



Project 099 Conceptual Analysis of Cryogenic Hydrogen Distribution to Airports

Washington State University

Project Lead Investigator

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University Participants

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- P.I.: Dr. Jacob Leachman
- FAA Award Number: 13-C-AJFE-WaSU-050
- Period of Performance: September 18, 2024, to September 17, 2025
- Tasks:
 1. Contribute to the State of the Technology Analysis considering current efficiencies, realistic 5-year efficiencies, and ideal/limiting efficiencies
 2. Site Selection Analysis to supplement/complement the ongoing National Laboratory of the Rockies (NLR) study
 3. Cryogenic hydrogen effects on demand modeling
 4. Cryogenic hydrogen fueling analysis including needs for technology development
 5. Cryogenic hydrogen infrastructure sizing estimates
 6. Cryogenic hydrogen infrastructure safety analysis

Project Funding Level

The Federal Aviation Administration (FAA) provided \$199,910 in funding. Airbus Americas is the cost share partner, partnering with NLR for the previous infrastructure study and investing over \$1M in WSU's HYPER Laboratory over the last couple years.

Investigation Team

Jacob Leachman, PI, Washington State University (WSU)
Kazunori Nagasawa, co-PI, National Laboratory of the Rockies (NLR)
Kyle Appel, Research Scientist, Washington State University – Responsible for conducting the research under all tasks
Justin Bracci, Hydrogen Delivery Scenario Analysis Model (HDSAM) modeling, National Renewable Energy Laboratory – Conducted HDSAM modeling under Tasks 2 and 3

Project Overview

This project partners with an existing project funded by the FAA at the NLR to analyze gaseous hydrogen delivery to airports. The goal of this project is to add corresponding cryogenic hydrogen infrastructure analysis to a previous study conducted at the NLR. This previous study, sponsored by the FAA, investigated hydrogen implementation at the Seattle-Tacoma International Airport (SEA), Portland International Airport (PDX), San Francisco International Airport (SFO), and Los Angeles International Airport (LAX), primarily focusing on gaseous hydrogen delivery and conducting technoeconomic, emissions, safety, and job analysis. NLR, WSU, and FAA agreed to this ASCENT project to complement the previous study by evaluating cryogenic hydrogen implementation. The following specific objectives were pursued:





1. Contribute to the State of the Technology Analysis by reviewing conceptual hydrogen delivery pathways to airports including liquid hydrogen tankers, trains, and liquid and or cryogenic gaseous pipelines. The analysis considered current efficiencies, realistic achievable efficiencies for technologies developed in the next five years, and ideal/limiting efficiencies.
2. Site Selection Analysis for suitability to cryogenic hydrogen deliveries. The site selection analysis was limited to no more than three sites from the current NLR study for ease of comparison. The analysis applied the realistic technology delivery pathways identified in the prior objective to the sites with information to supplement/complement the ongoing NLR study.
3. Cryogenic hydrogen effects on demand modeling. This considered the effects of boil-off and transfer losses of cryogenic hydrogen and the effects on demand.
4. Cryogenic hydrogen fueling analysis including needs for technology development. This objective considered needs for cryogenic technology development and interviewed key industrial players to verify the technology development needs.
5. Cryogenic hydrogen infrastructure sizing estimates. This objective considered differences in sizing/scaling of cryogenic hydrogen infrastructure for refueling stations relative to gaseous hydrogen and applying these to airport infrastructure.
6. Cryogenic hydrogen infrastructure safety analysis relevant to codes and standards. WSU considered the American Institute of Aeronautics and Astronautics (AIAA) and the National Fire Protection Association (NFPA) hydrogen safety codes specific to cryogenic hydrogen for setback and other safety requirements.

Task 1 – Contribute to the State of the Technology Analysis Considering Current Efficiencies, Realistic 5-year Efficiencies, and Ideal/Limiting Efficiencies

Washington State University

Objective

The objective of this task is to contribute to the State of the Technology Analysis by reviewing conceptual hydrogen delivery pathways to airports including liquid hydrogen tankers, trains, and liquid and or cryogenic gaseous pipelines. The analysis considered current efficiencies, realistic achievable efficiencies for technologies developed in the next five years, and ideal/limiting efficiencies.

Research Approach

An investigation into the state of cryogenic hydrogen technology was conducted through a literature review, exploring conceptual hydrogen delivery pathways for airports. Table 1 was created to compare the conceptual pathways discussed in previous studies. Based on the results of the literature review, delivery pathways of liquid hydrogen (LH₂) ships, rails, and cryogenic/cryo-compressed pipelines should be analyzed in Task 2.

Table 1. Previous hydrogen delivery pathway studies found in the literature.

Author	Year	Airport	LH ₂ Ship	LH ₂ Train	LH ₂ Truck	Cryo-Pipeline	Onsite Liquefaction
Brewer [1]	1975	San Francisco	x	✓	✓	✓	✓
Boeing and Nasa [2]	1976	O'Hare	x	x	x	x	✓
Alder [3]	1987	Zurich	x	x	x	x	✓
Gretz [4]	1994	Conceptual	✓	x	x	x	x
Sefain [5]	2006	Conceptual	x	x	x	✓	✓
Stadler [6]	2014	Conceptual	✓	x	✓	x	x
Amy [7]	2019	Conceptual	x	x	x	x	✓



Author	Year	Airport	LH ₂ Ship	LH ₂ Train	LH ₂ Truck	Cryo-Pipeline	Onsite Liquefaction
Clean Sky 2 JU and FCH 2 JU [8]	2020	Conceptual	x	x	✓	x	✓
Marksel [9]	2020	Tromso	x	x	✓	x	✓
ATI-ACI [10]	2021	Conceptual	x	x	✓	✓	✓
Alexandrou [11]	2022	Toulouse Blagnac	x	x	✓	x	✓
Hoelzen [12]	2022	Conceptual	✓	x	✓	x	✓
Degirmenci [13]	2023	Conceptual	✓	✓	✓	✓	✓
Dijk [14]	2024	Rotterdam	✓	x	✓	x	✓

Relevant metrics for current, 5-year, and limiting efficiencies for cryogenic hydrogen technologies were recorded as part of the literature review. Efficiencies are defined differently for storage, liquefaction, or cryo-compression. For hydrogen storage efficiency is defined by boil-off losses, which is hydrogen unutilized due to venting or transfers. This is also associated with a heat leak entering the tank that causes a normal background boil-off rate. The efficiency for hydrogen liquefaction is defined by the energy required to liquefy one kilogram of hydrogen, expressed as the Specific Energy Consumption (SEC) in kWh/kg. Cryo-compressed hydrogen efficiency can be measured by SEC required to compress and cool the hydrogen or by heat loss of the pipeline. These metrics are used in Task 2 to predict the levelized cost of hydrogen (LCOH) for each conceptual pathway with the advancement of technologies and scaling. The metrics are shown in Table 2.

Table 2. Current, 5-year, and limiting efficiencies for truck, rail, marine, cryo-compressed pipelines, and onsite liquefaction.

	Truck	Rail	Marine	Onsite Liquefier	Cryo-compressed pipeline
Current Losses	3.0 wt% [15]	1.0 wt% [16]	1.0 wt% [16]	-	-
5-year Losses	0.3 wt% [16]	0.3 wt% [16]	0.3 wt% [16]	-	-
Limiting Losses	0 %	0 %	0 %	-	-
Current Power Requirement	-	-	-	12.3 kWh/kg [17]	6.42 kWh/kg [18]
5-year Power Requirement	-	-	-	6.7 kWh/kg [17,19]	5.62 kWh/kg [18]
Limiting Power Requirement	-	-	-	2.98 kWh/kg [20]	-
Current Heat Leak to Fluid	300-400 W	300-400 W	300-400 W	-	1.0 W/m [21]
5-year Heat Leak to Fluid	126-168 W [22]	126-168 W [22]	126-168 W [22]	-	0.42 W/m [22]
Limiting Heat Leak to Fluid	0 W	0 W	0 W	-	0 W/m

Milestone

This task is complete and documented in a draft NLR report.



Major Accomplishments

Literature revealed with analyzed conceptual cryogenic hydrogen delivery pathways and estimated efficiency metrics for current, 5-year, and limiting cryogenic hydrogen technologies.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.

Student Involvement

None.

Plans for Next Period

None. The scope of work will be completed in December 2025 with an NLR report in progress for publication.

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Task 2 – Site Selection Analysis to Supplement/Complement the Ongoing NLR Study

Washington State University, National Laboratory of the Rockies

Objective

The objective of this task is to perform site selection analysis for suitability to cryogenic hydrogen deliveries. The site selection analysis was limited to no more than three sites from the previous NLR study for ease of comparison. The analysis applied the realistic technology delivery pathways identified in the prior objective to the sites with information to supplement/complement the ongoing NLR study.

Research Approach

HDSAM¹ is used to estimate the LCOH for the hydrogen delivery pathways. The technoeconomic analysis was conducted by Justin Bracci (NLR) utilizing the pathways, assumptions, and metrics generated in Task 1. The analysis includes conceptual pathways to deliver cryogenic hydrogen to the SEA, PDX, SFO, and LAX independent of location. Truck tanker and gaseous pipeline pathways assume hydrogen production and liquefaction is 50 km from any one of the airports. The rail tanker pathway assumes production and liquefaction are 1,000 km from the airport with last mile trucking from a rail spike near the airport. The ocean tanker pathways assume production and liquefaction are 10,000 km from the airport with last mile trucking from a marine port to the airport. In the analysis different station throughput capacities are used, evaluating the effect of scale on dispensing cost. The effect of technology advancement is analyzed utilizing the metrics of current, 5-year, and limiting efficiencies. The results of the analysis are shown in Figure 1 with 80% utilization and throughput capacity of 6, 12, and 24 metric tonnes per day (MTPD) for all delivery pathways. LCOH is shown on the y-axis and delivery method on the x-axis. Based on the assumptions made, the plot shows that delivering LH₂ via truck tankers currently yields the lowest LCOH, with onsite production and liquefaction as a close second lowest. For both the 5-year estimate and limiting efficiencies, the LCOH from rail and ocean tankers is less than that of truck tankers.

¹ <https://hdsam.es.anl.gov/index.php?content=hdsam>

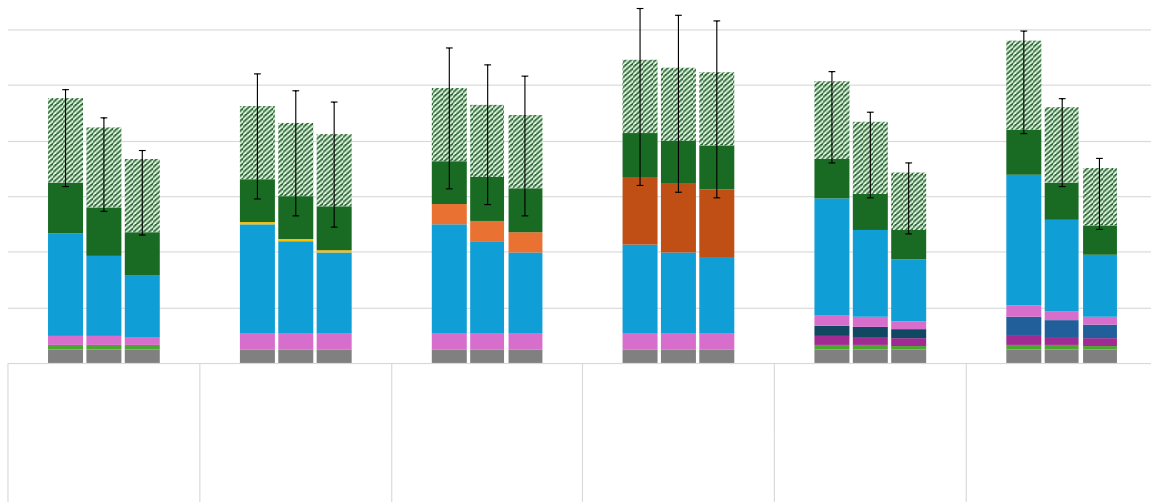


Figure 1. Results of Task 2 showing six delivery methods for LH₂, 80% utilization of the refueling station, and current/5-year/limiting losses and efficiencies.

Milestones

This task is complete.

Major Accomplishments

Levelized the cost of hydrogen estimates obtained via modeling in HDSAM by Justin Bracci and various altered assumptions and delivery pathway development. Effects of future technological development and scaling of LH₂ usage on LCOH are included.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.

Student Involvement

None.

Plans for Next Period

None. The scope of work will be completed in December 2025 with an NLR report in progress for publication.

Task 3 – Cryogenic Hydrogen Effects on Demand Modeling

Washington State University

Objective

The objective of this task is to identify the cryogenic hydrogen effects on demand modeling. This considered the effects of boil-off and transfer losses of cryogenic hydrogen and the effects on demand.



Research Approach

Using HDSAM, sensitivity studies are conducted evaluating the effect of boil-off and transfer losses, SEC of liquefaction, and capital cost of liquefaction plants on LCOH. The results are shown in Table 3.

Table 3. Sensitivity analysis on the levelized cost of hydrogen (LCOH) with different boil-off and liquefaction parameters for liquid hydrogen (LH₂). SEC: Specific Energy Consumption.

Scenario #	Delivery Method	Altered parameter	Parameter % change	LCOH % change	LCOH % / Input %
3.1	LH2 Truck Tanker	Liquefier SEC	-45.53	-7.28	0.160
3.1	LH2 Truck Tanker	Liquefier capital cost	-9.99	-2.20	0.220
3.1	LH2 Truck Tanker	LH2 unloading losses	-23.08	-2.98	0.129
3.1	LH2 Truck Tanker	Truck LH2 boil-off rate	-66.67	-0.69	0.010
3.5	LH2 Rail Tanker	LH2 unloading losses	-23.08	-5.69	0.247
3.5	LH2 Rail Tanker	Rail LH2 boil-off rate	-70.00	-0.51	0.007
3.6	LH2 Marine Tanker	LH2 unloading losses	-23.08	-5.78	0.250
3.6	LH2 Marine Tanker	Marine LH2 boil-off rate	-70.00	-8.04	0.115

Additionally, a numerical model which was previously validated and used to predict boil-off losses for in-service LH₂ tanks, was used to predict the number of tanks required to supply airport throughput. The model was used to evaluate single spherical tanks that would only be refilled once per day, sized to fit the airport throughput capacities of 6, 12, and 24 MTPD. Vertical or horizontal cylindrical tanks were also modeled using 2-12 tanks in a storage system. The total losses and number of times the tanks required refilling over a 6-day period were predicted. Losses and number of fills are shown below in Figure 2 for horizontally oriented tanks.

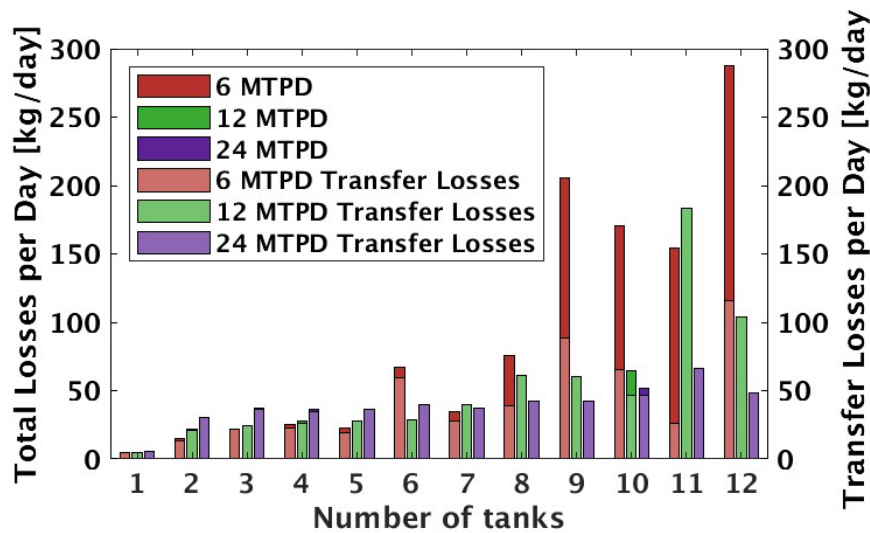


Figure 2. Average daily boil-off losses for a varied number of horizontal tanks for Cases 3.1-3.6 scenarios with 6, 12, and 24 metric tonnes per day (MTPD) refueling capacity.

Milestones

This objective is complete.



Major Accomplishments

The sensitivity of the LCOH is evaluated by altering boil-off and transfer losses, liquefaction SEC, and liquefaction capital cost for scenarios 3.1, 3.5, and 3.6. Hydrogen losses and tank filling requirements are predicted by a numerical model.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.

Student Involvement

None.

Plans for Next Period

None. The scope of work will be completed in December 2025 with an NLR report in progress for publication.

Task 4 – Cryogenic Hydrogen Fueling Analysis Including Needs for Technology Development

Washington State University

Objective

The objective of this task is to perform cryogenic hydrogen fueling analysis including needs for technology development. This objective considers needs for cryogenic technology development and during this task, key industrial players were interviewed to verify the technology development needs.

Research Approach

Analysis of current liquid hydrogen refueling technologies was conducted through literature review. Several technologies were identified that require advancement before commercial use in airports.

- High efficiency hydrogen production
- High efficiency cooling technologies
- Boil-off management systems
- LH₂ pumps
- LH₂ hydrant systems
- Mobile refuelers
- Mobile refueler safety devices
- Standardized refueling procedures

Industry partners including ZeroAvia, Airbus, and Joby Aviation were interviewed for their perspective on the technological advancement needed for LH₂ implementation. As part of this interview, a new list containing technological advancements industry believes is needed was created.

- LH₂ transportation and logistics
- Boil-off gas capture
- Liquefaction technologies
- Operational study of interim LH₂ integration
- Pumps and heat exchangers for refueling control
- Zero venting transfer line chill down
- Refueler sizing
- Advanced leak detection
- Easily manageable transfer lines



- Onsite production and liquefaction efficiency
- Hydrogen vent stack burn-off
- Standardized refueling components
- LH₂ storage tank materials and designs

Milestones

This objective is complete.

Major Accomplishments

Several technologies have been identified by industry for improvement to enable LH₂ integration with airport infrastructure.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.

Student Involvement

None.

Plans for Next Period

None. The scope of work will be completed in December 2025 with an NLR report in progress for publication.

Task 5 – Cryogenic Hydrogen Infrastructure Sizing Estimates

Washington State University

Objective

The objective of this task is to complete cryogenic hydrogen infrastructure sizing estimates. This objective considered differences in sizing/scaling of cryogenic hydrogen infrastructure for refueling stations relative to gaseous hydrogen and applying these to airport infrastructure.

Research Approach

Using the estimated number of tanks required for 6, 12, and 24 MTPD throughput capacity, the space required for storage is estimated. This estimation requires use of the NFPA-2 hydrogen codes and local Washington and California state codes for the minimum distance between LH₂ storage tanks. Setback distances are included for the tanks. Three example layouts for LH₂ storage tanks are shown in Figure 3 with horizontal tanks arrayed in one or two rows or as vertical tanks. The spatial requirement for singular spherical tanks or equivalent gaseous hydrogen storage tubes was also estimated. Table 4 shows the comparison of the different hydrogen storage methods.

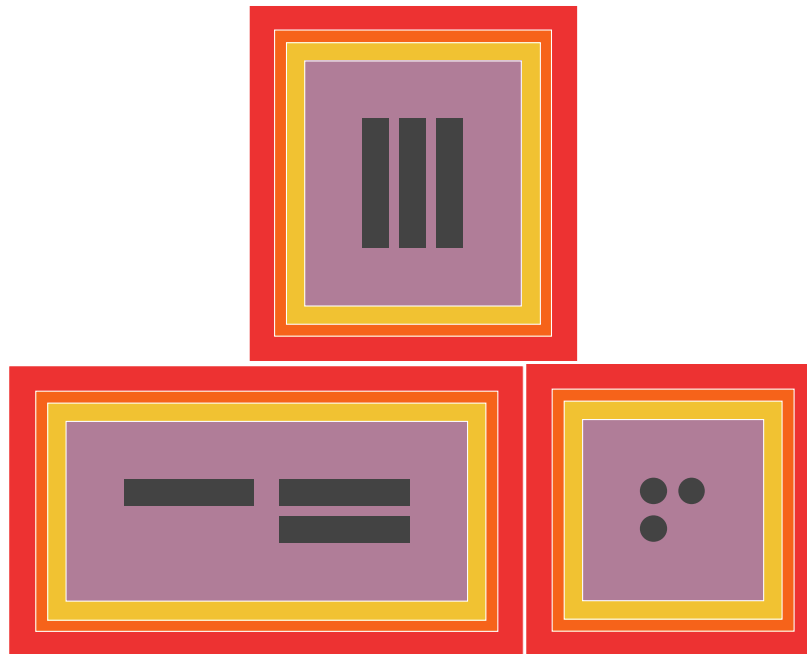


Figure 3. Single row of horizontal LH₂ tanks (top), two rows of horizontal LH₂ tanks (bottom left), two rows of vertical LH₂ tanks (bottom right).

Table 4. Spatial estimate for 6, 12, and 24 metric tonnes per day (MTPD) throughput with different LH₂ storage options. GH₂: gaseous hydrogen.

Refueling Capacity	One Spherical LH ₂	Horizontal One/Two Line LH ₂	Vertical LH ₂	GH ₂ Tube Array
6 MTPD	1397 m ²	2017 m ² /2567 m ²	1459 m ²	2380 m ²
12 MTPD	1533 m ²	2710 m ² /2896 m ²	1646 m ²	4369 m ²
24 MTPD	1695 m ²	3861 m ² /3877 m ²	2433 m ²	6750 m ²

Milestones

This objective is complete.

Major Accomplishments

Spatial requirements for multiple LH₂ tank configurations and one array for gaseous hydrogen (GH₂) have been estimated as shown in Table 4.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.



Student Involvement

None.

Plans for Next Period

None. The scope of work will be completed in December 2025 with an NLR report in progress for publication.

Task 6 – Cryogenic Hydrogen Infrastructure Safety Analysis

Washington State University

Objective

The objective of this task is to perform cryogenic hydrogen infrastructure safety analysis relevant to codes and standards. WSU considered the AIAA and NFPA hydrogen safety codes specific to cryogenic hydrogen for setback and other safety requirements.

Research Approach

Setback distance analysis was conducted as part of Task 5 to evaluate infrastructure required for LH₂ implementation at airports. Extensive safety analysis was conducted in the previous NLR report. The final report published with NLR may consider the following potential safety analyses:

- Excess fuel reserves
- Additional space required for LH₂ pumps, plumbing, and vaporizers
- A high-level overview of explosion distancing
- Needs for LH₂ aircraft fueling with passengers aboard
- Latest activities in LH₂ codes and standards

Milestones

This objective will be completed in December 2025.

Major Accomplishments

Spatial requirements are estimated and include NFPA-2 guidelines for LH₂ storage tank setbacks.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.

Student Involvement

None.

Plans for Next Period

None. The scope of work will be completed in December 2025 with an NLR report in progress for publication.

Summary and Recommendations for Future Research

This study partnered with NLR to analyze conceptual liquid hydrogen delivery scenarios to airports, expanding on a prior study completed by NLR for gaseous hydrogen distribution. SEA, PDX, SFO, and LAX were considered for refueling of liquid hydrogen aircraft at 6, 12, and 24 MTPD. Several new conceptual delivery pathways were considered that had not previously been analyzed in the literature. Modifications were made to the HDSAM tool developed by the U.S. Department of Energy for uniform comparison between pathways. A recently developed boil-off model was adapted to analyze losses from on-site storage and filling for various numbers and configurations of on-site tanks. An industrial survey for



technology development needs was conducted, identifying high-efficiency hydrogen production and cooling technologies as the primary needs. A safety codes analysis completed for the NLR gaseous hydrogen study was extended to liquid hydrogen.

Several opportunities for technology advancement were identified during this program and warrant consideration for future research. High-efficiency cooling technologies to maintain liquid hydrogen in a sub-cooled state to eliminate boil-off would increase technology performance and reduce losses for all pathways considered. These cooling technologies, also known as cryocoolers, reduce losses from any cryogenic fuel (hydrogen or natural gas) and have yet to be comprehensively surveyed for terrestrial applications to determine a design specification, including price points, capacities, and efficiencies.