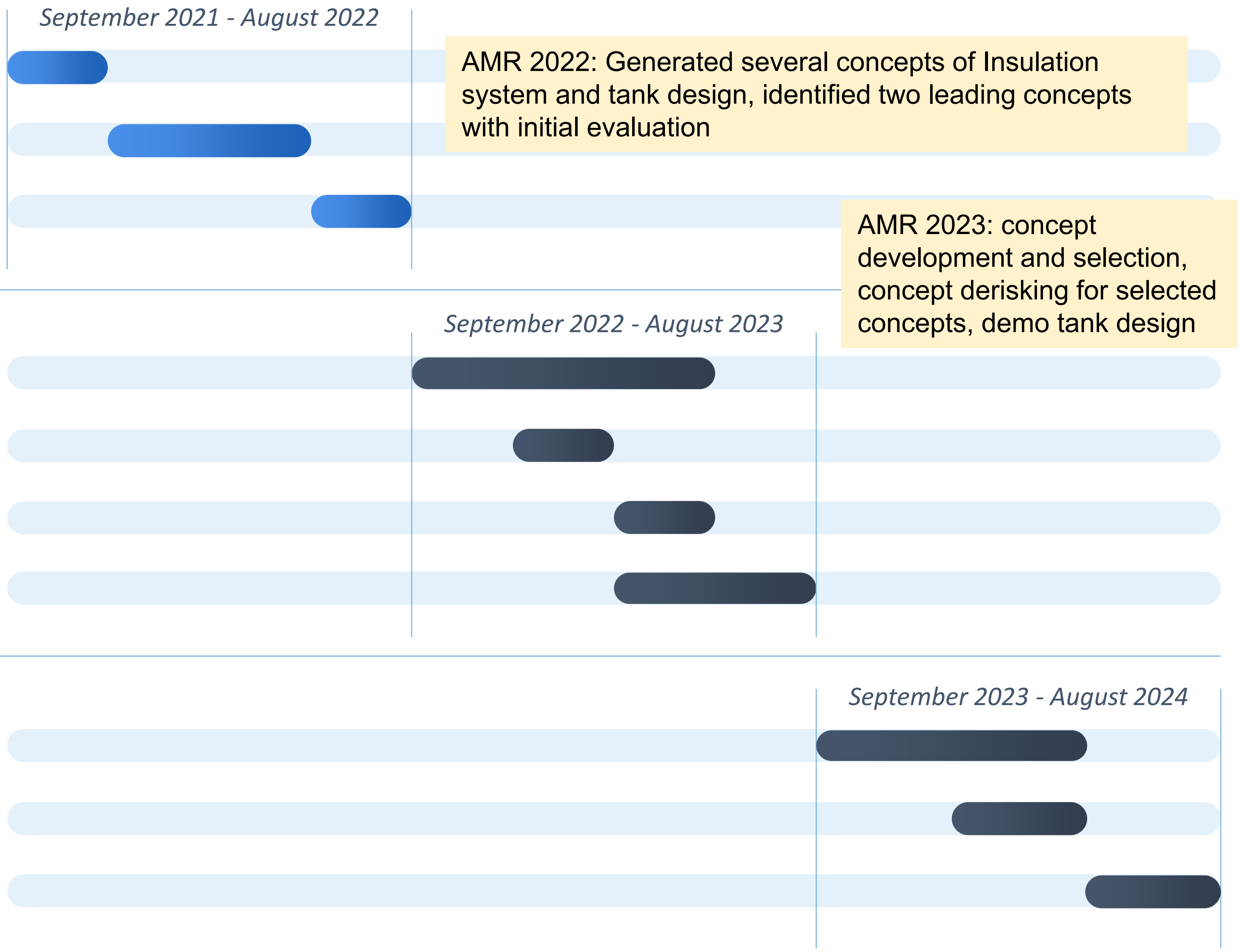
- Concept Generation
- Evaluations & Shortlisting
- Concept Selection

TASK 2
Demo Tank Detailed Design & Engineering

- Insulation Installation
- 3D Thermal Model
- LH2 Based Testing
- Design & Engineering

TASK 3
Demo Tank Construction, Performance Testing & Design Validation

- Demo Tank Construction
- Startup, Testing & Evaluation
- Model Validation & Design Updates



Approach

Concept Evaluation and Selection

Project goals

Boiloff Rate
<0.1%/day

CAPEX
below 150% of LNG

Safety & Integrity
Regulatory Bodies

LH2 storage tank design:

- **Tank configuration**
- **Insulation system design**
- **Support structure**

Thermal modeling for BOR prediction

Cost analysis

Effective thermal conductivity for large ΔT conditions (20K-300K boundary temp)

Mechanical analysis
Constructability review
Technology safety review
Codes & standards

LN_2 based Ke measurement with H_e / H_2 gas

Insulation property model to predict Ke

Development of LH_2 based equipment for Ke measurement

Lack of Ke data for LH_2 test conditions; Lack of equipment / capability for Ke measurement with LH_2

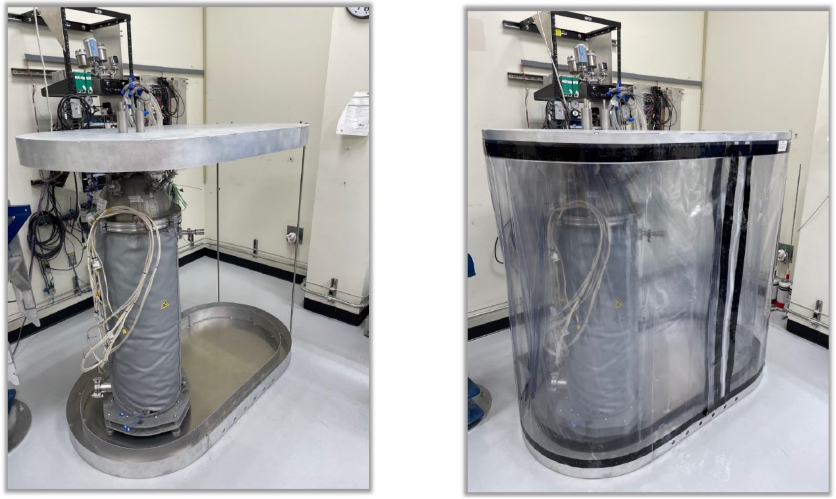
Concept selection:
Go/No-Go DP: To identify the most promising tank configuration reaching the targeted BOR of <0.1%/day while achieving a CAPEX of < $175 million target cost for 100,000 m^3 LH2 storage tank.

Accomplishments and Progress

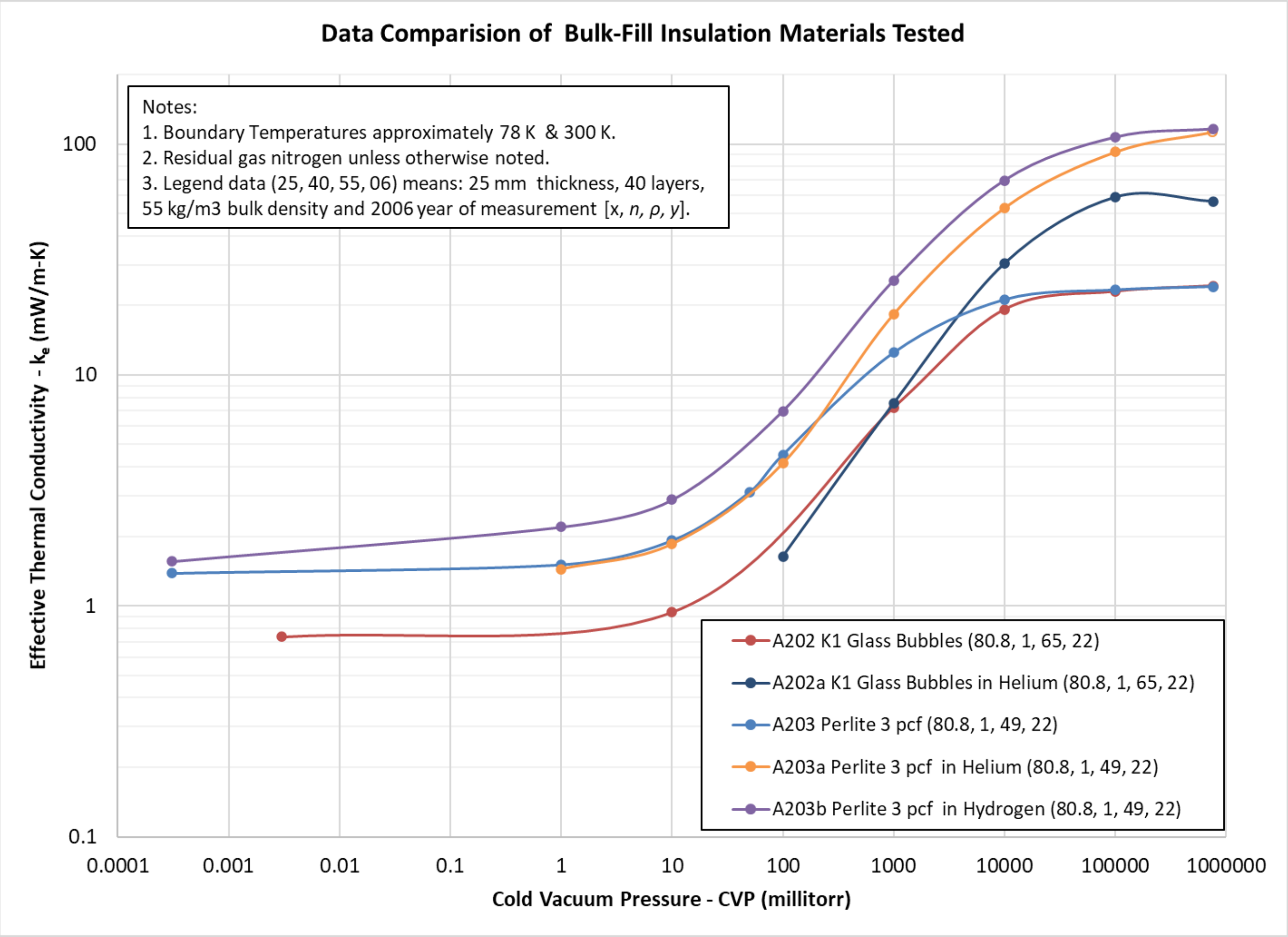
Task 1.2 Concept development / evaluation

- **Effective thermal conductivity measurement**

To-date, 3M K1 Glass Bubbles have been fully characterized in nitrogen and helium, and perlite 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



Accomplishments and Progress

Task 1.2 Concept development / evaluation

- **Updated insulation system thermal model**

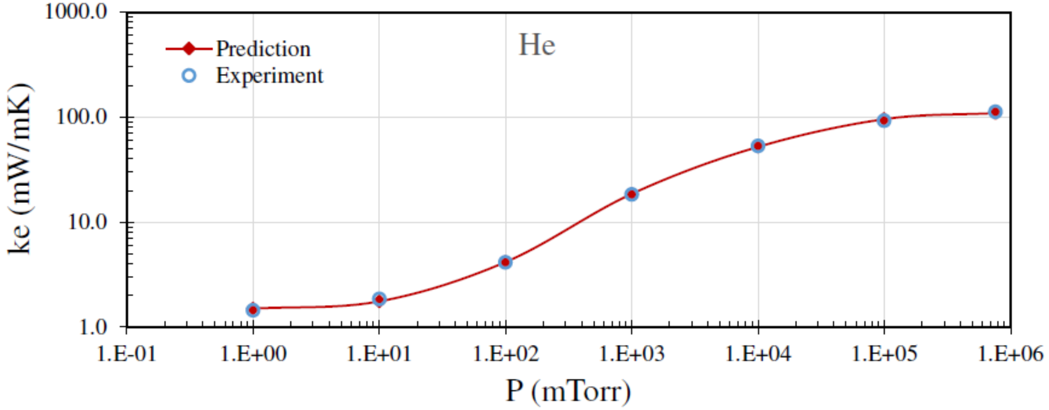
Effective thermal conductivity data of bulk fill materials (perlite, glass bubble, etc.) filled with different gases obtained from the NASA KSC LN_2 based experiments

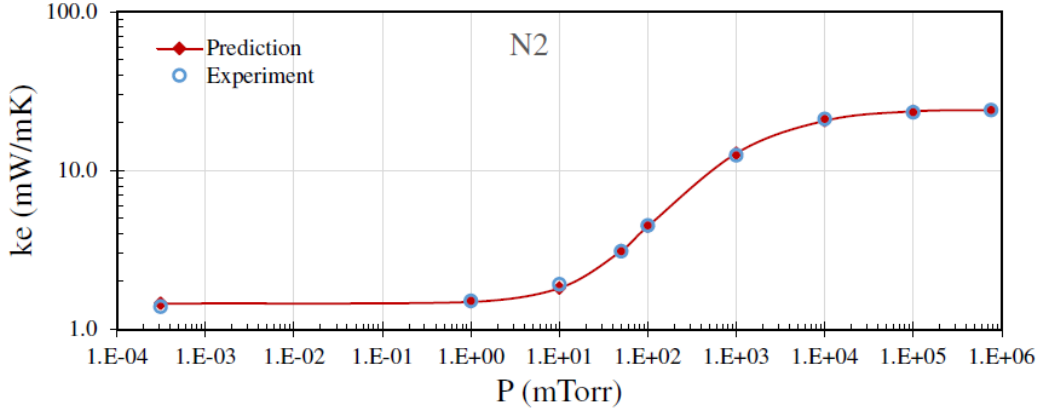
$$k_e = AT + BT^3 + \frac{CT^m P}{DT+P} + \frac{ET^n P}{FT+P} \quad \text{Equation 1}$$

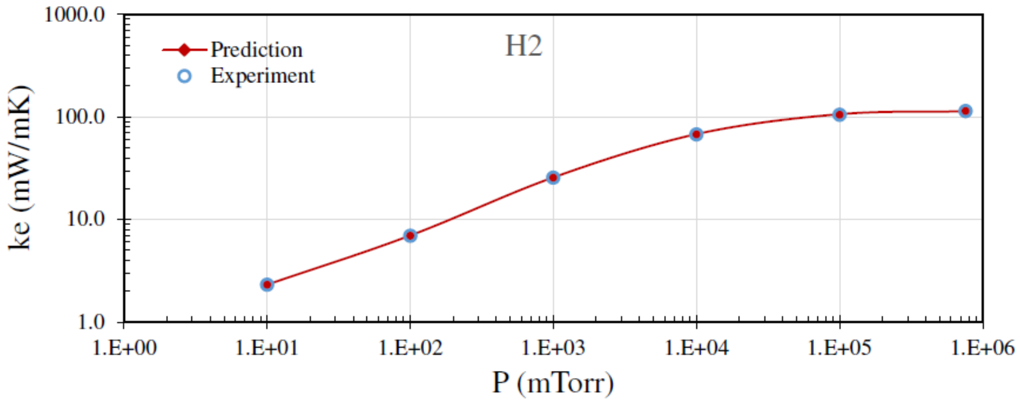
$$k_e = a_1 + \frac{a_2 P}{a_3+P} + \frac{a_4 P}{a_5+P} \quad \text{Equation 2}$$

Table 1: Parameter values from fitting

Parameter	H2 Perlite	N2 Perlite	He Perlite	N2 GB	He GB
a_1 $(AT+BT^3)$	1.705	1.453	1.467	0.776	0.958
a_2 $(C\sqrt{T})$	22.933	13.695	30.553	23.148	57.550
a_3 (DT)	55.844	51.180	159.041	341.013	1093.667
a_4 $(E\sqrt{T})$	90.490	8.953	79.459	-	-
a_5 (FT)	1389.586	657.198	3201.382	-	-







Accomplishments and Progress

Task 1.2 Concept development / evaluation

- **Mechanical analysis**
- Mechanical structure analysis on the tank configurations including tank size, tank shell design, tank materials and thickness, support design, insulation thickness, etc.
- Finite element analysis modeling to integrate the thermal and mechanical design and provide temperature contour outputs
- **HAZID analysis**
- 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
- **Initial insulation installation testing**
- To familiarize with insulation raw materials and application techniques for installation

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 / testing

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.

Accomplishments and Progress

Task 1.2 Concept development / evaluation

- **Cost analysis**
- Project Targets

❑ <150% of LNG full containment tank (~175M for 100k m3)

❑ BOR < 0.1%/d

- Relative cost comparison:

Vacuum jacketed LH_2 tank > Concept 1 > Concept 2 meeting cost target

- **Cost sensitivity analysis**
- conducted a Monte Carlo simulation for each design concept to determine the sensitivity of the estimates to the major technical uncertainties.
- The simulation showed that the variations in the technical uncertainties had an insignificant impact on the original estimates

Accomplishments and Progress

Task 1.3 Concept selection

Concept Select Matrix

	Concept 1	Concept 2
Design Safety	Good	Good
BOR target	Designed to meet the target	Designed to meet the target
Cost	> 150% LNG	= 150% LNG
Schedule	40 months	43 months
Constructability	Feasible	Feasible
Supply chain	No constraint identified	No constraint identified
Inspection and maintenance	Similar to LNG	Uncertain, to be evaluated
Insulation Scalability	May not scale down economically	Should scale down economically
Technical uncertainty	Low technical uncertainty	High technical uncertainty

Concept Select Decision Quality

1. Appropriate frame
Sufficient

1. DOE Project framed adequately
2. Concept select criteria identified.
3. Focused decision for current phase identified.

2. Creative doable alternatives
Sufficient

1. Seven distinctive concepts generated.
2. Two concepts shortlisted and the alternatives fully examined.

3. Useful information & ranges
Within acceptable range with residual risks

1. Insulation conductivity models below 70K to be validated
2. Uncertainity in insulation long term performance & mechanical integrity is acknowledged.
3. Mitigation plan to address risk developed.

4. Clear value measures & trade-offs
Sufficient

1. Key concept select criteria were formulated in the project objectives
2. Concepts are ranked across nine different value drivers
3. Technical risks were accounted for in the ranges of the cost estimates

5. Sound reasoning
Sufficient

1. Selected concept carries high risk (technical) high reward (cost)
2. Alternative concept does not meet the cost targets

6. Commitment to action
Sufficient

1. Unanimous support by the Steerco
2. Realistic plan for next stage in place.
3. Appropriate workstream leads identified
4. New resources/testing facilities are being secured.

Version: [insert file name]

Concept 2 selected with endorsement of DOE

Overall Assessment: Decision Quality is within acceptable range, but with residual risk

Accomplishments and Progress

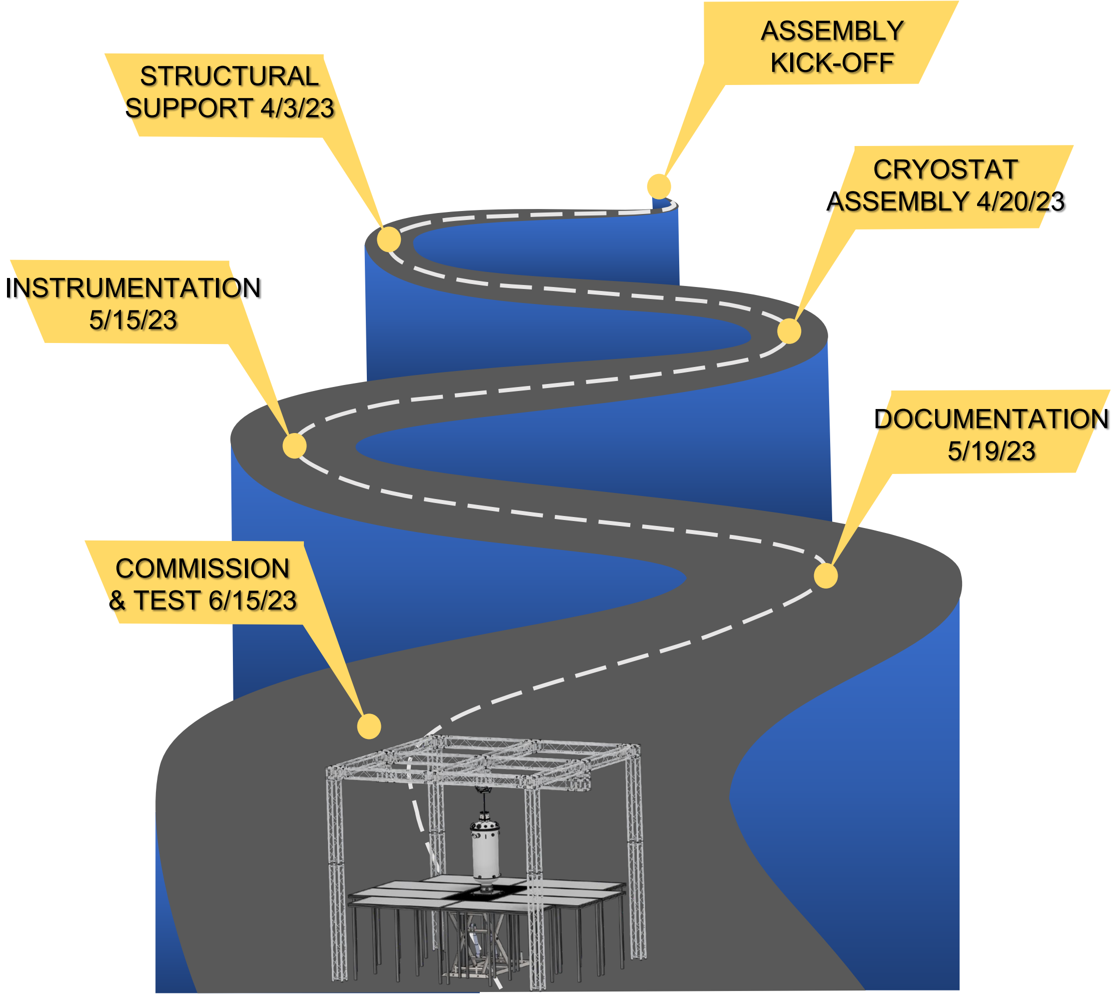
Task 2.4 Cryostat CS900-1 LN_2-based thermal performance measurement

Completed milestones

- Major items delivered ready for installation
- In-house fabrication items completed
- Test plan and matrix established
- Truss and stage completed

Current tasks

- Assembly of components
  - Base system
  - Lid hanger
  - Cryostat vessel
  - Heater sleeves
  - Thermal modulator
  - Instrumentation



Accomplishments and Progress

Task 2.4 Cryostat CS900-2: LH_2-based thermal performance measurement

The Modular Test Facility consists of two main modules:

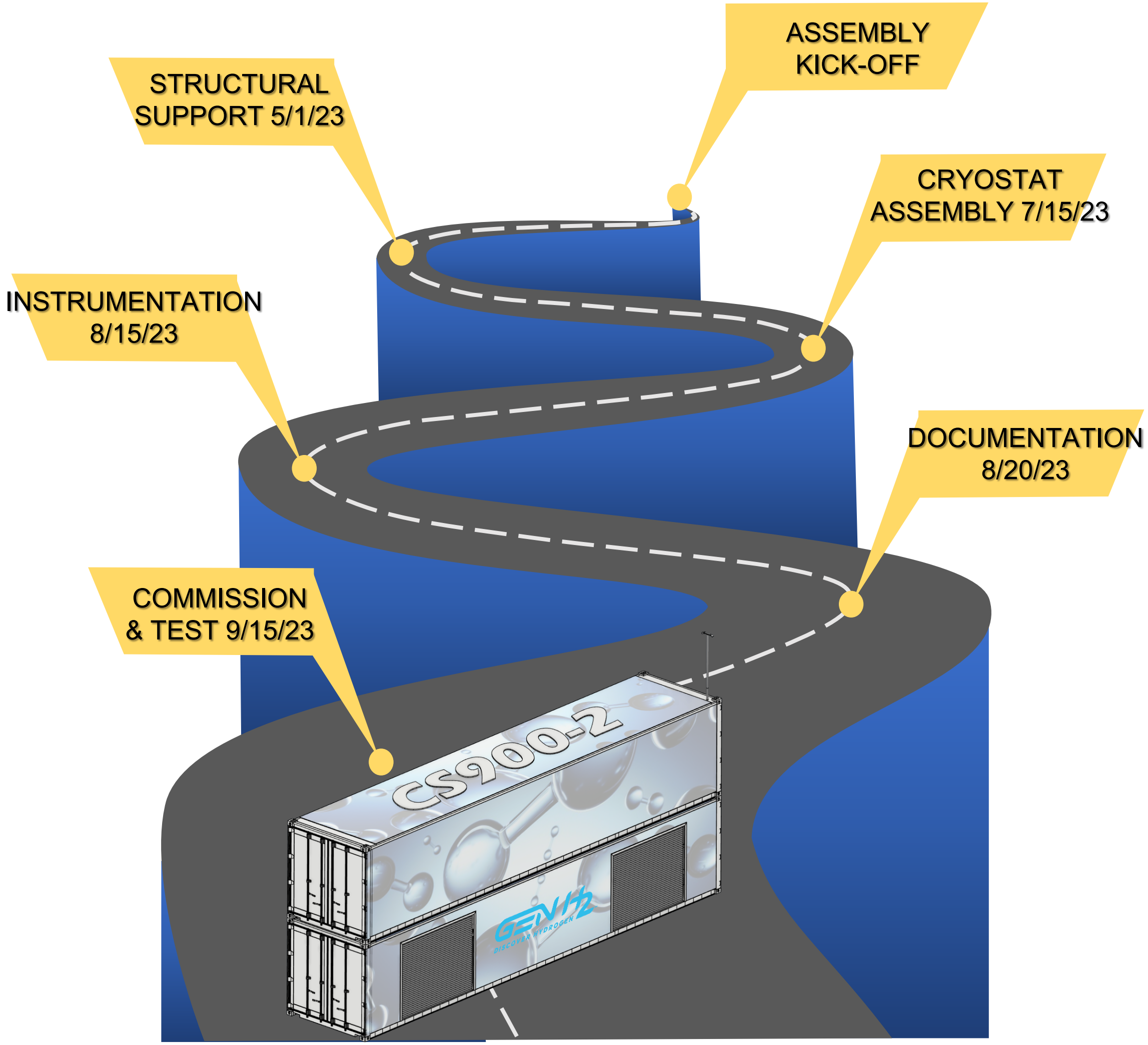
- **LS20 Module:** Hydrogen liquefaction and storage unit, capable of producing 20kg of LH_2 per day, as well as storing 400L in its custom-made storage tank.
- **CS900-2 Module:** LH_2 boiloff test instrument with a vacuum chamber and interchangeable cold mass assemblies based on the commissioned CS900-1 LN_2 system

Completed milestones

- P&ID revised and updated
- Component procurement list consolidated
- Test procedure outline
- High-level design of layout and final product rendering

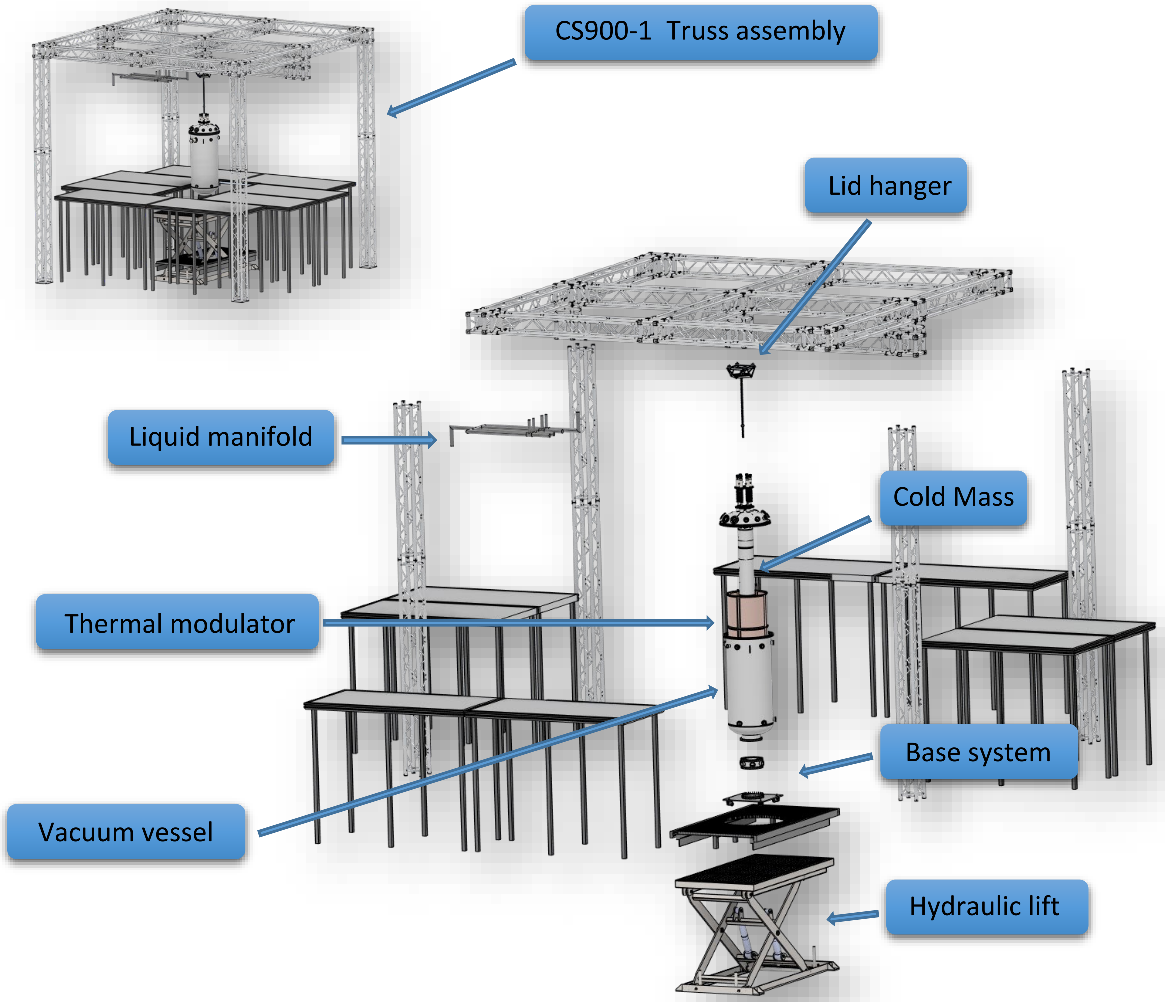
Current tasks

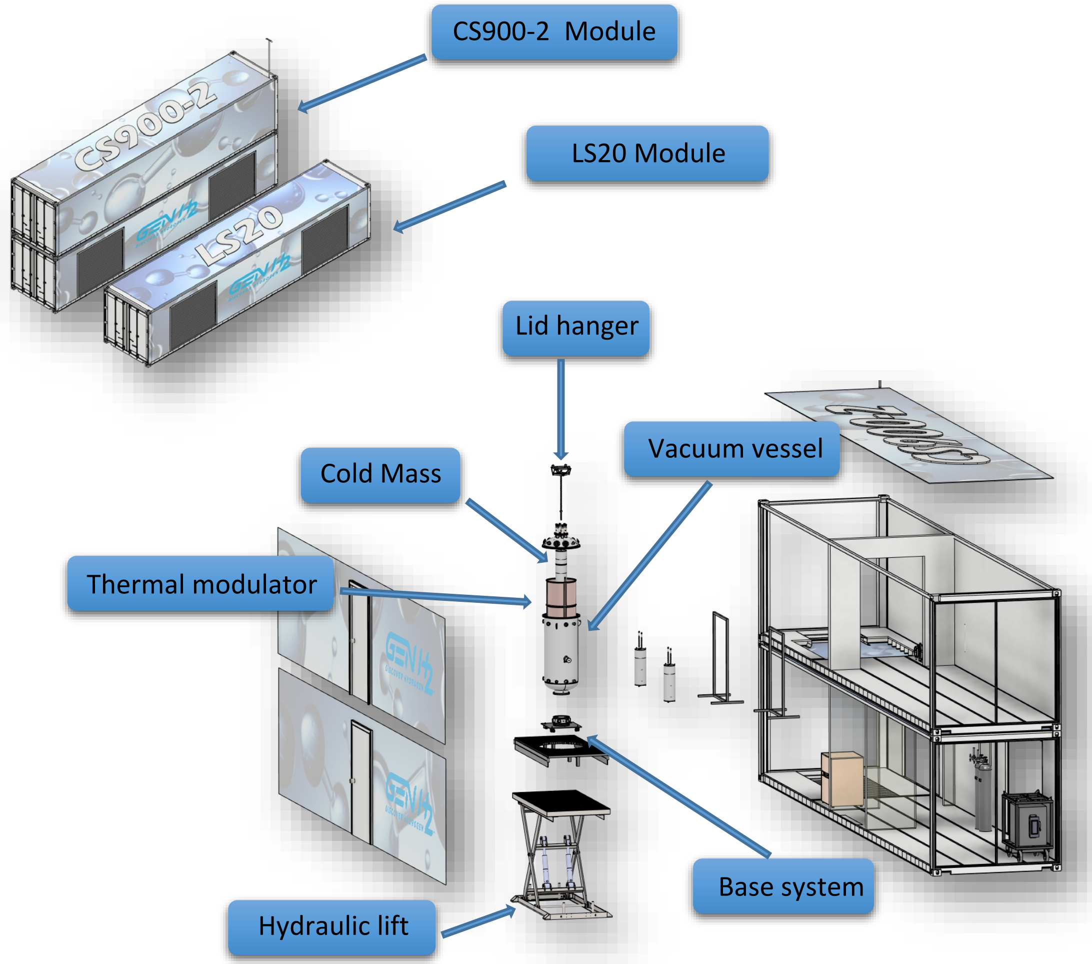
- Modular containers on order
- LH_2 transfer manifold
- Instrumentation and controls
- Software and DAQ
- In-house fabrication



Accomplishments and Progress

Cryostat CS900-1 & CS900-2 Assemblies





Accomplishments and Progress

Task 2.6 Demo tank detailed design and Engineering

Completed:

Demo Tank Configuration and Design Criteria:
- Inner tank design
- Inner tank support system
- Outer tank design/support
- Nozzles List

P&ID draft:
- Valves
- Instrumentation

Demo Tank Location evaluation

Next Steps:
- Select demo tank location and establish the contract with owner
- Finalize inner sphere support system
- Finalize nozzle orientation and annular space pipe routing
- Begin detail engineering for fabrication and construction drawings
- Engage VJ piping manufacturer to get quotes on the VJ spools
- Complete PSV sizing
- Develop valve lists and generate MR packages

Milestone table

Year 1 Milestone

September 2021 - August 2022

Milestone #	Project Milestones	Task Completion (Percent)
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 (100%)
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 cost for 100,000 m^3 LH_2 storage tank.	Q4 Y1 (100%)

Year 2/3 Milestone

September 2022 - August 2023

Milestone #	Project Milestones	Task Completion
M2.5.1	The insulation system thermal model validation with H_2 and H_e gas in the insulation space	Q1 Y2 (100%)
M2.2.1	Development of equipment and procedure for insulation system installation	Q2 Y2 (90%)
M2.3.1	Establishment of 3D thermal-mechanical tank model	Q2 Y2 (90%)
M2.4.1	Obtain the Ke from new-built LH_2-based cryostat CS-900	Q3 Y2 (60%)
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_2 for the first time	Q3 Y3
EOP	Demonstrate and validate the design via testing	Q4 Y3

Responses to Previous Year Reviewers' Comments

- No review from 2022 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
	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 schedule is likely to be impacted by the uncertainty in equipment supply chain with long lead time.
- Mitigation: early planning

- 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, etc.
- Mitigation: early planning and early ordering

Proposed Future Work in FY2023

- **Insulation system supply chain:**
  - To develop the supply chain of insulation materials for the selected concept and supplier qualification program with required technical specifications
- **Insulation material installation testing:**
  - To design the method, equipment, and procedures necessary to apply the insulations systems on the vessel walls, as well as required field evaluation techniques and procedures for quality control and quality assurance
- **Thermal modeling:**
  - To continue updating of the insulation thermal conductivity model to any new data obtained from experiments, especially extension of the model to lower temperatures, i.e. from 78K to 20K
- **LH_2-based thermal conductivity measurement:**
  - To establish all the protocols and commission the newly built CS-900; to measure thermal conductivity data of selected insulation material with cold wall temperature down to 20 K
- **Detailed design and engineering of the demo tank**

Note: Any proposed future work is subject to change based on funding levels

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:**
  - Completed the mechanical structure analysis, 3D finite element analysis, hazard identification analysis, initial installability testing, preliminary cost estimates and sensitivity analysis for the two leading concepts
  - Completed the concept selection with Concept 2 selected as the concept meets the cost target with more margins, and the insulation system design could economically scale down to smaller capacities. The concept selection process was discussed with DOE official and got their endorsement with the approval for Year 2 funding support.
  - Completed the LN_2-based Ke measurements on perlite at different pressures in nitrogen, helium, and hydrogen background gas, and updated the previously developed effective thermal conductivity model using the new measured data from LN_2-based experiments
  - In progress: development of Liquid Hydrogen Center and design of the Cryostat CS-900 for the LH_2 testing
  - In progress: demo tank detailed design and engineering
- **Future work:**
  - Insulation material installation testing
  - Ke measurement using newly-built LH_2-based cryostat CS-900
  - Milestone: Verification of tank constructability, cost and BOR based on the updated design
  - Year 3: Demo tank construction and performance testing

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TECHNICAL BACKUP AND ADDITIONAL INFORMATION

Technology Transfer Activities

- Currently no technology transfer activities

Special Recognitions and Awards

- None

Publications and Presentations

- Jo-Tsu Liao, Kun Zhang. First demonstration of a commercial scale LH2 storage tank design for international trade application, presented in 2022 Annual Merit Review and Peer Evaluation Meeting (virtual), June 2022.

- Ram Ratnakar, Zhe Sun, Vemuri Balakotaiah. Effective thermal conductivity of insulation materials for cryogenic LH2 storage tanks: A review. International Journal of Hydrogen Energy. 2023, 48(21): 7770-7793 (https://doi.org/10.1016/j.ijhydene.2022.11.130)

- Mahsa Taghavi, Swapnil Sharma, Vemuri Balakotaiah. Natural convection effects in insulation systems of large-scale cryogenic storage tanks, paper 308b, presented at the AIChE conference, held at Phoenix, AZ from 13th-18th November 2022.

- Swapnil Sharma, Mahsa Taghavi and Vemuri Balakotaiah, Natural convection effects in insulation layers of cryogenic storage tanks, poster presentation at the 3rd Competitive Energy Systems Symposium, held at Honolulu, HI from 6th-8th December, 2022.