IV.D.4 Integrated Insulation System for Automotive Cryogenic Storage Tanks

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- Aspen Aerogels, Northborough, MA
- Energy Florida, Cape Canaveral, FL
- Hexagon Lincoln, Lincoln, NE
- ITB Inc, Merritt Island, FL
- NASA, Kennedy Space Center, FL
- Savannah River National Laboratory, Savannah River Site, Aiken, SC

Project Start Date: October 1, 2016
Projected End Date: September 30, 2019 – Project continuation/direction determined annually by DOE

Overall Objectives

- Develop integrated insulation system concepts for cold/cryo-compressed hydrogen storage systems.
- Complete preliminary component testing and thermal models.
- Validate system concepts and design a sub-scale prototype.
- Fabricate and test a prototype system.
- Develop a market commercialization plan.

Fiscal Year (FY) 2017 Objectives

- Complete preliminary design for full-scale storage system.
- Down-select potential concept technologies based on system requirements.
- Complete initial component testing.
- Update system concept based on costs.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

(A) System Weight and Volume

(D) Durability/Operability

(G) Materials of Construction

(H) Balance of Plant Components

(J) Thermal Management

(N) Hydrogen Venting

Technical Targets

This project is developing an integrated insulation system for cryogenic automotive tank applications that is designed to meet the following 2020 DOE technical targets.

- Demonstrate a dormancy target time of <u>7 d</u> (minimum time until first release of hydrogen from initial 95% usable capacity)
- Demonstrate a boil-off loss target of <u>10%</u> (max reduction in stored hydrogen from initial 95% usable capacity after 30 days)

Project specific targets also include:

- Utilize a full-scale 100 L tank with geometries from 3:1 to 6:1 length-to-diameter
- Demonstrate a heat leak for the overall integrated system ≤7 W under a reduced vacuum of 0.1 torr, assuming an insulation thickness of ≤2.5 cm

FY 2017 Accomplishments

- Identified several potential thermal insulation systems/materials for evaluation as part of the thermal analysis model.
- Completed the initial version of the thermal analysis model.
- Initiated the evaluation of potential aerogel-based insulation materials.
- Identified and obtained potential tanks for evaluation of vacuum retention/stability, permeation, outgassing, and structural–mechanical properties
- Completed the initial cost estimate for a cryo-compressed hydrogen storage system with an insulated

4:1 Type 3 pressure vessel, including the necessary balance of plant components for integration with a light-duty fuel cell vehicle.

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INTRODUCTION

Cryo-compressed and cryo-adsorption are two leading candidate technologies for storing hydrogen onboard light-duty vehicles. The technical hurdles hindering the application of these technologies are simultaneously achieving high volumetric density, high gravimetric density, and low loss of useable hydrogen while the vehicle is not in use. The primary cause of loss of useable hydrogen in cryogenic systems is through heat ingress and the resultant rise in hydrogen pressure requiring activation of a pressure relief device. While multi-layer vacuum insulation (MLI) may be able to achieve the ≤7 W heat leak required for these systems, the maintenance of very high vacuum levels would require frequent evacuation, a cost element which may not be supportable by the commercial automobile industry. The objective of this effort is to develop an integrated insulation system that would utilize low maintenance, lightweight, inexpensive insulation.

APPROACH

The initial approach to this project involves data mining of the cryostat libraries at the Cryogenics Test Laboratory (CTL) to identify potential insulation systems that can meet or exceed the project's target heat leak of ≤7 W and evaluation of commercially available insulation material. Part of the evaluation process for these insulation systems/materials will be to narrow the search to those candidates that are best suited to work in the soft to medium vacuum range (1 mTorr to 1,000 mTorr). This range provides a distinct advantage over traditional MLI in requiring minimal or no periodic maintenance.

The development of an integrated insulation system will rely heavily on modeling of cryogenic tank and insulation material properties along with balance of plant component test data to facilitate the choice of the final system. To this end, discrete elements of heat transmission have been identified for the insulated tank to aid in modeling the overall heat leak. This heat leak is part of the overall hydrogen system model that represents a full-scale cryo-compressed hydrogen storage system and includes full balance of plant hardware.

RESULTS

Screening of the test results contained in the data libraries of the CTL were initiated using the following criteria:

- *Effective thermal conductivity (k_e)* < 2 mW/m-K at 100 mTorr cold vapor pressure (CVP) with any thickness up to 23 mm
- *Heat flux (q)* < 20 W/m^2 at 100 mTorr CVP; based on approximately 23 mm thickness.

The results of this screening were compared to the iCAT target parameters of:

- *Heat Leak (Q)* <7 W for 100-L tank with boundary temperatures of 300 K (warm) and 78 K (cold);
- $q < 5$ W/m^2
- A system thermal conductivity (k_s) < 0.5 mW/m-K

To date, approximately 50% of over 700 materials and systems have been analyzed. The results of screening the CTL data libraries are shown in Figure 1. The shaded area of the graph represents the "moderate cryogenic vapor pressure" region that holds the greatest potential for applicability in an integrated insulation system. The use of a system that runs at a lower overall pressure will require less maintenance. Note that this graph shows a sample of the representative data materials that have been tested at the CTL and is not intended to encapsulate the "best" or "final" materials being considered.

The modeling of heat transmission for an integrated tank includes considering elements such as penetrations, structural supports, facing surfaces, and all thermal insulation to approximate the overall heat leak. Table 1 identifies each of these elements, while Figure 2 provides a schematic of the pressure vessels elements. The materials that comprise the integrated insulation system are chosen to minimize heat loss through each element and, thus, minimize the full heat load.

A full-scale cryo-compressed hydrogen (CcH_2) storage system (Figure 3) includes a full balance of plant hardware with the following characteristics:

1. Operating Temperature Range: 40 K to 80 K
2. Operating Tank Pressure: 300 bar (designed to vent at 350 bar)
3. Tank Characteristics: Type 3 aluminum-carbon fiber tank
4. Tank Shell: 2-mm outer aluminum shell
5. Insulation thickness: 23-mm thick with supports

Each of the elements shown in Figure 3 can have multiple materials within an element, or use extremely different materials from element to element, to minimize the thermal load of each element as well as the total system heat load. The balance of plant, which has been minimized to match the needs of a cryo-compressed system, can be easily changed to match any hydrogen storage system. The pressure

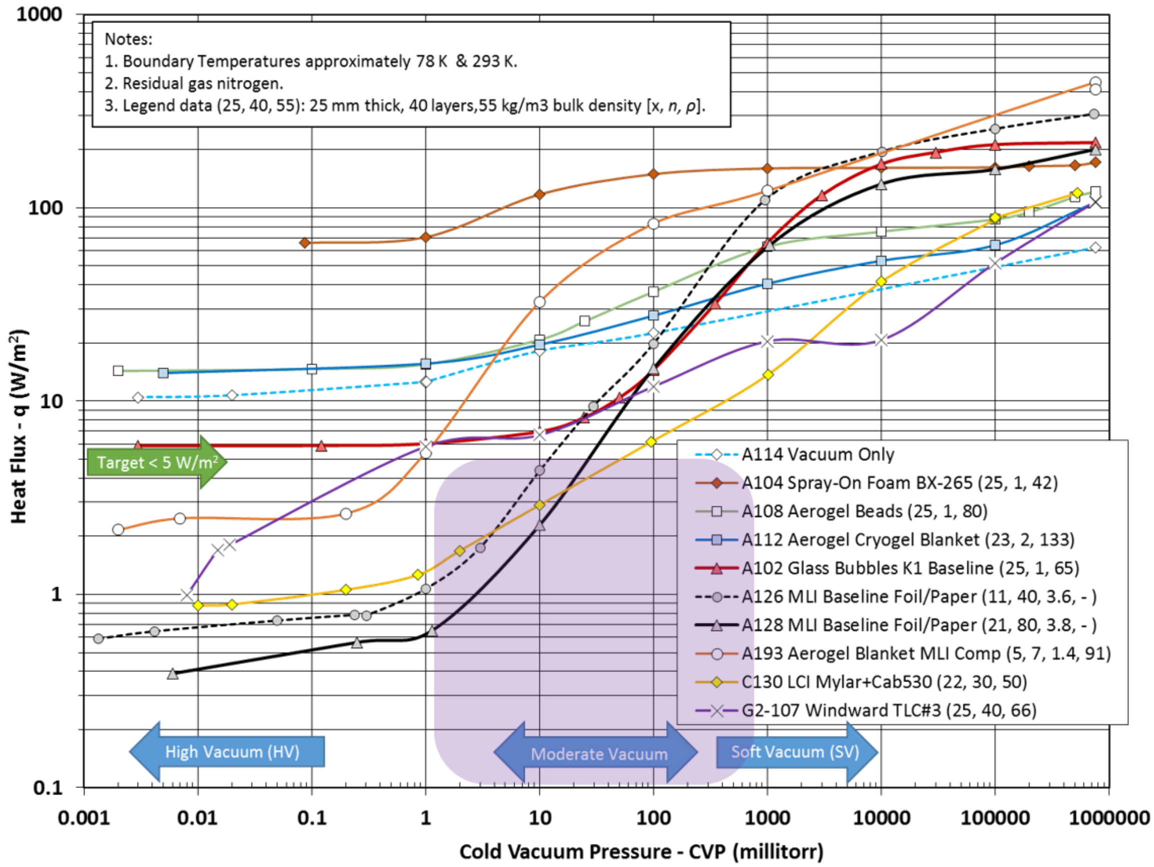


FIGURE 1. Selected cryostat data: insulation system heat flux (q)

TABLE 1. Integrated Tank Heat Transmission Elements

Heat Transmission Element	Designator	Description
Penetration	F	Fill Line [End-A]
	V	Evacuation/Service [End-B]
	A	Auxiliary/Instrumentation
Structural Supports	S_A	Support, End A
	S_B	Support, End B
	S_C	Support, Side (Cylinder)
Facing Surfaces	R_1	Reflective Surface One, Outer of Inner Vessel (zero for e = 0)
	R_2	Reflective Surface Two, Inner of Outer Jacket (zero for e = 0)
Thermal Insulation	Z_{1A}	Insulation Zone 1A, End-A support area
	Z_{1B}	Insulation Zone 1B, End-B support area
	Z_{2A}	Insulation Zone 2A, End-A support area
	Z_{2B}	Insulation Zone 2A, End-B support area
	Z_3	Insulation Zone 3, Side (Cylinder)
Insulation Quality Factor (IQF) [degradation; one for each zone]	Q_{1A}	
	Q_{1B}	
	Q_{2A}	
	Q_{2B}	
	Q_3	

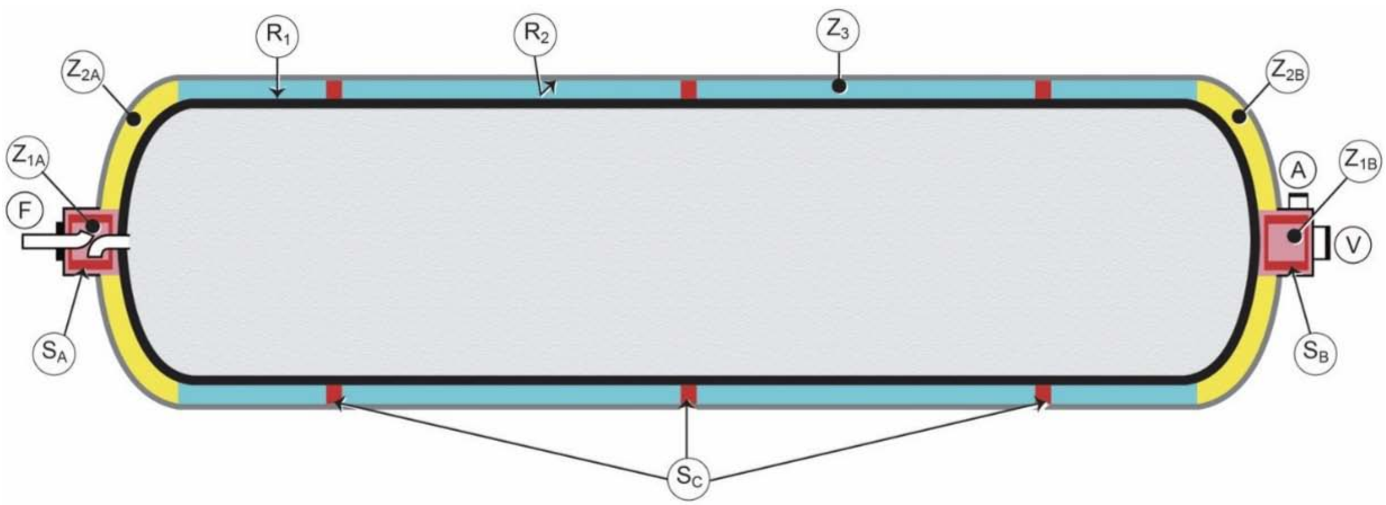


FIGURE 2. Cryogenic tank and heat transfer elements

vessel type, volume, and length-to-diameter relationship can also be changed as necessary.

Several cryo-compressed hydrogen storage systems have been designed as a basis for the thermal analysis model. These systems each use a 100-L internal volume Type 3 aluminum-carbon fiber pressure vessel with length-to-diameter ratios of 3:1, 4:1, and 6:1. The vacuum insulation thickness around the pressure vessel has been set to 23 mm with a 2 mm outer aluminum shell. The pressure vessel's boss/plug (penetrations) and support rings are pre-defined based on the designs used by the Hydrogen Storage Engineering Center of Excellence (HSECoE), but with updates based on the current design decisions. Because the pipe/tube penetration is part of the tank pressure boundary, the total heat load to the tank heat will depend, in part, on the design pressure of the vessel. Therefore, new approaches to the design of the pipe/tube penetration must be considered for a given pressure(s) as part of the complete thermal insulation system.

Estimates for the cost of the integrated insulation system were developed that integrated the components illustrated in Figure 3 along with previously published analysis for similar systems [1]. Some balance of plant components were also taken from the cryo-adsorbent designs originating in the HSECoE. The Type 3 pressure vessel cost is based on the material costs plus a 56% addition for manufacturing. Working with Hexagon Lincoln, these manufacturing costs will be updated in future iterations. In addition, the cost and manufacturing of insulation system components has been considered in updating the current design selections as well as the current working costs. The following assumptions were used in the cost model and analysis:

- A linear process for development: prototypes (quantity 3); beta test units (quantity 100); first production run (quantity 1,000); mass production quantities (quantity 10,000).
- A standard model for economies of scale for this type of manufacturing.
- A reduction of labor cost at the mass production scale due to automation.
- The cost of the insulation and its' application do not realize economies of scale in this model.
- No vacuum pump was included in this model. Maintaining a quality vacuum in the systems was determined to be a service and an operational cost and not assumed in this model.
- Standard manufacturing overhead cost structures were applied to this model.

Table 2 illustrates the methodology used in estimating the overall system cost (NOTE: For clarity, only a subset of the total system components is shown). The preliminary working total cost estimate for the current design, utilizing all components, is $2,732.45 as of June 30, 2017.

Progress has been made in identifying a potential wrapping technique for insulation material used in the integrated system. Some of the wrapping techniques employed when using aerogel-type insulation materials are illustrated in Figure 4. These techniques are called "cigarette wrapping" and may be applicable to facilitate the wrapping of balance of plant components. The benefit of using this technique is the prevention of direct heat leak through insulation seams. Aerogel material (5–10 mm thick) is easy to cut using a razor blade or scissors and is flexible so installation by wrapping is simple and fast. The use of these wrapping techniques will lower the heat leak and improve the thermal performance of the insulated system.

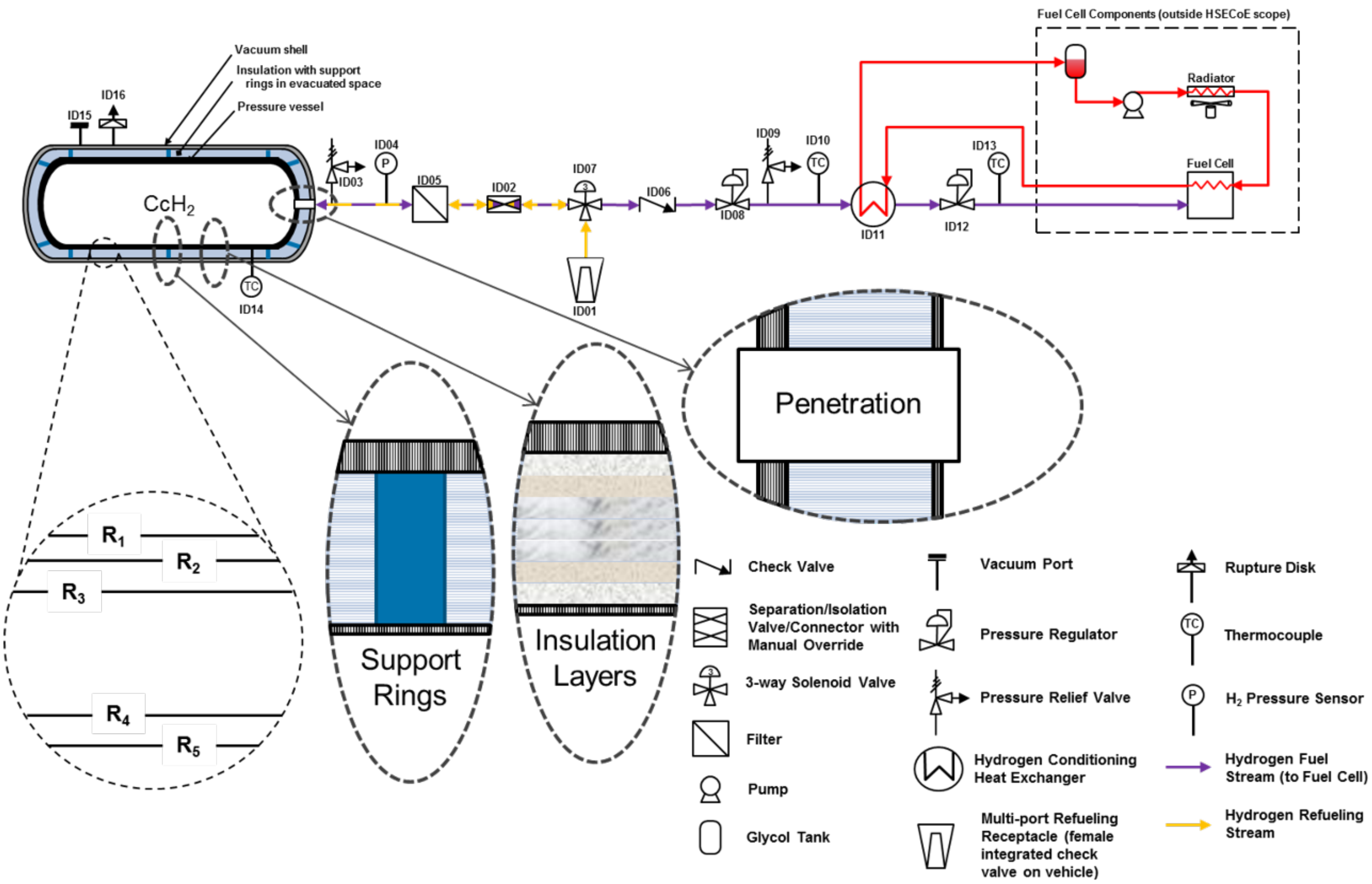


FIGURE 3. Hydrogen system model diagram

TABLE 2. Cost Estimate for Integrated Hydrogen Storage System

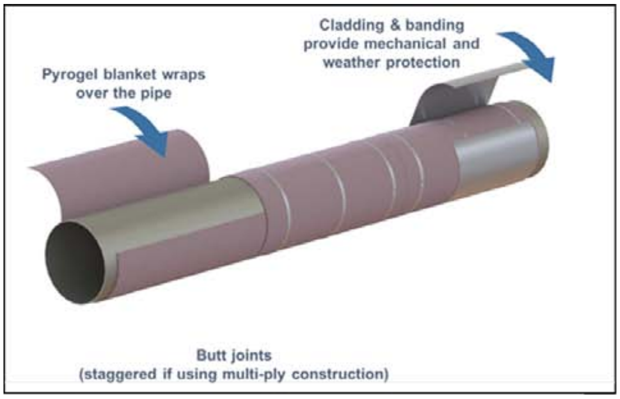
Component	Estimate Cost	Comments
Tank – PV Liner	$199.50	Aluminum liner
Tank – CF Wrap	$1,397.28	Carbon fiber wrap
Tank – Insulation and Vacuum Vhamber	$100.09*	Integrated insulation system (place holder)
Tank – Al Shell	$66.07	2 mm thick outer aluminum shell
Balance of Plant	$969.52	Full BOP connecting the CcH2 tank and the vehicle's fuel cell
Total System Estimate	$2,732.45	Total cost estimate as of 6/30/2017

*Note that this value will change with each iteration of the integrated insulation system throughout the project.
PV – pressure vessel ; CF – carbon fiber; BOP – balance of plant

CONCLUSIONS AND UPCOMING ACTIVITIES

The work completed this past year has identified potential insulation materials, initiated modeling for cryogenic tank heat leak elements, identified leading candidate material options for each element of heat transmission and developed a general model for the overall hydrogen integrated system. Upcoming activities include the following:

- Complete data mining of cryostat data libraries for material data relevant to development of the integrated cryogenic hydrogen storage system.
- Complete the thermal analysis model and perform a parametric study of the leading hydrogen storage designs.
- Initiate component testing of insulation material and tanks.
- Continue development of vacuum stability protocol for component testing.



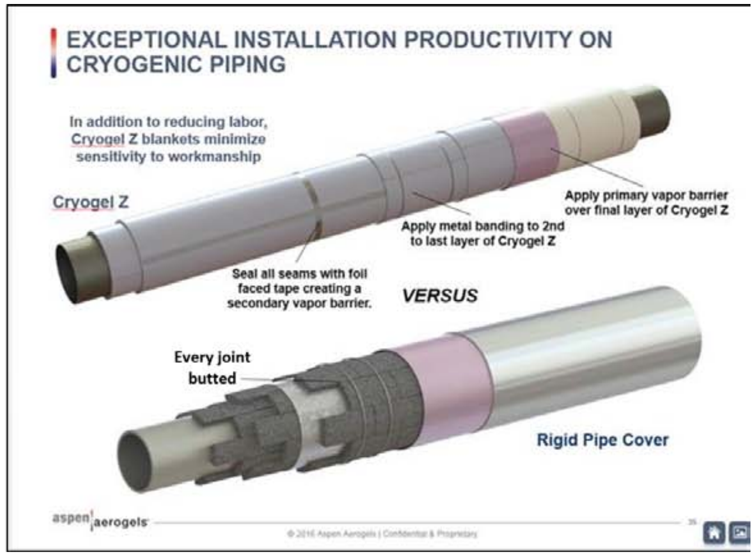


FIGURE 4. Potential wrapping schemes for aerogel-type material

- Update the system concept based on the parametric study results, the component thermal testing, and the integrated insulation system cost analysis.

REFERENCES

1. https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf