Preliminary Investigation

Caltrans Division of Research, Innovation and System Information

Current Availability and Feasibility of Mobile, Fast Fill Hydrogen Refueling Stations

Requested by
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August 12, 2019

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Executive Summary

Background

The transportation sector in the United States accounts for 28% of U.S. energy consumption and generates 34% of energy-related greenhouse gas (GHG) emissions. While petroleum remains the predominate fuel source, alternative fuels such as compressed natural gas, hydrogen, and electricity/battery offer the potential for reduced emissions, reduced oil dependency and improved air quality [33]. In addition, massive adoption of zero-emission vehicles (ZEVs) is essential for California to meet air quality health requirements and climate driven greenhouse gas emissions targets in the future. After decades of research and development, automakers have refined hydrogen fuel technology to the point where they can commercially produce zero-emission cars powered by hydrogen fuel. However, ZEV success depends on a robust refueling infrastructure. The dilemma is whether to first build out the refueling infrastructure or wait until the demand for hydrogen fuel manifests itself.

In an effort to encourage the conversion to hydrogen fueled vehicles, the State of California has taken the lead, beginning with The California Hydrogen Highway Network (CaH2Net) initiated in April of 2004 by Executive Order S-07-04 under Governor Arnold Schwarzenegger. The goal was to ensure hydrogen fueling stations were in place to satisfy the demands of fuel cell and other hydrogen vehicle technologies being placed on California's roads. This goal was further reinforced by Governor Brown's issuance of an executive order in March 2012 to support and accelerate the market transition to ZEV. Executive Order B-16-12 was issued to "encourage the development and success of zero-emission vehicles." Lastly, the California State Legislature passed AB 739 in October 2017, establishing procurement targets to replace vehicles in the State fleets exceeding 19,000 pounds [5]. To satisfy legislative targets established by AB 739 and comply with the Executive Orders, the California Department of Transportation (Caltrans) has begun to procure light duty vehicles such as pickup trucks and street sweepers. Caltrans is also investigating the purchase of mobile hydrogen refuelers as a means to augment fueling their planned fleet of hydrogen vehicles, as well as strategically locating these refuelers to encourage private development of permanent stations.

The objective of this preliminary investigation is to review the state of the art as it pertains to hydrogen mobile refuelers. More specifically, this review will focus on the following topics, namely: (i) mobile refueling stations, including design, operation and maintenance; (ii) requirements to transport and store hydrogen fuel; (iii) safety standards for hydrogen refueling; and lastly (iv) best practices as related to hydrogen refueling in general. Based on this investigation, the findings are summarized, gaps or weaknesses in the findings are identified and future work to close these gaps are recommended. A bibliography is included which summarizes work reviewed here, as well as other applicable works. Following the bibliography are the detailed findings from this investigation, including a list of potential mobile refueler suppliers (as of this writing) and finally a summary of personal communications with people at different organizations involved in the implementation of hydrogen vehicles.

Summary of Findings

Based on a review of the work, the following findings or statement of facts are provided in response to the questions noted in the objective:

1) *Mobile Hydrogen Refuelers*

   a) The majority of the published work discusses permanent fueling stations in the United States. Limited discussion on the operation and maintenance of a mobile refueler was found in Heydorn (2013), Interreg (2019), Stancil (2018), Sun et al. (2014) and Zhiyong et al. (2014) [13,16,39,41,46].

   b) A total of four (4) mobile refuelers have been identified in the State of California since 2006. Three of the units were manufactured by Air Products and located in Placerville, Long Beach and San Francisco. The San Francisco unit operated by PG&E (18th and Harrison) was in service from 2006 – 2008. The Long Beach unit was in-service between October 2006 and March 2009 and the Placerville unit was only in service for 11 months from March 2010 to January 2011. Allegedly Honda operated a fourth unit in San Francisco, but details are sketchy. All were the old 35 MPa systems (5000 psi). None remain in service and it is unknown if any were replaced with a permanent station [23].

   c) Electricore of Valencia, CA is under contract with the US Department of Energy to: (i) design and build an Advanced Hydrogen Mobile Fueler (AHMF); (ii) deploy the AHMF to support a network of hydrogen stations and vehicles in the United States; and (iii) gather and analyze fueling data for the National Renewable Energy Laboratory Technology Validation Team (See Attachment I).

   d) A European Organization (Interreg) consisting of Belgium, The Netherlands and Germany has developed a specification for a 35 MPa mobile refueler [16].

   e) There is a significant effort underway in Japan and China to implement mobile refuelers as documented by Zhiyong et al. and Sun et al. [41,46].

   f) As a result of an incident involving a mobile hydrogen refueler in 2018 and a permanent station in 2019, the Pacific Northwest National Laboratory has been retained to evaluate the safety of mobile hydrogen and fuel cell applications (mobile auxiliary power units, mobile fuelers, permanent stations, multi-cylinder trailer transport, refrigeration units, etc.) using the Hydrogen Safety Panel. The review will identify specific safety or code gaps and draft a report to summarize the status, offer conclusions and provide recommendations to improve safety for this type of mobile equipment. The report is expected to be released late 2019 [3].

   g) California AB 739 requires at least 15 percent of newly purchased vehicles with a gross vehicle weight rating of 19,000 pounds or more purchased by the Department of General Services for the state fleet shall be zero emission, beginning December 31, 2025. Note, that the legislation does provide a means to postpone these target dates if the Department cannot meet the needs of the State while meeting this requirement [5].

2) *Transportation / Storage Requirements*

   a) Moradi and Groth (2019) presented a review paper on hydrogen storage and delivery options. Safety and reliability of hydrogen infrastructure is a necessary enabling condition for public acceptance of these technologies and <u>any major accident involving hydrogen can be difficult to neutralize</u>. One of the recommendations in their paper was: selection of the delivery method should be based on regional specifications and potentials, demand, and economics [29].

   b) Mobile refuelers require specific approvals. Tanks on the mobile refueler will need to meet U.S. Department of Transportation (DOT) standards for moving flammable gases, either as pre-approved DOT tanks or special permit tanks. The Compressed Gas Association TB25 "Design Considerations for Tube Trailers," which has been incorporated by reference into 49 CFR 173.01, offers a solid starting point for planning to comply with DOT regulations. It should be used for performing analysis or performance testing. For composite tanks commonly used to store hydrogen, DOT standards require a full range of testing to verify integrity [14].

   c) SAE has published J2601 "Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles [39]. But as noted by Brown et al (2012) *Hydrogen station performance standards prescribed in SAE J2601 help to better describe actual station capacity through the understanding that refueling does not occur methodically over each 24 h period. Caution must be used to ensure that the SAE J2601 standards for 1 h and daily capacity are fully understood when comparing station designs. A model for the UCI Hydrogen Station shows the capability to dispense 28 kg in 1 h under ideal conditions. However, the station would then take nearly 24 h to recover before more fuel could be dispensed. Similarly, the model predicts a daily capacity of 35 kg per SAE J2601 specifications, but that capacity could not be repeated for consecutive days [4].*

3) *Safety Standards*

   a) A study by Lipman et al (2018) showed that despite positive responses from bus drivers operating hydrogen fueled buses, the overall response regarding the safety of these buses was neutral [24, 25].

   b) Moradi and Groth (2019) discussed hydrogen storage and delivery options. Safety and reliability of the hydrogen infrastructure is a necessary enabling condition for public acceptance of these technologies, as any major accident involving hydrogen can be difficult to neutralize. Among the recommendations provided are: (a) topics like pressure vessel's production cost, liner blistering issue, resistance to fire, contamination and leakage control, and large scale utilization of hydrogen have only preliminary studies, and need significant development; and (b) composite storage vessels reliability needs to be further improved, as damage mechanisms, inspection methods, and maintenance policies have yet to be determined [29].

   c) The US DOT (NHTSA) does not currently have an FMVSS regulation covering hydrogen vehicles. In the near future, NHTSA should adopt the phase 2 version of the UN GTR 13 regulation, and it will be published (after advertised notices of rulemaking) as an FMVSS regulation for hydrogen vehicles. In the meantime, vehicle OEMs self-certify their tanks and fuel systems to industry standards such as SAE J2579, CSA HGV 2, CSA HGV 3.1 and CSA HPRD 1. In Europe, vehicle OEMs achieve type approval to EC R79 and UN ECE R134 (UN ECE R134 is a regulation based on phase 1 of the UN GTR 13 – already adopted by the EU) [2].

d) Kurtz et al (2019) reviewed the engineering and deployment of modern hydrogen infrastructure, including the costs, benefits, and operational considerations (including safety, reliability, availability), as well as challenges to the scale-up of hydrogen infrastructure. The results identify hydrogen station reliability as a key factor in the expense of operating hydrogen systems [19].

e) Some of the major technical hurdles to large-scale hydrogen system commercialization are the low reliability, high maintenance costs, and limited availability of modern hydrogen stations [19]. For example, both Kodoth et al. (2018) and Sun et al (2014) stressed the importance of reducing the risk to external parties to ensure rapid widespread implementation. Kodoth et al, (2018) noted *Hydrogen, as a future energy carrier, is receiving a significant amount of attention in Japan. From the viewpoint of safety, risk evaluation is required in order to increase the number of hydrogen refueling stations (HRSs) implemented in* Japan [17,41].

f) The National Fire Protection Association (NFPA-2) provides fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas (GH2) form or cryogenic liquid (LH2) form. This code shall apply to the production, storage, transfer, and use of hydrogen in all occupancies. Depending on the Authorities Having Jurisdiction (AHJ), a performance based design approach can be used if the site does not meet NFPA-2 [32].

4) *Best Practices*

a) In California, local governments have the ultimate authority to approve or deny any project. Developing a hydrogen station can be time intensive, especially for the first station in a community. In an effort to reduce the time required to bring a hydrogen station on line, the Governor's Office (2015) has developed guidelines to reduce to time required for the development of hydrogen stations, including permitting, however the final approval is given by the AHJ (Authorities Having Jurisdiction) [10].

b) In general, the majority of papers reviewed discussed challenges associated with refueling small vehicles, although Sun et al. (2014) and Zhiyong et al. (2014) discussed challenges related to mobile refuelers in China, including potential failure mechanisms [41,46].

c) While hydrogen fuel cell buses have been successful demonstrated, it should be noted that the H2 fuel cell bus was typically smaller in capacity that the diesel counterpart. A standard diesel bus is approx. forty (40) ft in length and can seat 38 passengers. For the study conducted in Delaware, the hydrogen powered buses were only 22 foot in length and placed in operation as part of the University of Delaware shuttle bus system [34]. Another study conducted in Connecticut used a hydrogen powered bus that was forty foot in length, yet only carried thirty (30) seated passengers [7]. However, more recently Dixon et al (2011) claims a 12m (i.e., 40 foot) bus carrying 53 passengers was used in the 2010 Shanghai EXPO [8]. These studies imply the “production” associated with a hydrogen vehicle maybe reduced compared to its diesel counterpart.

d) Based on work by Weinert et al. (2006), refueling with a mobile hydrogen refueler results in the most expensive fuel option, approaching $30/kg [42]. However, from a capital perspective, it is the least expensive option. It should be noted these cost estimates do not include costs associated with a loss of production if there are fueling anomalies. No recent work cited a hard cost other than to claim it was reduced.

Gaps in Findings

Based on the work reviewed here, the following gaps for implementation were identified:

- Although the technology to develop a hydrogen vehicle is advancing, it is questionable whether the protocols and standards necessary to ensure the risks associated with hydrogen vehicles, including refueling, transport and storage are at an acceptable level. For example, a recent incident in Diamond Bar, CA points to a need for improved standards for the design and operation of mobile refuelers. In a review of the state of the art in safety and reliability analysis for the storage and transport technology for hydrogen, Moradi and Groth (2019) cited the lack of data and appropriate modelling paradigms for the entire fueling system, not just individual components [29]. This issue is also supported by Barilo (2018) [2].
- While several papers discussed the economic benefits of a mobile refueler, there have been few implementations. A major component of the high cost of hydrogen fuel is the low throughput. Unlike a gas station, the base load electrical power consumption for a hydrogen station is high due to maintaining the cooling block temperature when idle. Further work/planning is needed to increase throughput for a hydrogen station in concert with a mobile hydrogen refueler.
- Additional work is needed to investigate the time required to permit a permanent hydrogen station vs a mobile refueler. A feasibility study conducted for Vancouver indicated permitting a mobile refueler could be as long or longer than a permanent station which contradicts personal communications [14]. Barilo (2018), in a review of refueling stations in California noted that most stations are challenged to meet separation distances [2].
- No “standard specification” guiding the design, fabrication and operation of a 70 MPa mobile refueler was found.
- Regulations by which US DOT would certify a mobile refueler loaded with fuel are pending. Currently tanks are certified by the original equipment manufacturer (OEM).

Next Steps

The following steps are recommended to begin to close the gaps in findings listed above:

- Review the potential high fueling costs associated with a mobile refueler as well as the potential safety issues associated with fueling. Develop a deployment plan for mobile refuelers in a Caltrans Maintenance Yard that can service both Caltrans vehicles as well as private vehicles, thus increasing throughput and encouraging private development of a permanent station.
- Review the pending report from Pacific Northwest National Laboratory (PNNL) on the Diamond Bar and Santa Clara incidents and engage PNNL to develop standards for 70 MPa mobile fuelers, similar to Interreg [16].
- Investigate the application of performance-based design techniques for hydrogen (HPBD), as described in Chapter #5 of NFPA-2, to determine how HPBD can improve safety, while reducing the cost of hydrogen. For example, could a performance based approach be used to justify a reduced separation distance [2]? It is recommended a system approach be followed similar to the performance based seismic design methodology developed by PEER (Pacific Earthquake Engineering Research Center).

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Detailed Findings

Introduction

This section presents the results from a review of the technical literature pertaining to the design, operation, maintenance and fueling of hydrogen vehicles. Due to the limited number of papers found, the search was expanded to include permanent fueling stations as well. The search was performed using key words such as mobile refueler, mobile hydrogen refueler hydrogen refueler and variations of these terms. In an effort to assess the state of the art, only reports and papers published in the past decade were reviewed. Those references reviewed are classified according to one of the following categories:

Hydrogen Refueling Stations

Given the limited amount of work found in the technical literature, this group includes permanent as well as mobile hydrogen refueling stations. Papers found discussed the operation and maintenance of refueling stations.

Requirement to Transport and Store Hydrogen Fuel

Included in this category are papers discussing current and past requirements to transport and store hydrogen. Papers discussing improvements to the process, but not yet incorporated in the codes, are included in Best Practices.

Best Practices

Included in this category are works which document best practices, included new work proposed, but not yet codified. One such topic would be performance based design to site a refueling station.

Safety Standards for Hydrogen Refueling

As the title suggests, included in this category are papers that summarize current standards as well as proposed improvements to the current standards, as well as potential shortfalls.

Hydrogen Refueling Stations

An Assessment of the Near-Term Costs of Hydrogen Refueling Stations and Station Components

Jonathan X. Weinert and Timothy E. Lipman

ABSTRACT

Interest in hydrogen as a transportation fuel is growing in California. Plans are underway to construct a “Hydrogen Highway” network of stations across the state to stimulate fuel cell vehicle deployment. One of the key challenges in the planning and financing of this network is determining the costs of the stations. The purpose of this report is to examine the near-term costs of building hydrogen stations of various types and sizes.

The costs for seven different station types are analyzed with respect to size, siting factors, and operating factors. The first section of the report reviews the existing body of knowledge on hydrogen station costs. In the second section, we present hydrogen station cost data from the Compendium of Hydrogen Refueling Equipment Costs (CHREC), a database created to organize and analyze data collected from equipment suppliers, existing stations and literature. The third section of the report presents the Hydrogen Station Cost Model (HSCM), an engineering/economic model developed to analyze the cost of stations.

Based on the hydrogen station cost analysis conducted here, we conclude the following:

- Commercial scale hydrogen station costs vary widely, mostly as a function of station size, and with a range of approximately $500,000 to over $5 million for stations that produce and/or dispense 30 kg/day to 1,000 kg/day of hydrogen. Mobile hydrogen refuelers represent less expensive options for small demand levels, with lower capital costs of about $250,000.
- Existing hydrogen station cost analyses tend to under-estimate true station costs by assuming high production volume levels for equipment, neglecting station installation costs, omitting important station operating costs, and assuming optimistically high capacity factors.
- Station utilization (i.e. capacity factor) has the most significant impact on hydrogen price.
- Hydrogen fuel costs can be reduced by siting stations at strategic locations such as government-owned fleet yards and facilities that use hydrogen for industrial purposes.
- Hydrogen fuel costs ($/kg) are higher at small stations (10-30 kg/day) that are burdened with high installation costs and low utilization of station infrastructure.
- Energy stations that produce electricity for stationary uses and hydrogen for vehicles have the potential for low-cost hydrogen due to increased equipment utilization. Costs of energy stations are uncertain because few have been built.

CSULA Hydrogen Refueling Facility Performance Evaluation and Optimization

David Blekhman

Executive Summary

Throughout its history, Cal State LA has been in the forefront of advanced energy and transportation technologies. The station is located at the intersection of two major highways in Los Angeles region and has a convenient access. It is capable of producing up to 60 kg/day and can fuel 15-20 vehicles per day. Cal State LA had partnered with DOE to establish a robust station operation and performance data collection program. This consisted of equipping the station with additional instrumentation and collecting fueling performance data for several years. The data was further furnished to NREL for processing and agglomeration with data from other stations. In addition to fueling, maintenance and failure events were shared as well as hydrogen purity reports. The station has also undergone several upgrades in fueling protocols and hardware for improved performance and code compliance.

Goals and Accomplishments

The project was a success accomplishing all of the goals proposed to DOE. The project objectives were to test, collect data, and validate hydrogen-refueling architecture deployed at Cal State LA and its individual components in a real-world operating environment. The performance evaluations data was provided quarterly to the National Fuel Cell Technology Evaluation Center at NREL. Utilizing fiscal diligence, the team was able to expand the data collection by two years. More specifically,

- the existing data acquisition setup (DAQ) was utilized to evaluate the initial station performance with existing capability;
- utilizing the data collected, the team identified limitations of the DAQ and additional instrumentation was acquired and installed;
- hydrogen quality was considered excellent for an electrolyzer based station, based on regular hydrogen purity tests; and
- lastly, the station provided regular collection and reporting of data collected for analysis and agglomeration to NREL.

Status of Existing Hydrogen Refueling Stations

Andris R. Abele

The California Energy Commission awarded a contract to the South Coast Air Quality Management District to develop, release, and manage a competitive request for proposals; develop agreements; and fund companies that refurbish and upgrade existing, publicly accessible hydrogen refueling stations. This report assessed the current state of selected hydrogen refueling stations that may be candidates for upgrades, including increased capacity to address projected fuel cell vehicle growth, higher pressure 700 bar (10,000 pounds per square inch [psi]) vs. 350 bar (5,000 psi) onboard vehicle storage systems, point-of-sale systems, and other related equipment. Interviews and site visits were conducted with the owners, operators, and technology suppliers of existing hydrogen refueling stations to gather information and document the design, equipment, operating and maintenance experience, and potential for upgrades for each station. The existing hydrogen refueling stations that were included in this study are listed in the executive summary. The California Energy Commission and the South Coast Air Quality Management District will draw on this report in evaluating competitive bids submitted for refurbishment and upgrades to existing, publicly accessible hydrogen refueling stations

Research on the design of hydrogen supply system of 70 MPa hydrogen storage cylinder for vehicles

Ying Wang, Xingtao Dai, Hongxin You, Mengchun Gao

Abstract: A hydrogen supply system of 70 MPa hydrogen storage cylinder on vehicles is designed, in which a compressor is proposed to use the new type of ion compressor. The system is simulated statically by Aspen Plus. Meanwhile, during the process of hydrogen charged from the third-stage high-pressure hydrogen storage tank to the hydrogen storage cylinder on vehicles, the dynamic variety of the third-stage high-pressure hydrogen storage tank is simulated dynamically by Aspen HYSYS Through the simulation, obtaining the results that there are difference between theoretical calculation and simulation for the volume of third-stage high-pressure hydrogen storage tank and the average volume flow of hydrogen in a third-stage high-pressure hydrogen storage tank varies with its pressure and volume. By comparing the results of Aspen Plus simulation and Aspen HYSYS simulation, there are some differences. The designed system can be applied to hydrogen stations and any operating conditions involving the supply hydrogen.

Quantitative analysis of a successful public hydrogen station

Tim Brown, Shane Stephens-Romero, G. Scott Samuelsen

Reliable hydrogen fueling stations will be required for the successful commercialization of fuel cell vehicles. An evolving hydrogen fueling station has been in operation in Irvine, California since 2003, with nearly five years of operation in its current form. The usage of the station has increased from just 1000 kg dispensed in 2007 to over 8000 kg dispensed in 2011 due to greater numbers of fuel cell vehicles in the area. The station regularly operates beyond its design capacity of 25 kg/day and enables fuel cell vehicles to exceed future carbon reduction goals today. Current limitations include a cost of hydrogen of $15 per kg, net electrical consumption of 5 kWh per kg dispensed, and a need for faster back-to-back vehicle refueling.

The UCI Hydrogen Station has successfully dispensed over 25,000 kg of fuel to over 8900 vehicles in the course of 5 years without any safety issues. This does not minimize the potential hazard associated with flammable gas stored at high pressure, but does indicate that the hydrogen vehicle refueling process can be safe through a judicious safety protocol, much as gasoline refueling safety is routine and transparent for drivers today.

Base load electrical power consumption at the UCI Hydrogen Station is a substantial cost and greenhouse gas factor when throughput is low. Electricity used to maintain cooling block temperature when idle, provide lighting, and power control equipment is a fixed penalty that is best mitigated by increasing throughput. The actual electricity consumed to pressurize hydrogen from 1.3 MPa (liquid vapor pressure) to 35 MPa or 70 MPa ranges from 2.5 to 2.7 kWhr/kg.

Hydrogen generation, distribution, and dispensing costs for UCI's small (25 kg/day), liquid supplied hydrogen station are significantly higher on a cost-per-mile basis than equivalent gasoline fuel. In 2011, hydrogen cost, not including station management, land, or insurance was $14.95 per kg. Assuming FCV efficiency is 2.2 times higher than a standard vehicle (e.g. Honda FCX Clarity compared to Honda Accord per U.S. Department of Energy), then the UCI Hydrogen Station cost equated to gasoline priced at $6.79 per gallon. Next generation distribution and dispensing technology combined with greater station throughput aims to achieve parity with gasoline on a per mile basis. Given the domestic sourcing of hydrogen and the geo-economics and finite resources associated with petroleum, the future cost of hydrogen per mile is envisioned to be less than that of gasoline with an increasing margin of difference.

Hydrogen station performance standards prescribed in SAE J2601 help to better describe actual station capacity through the understanding that refueling does not occur methodically over each 24 h period. Caution must be used to ensure that the SAE J2601 standards for 1 h and daily capacity are fully understood when comparing station designs. A model for the UCI Hydrogen Station shows the capability to dispense 28 kg in 1 h under ideal conditions. However, the station would then take nearly 24 h to recover before more fuel could be dispensed. Similarly, the model predicts a daily capacity of 35 kg per SAE J2601 specifications, but that capacity could not be repeated for consecutive days

Modeling Hydrogen Refueling Infrastructure to Support Passenger Vehicles

Matteo Muratori, Brian Bush, Chad Hunter and Marc W. Melaina

Abstract:

The year 2014 marked hydrogen fuel cell electric vehicles (FCEVs) first becoming commercially available in California, where significant investments are being made to promote the adoption of alternative transportation fuels. A refueling infrastructure network that guarantees adequate coverage and expands in line with vehicle sales is required for FCEVs to be successfully adopted by private customers. In this paper, we provide an overview of modelling methodologies used to project hydrogen refueling infrastructure requirements to support FCEV adoption, and we describe, in detail, the National Renewable Energy Laboratory's scenario evaluation and regionalization analysis (SERA) model. As an example, we use SERA to explore two alternative scenarios of FCEV adoption: one in which FCEV deployment is limited to California and several major cities in the United States; and one in which FCEVs reach widespread adoption, becoming a major option as passenger vehicles across the entire country. Such scenarios can provide guidance and insights for efforts required to deploy the infrastructure supporting transition toward different levels of hydrogen use as a transportation fuel for passenger vehicles in the United States.

Comparison of conventional vs. modular hydrogen refueling stations, and on-site production vs. delivery

Ethan S. Hecht and Joseph Pratt

To meet the needs of public and private stakeholders involved in the development, construction, and operation of hydrogen fueling stations needed to support the widespread roll-out of hydrogen fuel cell electric vehicles, this work presents publicly available station templates and analyses. These 'Reference Stations' help reduce the cost and speed the deployment of hydrogen stations by providing a common baseline with which to start a design, enable quick assessment of potential sites for a hydrogen station, identify contributors to poor economics, and suggest areas of research. In the near term, delivered hydrogen results in a lower cost of hydrogen compared to on-site production via steam methane reforming or electrolysis, although the on-site production methods have other advantages. Modular station concepts including on-site production can reduce lot sizes from conventional assemble-on-site stations. As noted in Figure ES-1 of the report, the price decreases with increased throughput.

February 11, 2018, Tube Trailer Module Hydrogen Release and Fire, Diamond Bar, California. Report # HMD18FR001

Paul L. Stancil

Incident Summary

On February 11, 2018, about 1:15 p.m. PST, a fire occurred during transportation of an Air Products and Chemicals, Inc. (Air Products) 2014 Mack CXU613 tractor, fleet number 325512, in combination with a 2015 Cheetah Chassis, fleet number 794274, California plate 4NG3315, on which was mounted a CT-250 tube trailer module, fleet number 430003. The tube trailer module contained 25 non-DOT specification fully wrapped carbon fiber reinforced aluminum lined (CFFC) cylinders, 24 of which were fully loaded with 240 kg of UN1049 compressed hydrogen. The module caught fire on Golden Springs Drive, near Brea Canyon Road in Diamond Bar, California. Pressure relief devices activated on 12 of the cylinders, releasing an estimated 120 kg of hydrogen that was consumed in the fire. After the fire was extinguished, Air Products technicians vented 120 kg of hydrogen to depressurize the remaining 12 cylinders. The cylinders themselves were not breached from the fire exposure. Weather at the incident scene was clear, the temperature was 75℉ and winds were out of the southwest at 5-8 mph. No injuries were reported. Based on the size of the evacuation area, the Los Angeles County Fire Department estimated that 500 to 1,000 persons were evacuated from the adjacent business district and about 900 to 1,000 nearby residents were also evacuated. Equipment damages were estimated at about $175,000.

The cylinders were manufactured by Structural Composite Industries, subsidiary of Worthington Industries (SCI/Worthington) of Pomona, California, under Department of Transportation (DOT) special permit DOT-SP-14576. FIBA Technologies, Inc. (FIBA), a registered inspector and cylinder testing facility, performed a 5-year requalification inspection of the cylinders six weeks before the incident. The load of compressed hydrogen originated from the Air Products Wilmington, California, terminal and was destined for the California South Coast Air Quality Management District, 21865 Copley Drive, Diamond Bar, California. The vehicle was operated by an Air Products employee. The tube trailer module was to be used to supply a hydrogen fuel cell vehicle fueling station

https://www.youtube.com/watch?v=lE4RmMvlIVw&feature=share

Hydrogen Transport and Storage Requirements

Regulations, Codes, and Standards (RCS) Template for California Hydrogen Dispensing Stations

C. Rivkin, C. Blake, R. Burgess, W. Buttner, and M. Post

Executive Summary

The purpose of this report is to provide information on codes and standards that would help the design and construction and regulatory approval of hydrogen dispensing stations. Although this document is directed at California projects, many of the procedures and codes and standards requirements are similar in other parts of the United States. The California Environmental Quality Regulations are not in effect outside of California, but the Risk Management Plans required in California are part of a national program that has very similar requirements across the country.

Building hydrogen dispensing stations for hydrogen fuel cell vehicles is a critical piece of the infrastructure required to support the deployment of hydrogen fuel cell vehicles on a commercial scale. There are fewer than 50 publicly accessible [1] hydrogen dispensing stations in the United States as of April 2012 and all of these stations are prototype or developmental stations. They do not fuel at the volume of commercial liquid fuel stations. They are dissimilar to the common commercial gasoline retail dispensing stations that often contain convenience stores and other products sales such as propane as well as multiple dispensers and multiple dispenser islands. They also differ from existing retail stations in the relatively low number of vehicles they fuel.

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Fuel Cell Technologies Program Safety, Codes and Standards (SCS) Project has as one of its objectives the accelerated deployment of hydrogen and fuel cell technologies. To achieve this objective the National Renewable Energy Laboratory (NREL) through direction and funding from EERE has developed a template for a commercial hydrogen dispensing stations to streamline the project development and permitting process for widespread deployment of hydrogen dispensing stations.

Project Title: Codes and Standards for the Hydrogen Economy
Principal Investigator: Gary Nakarado

Objectives

- Develop a robust supporting research and development program to provide critical hydrogen behavior data and a detailed understanding of hydrogen combustion and safety across a range of scenarios, needed to establish setback distances in building codes and minimize the overall data gaps in code development.
- Support and facilitate the completion of technical specifications by the International Organization for Standardization (ISO) for gaseous hydrogen refueling (TS 20012) and standards for on-board liquid (ISO 13985) and gaseous or gaseous blend (ISO 15869) hydrogen storage by 2007.
- Support and facilitate the effort, led by the NFPA, to complete the draft Hydrogen Technologies Code (NFPA 2) by 2008.
- With experimental data and input from Technology Validation Program element activities, support and facilitate the completion of standards for bulk hydrogen storage (e.g., NFPA 55) by 2008.
- Facilitate the adoption of the most recently available model codes (e.g., from the International Code Council [ICC]) in key regions.
- Complete preliminary research and development on hydrogen release scenarios to support the establishment of setback distances in building codes and provide a sound basis for model code development and adoption.
- Support and facilitate the development of Global Technical Regulations (GTRs) by 2010 for hydrogen vehicle systems under the United Nations Economic Commission for Europe, World Forum for Harmonization of Vehicle Regulations and Working Party on Pollution and Energy Program (ECE-WP29/GRPE).
- Support and facilitate the completion by 2012 of necessary codes and standards needed for the early commercialization and market entry of hydrogen energy technologies.

Hydrogen storage and delivery: Review of the state-of-the-art technologies and risk and reliability analysis

Ramin Moradi and Katrina M. Groth

Among all introduced green alternatives, hydrogen, due to its abundance and diverse production sources is becoming an increasingly viable clean and green option for transportation and energy storage. Governments are considerably funding relevant researches and the public is beginning to talk about hydrogen as a possible future fuel. Hydrogen production, storage, delivery, and utilization are the key parts of the Hydrogen Economy (HE). In this paper, hydrogen storage and delivery options are discussed thoroughly. Then, since safety and reliability of hydrogen infrastructure is a necessary enabling condition for public acceptance of these technologies and any major accident involving hydrogen can be difficult to neutralize, we review the main existing safety and reliability challenges in hydrogen systems. The current state of the art in safety and reliability analysis for hydrogen storage and delivery technologies is discussed, and recommendations are mentioned to help providing a foundation for future risk and reliability analysis to support safe, reliable operation.

Hydrogen Powered Automobiles: Problems and Solutions

A. S. Koroteev and V. A. Smolyarov

The development of hydrogen power for switching the most energy-intensive segments of industry and transportation to a qualitatively new energy carrier – hydrogen – as a strategic direction for decreasing the acuteness of the problems of environmental pollution and the growing shortage of petroluem-based fuel for automobiles is examined.

It is concluded for vehicular transportation systems in megalopolises and large cities that the main solution is to develop an ecologically safe means of transportation powered by an electrochemical generator operating on hydrogen and atmospheric air. A preliminary conclusion is drawn on the basis of a comparison of various types of electrochemical generators that electrochemical generators with a solid-polymer membrane have merit.

Various systems for storing hydrogen in an automobile are examined. The system which is closest to practical implementation is a system for storing hydrogen gas at high pressure in a tank made of composite materials. An assessment is made of the danger that the hydrogen stored in a high-pressure tank in an automobile will catch fire or explode.

Hydrogen Safety Standards & Fueling Requirements

Hydrogen Safety Panel Review of Mobile Hydrogen Applications

Pacific Northwest Laboratory, Nick Barilo

A recent incident (March 5, 2018) involving a hydrogen mobile storage trailer in Diamond Bar, CA, brought attention to potential impacts of mobile hydrogen storage and use. Road transport of bulk hydrogen presents unique hazards that can be much different from those for stationary equipment, and new equipment developers may have less experience and expertise than seasoned gas providers. Additionally, there appears to be a lack of specific requirements and uncertainty over who is responsible for development and implementation of such requirements. Incidents involving mobile equipment can have detrimental impacts on California's commitment to hydrogen as an alternative transportation energy resource.

To ensure that potentially impactful safety issues are identified in accordance with Task 5 "Identification of Project and Stakeholder Learnings" of Agreement 600-15-014, the Pacific Northwest National Laboratory proposes to use the Hydrogen Safety Panel to evaluate the safety of mobile hydrogen and fuel cell applications (mobile auxiliary power units, mobile fuelers, multicylinder trailer transport, refrigeration units, etc.). The activity will identify specific safety or code gaps and draft a report to summarize the status, offer conclusions and provide recommendations to improve safety for this type of mobile equipment.

EXAMPLES OF ISSUES THAT WILL BE CONSIDERED/EVALUATED

- Vulnerabilities of hydrogen systems in mobile applications:
    - Higher pressures
    - Use in transport – acceleration, vibration and suitability of pipe fittings, etc.
    - Potential vehicle and accident impacts
    - Manifolding and lack of isolation of storage tanks
    - Enclosed compartments/unique ventilation issues
- What is being done to evaluate potential and unique hazards and what criteria are applied for acceptable risk
- Storage tank performance and system-level safety integration that may be needed for issues related to hydrogen fueling tanks when they are used for other than light-duty vehicles (mobile applications)
- Fueling protocols and safety implications for refueling nonstandard equipment at existing stations
- Gaps in requirements, including consideration of lack of requirements and, if there are existing requirements, determining if they are comprehensive enough to suit these types of designs:
    - What is needed to get mobile applications approved for use (certifications, examinations, etc.)
    - If necessary requirements are not available, fundamental issues (specific attributes or safety features) could be identified (and support development of future requirements)
- How affected cylinders are offloaded if an incident occurs
- Safe disposal of damaged cylinders and equipment

Quantitative risk assessment of an urban hydrogen refueling station

Hye-Ri Gye, Seung-Kwon Seo, Quang-Vu Bach, Daeguen Ha, Chul-Jin Lee

Hydrogen is an important energy source for the next generation of renewable energy. It has several strengths such as no emission from CO2 for fuel, Nevertheless, many countries have difficulties to expand hydrogen infrastructure due to high risks from hydrogen. In particular, the hydrogen refueling station which is located in urban area has congested structure and high population around, it has higher risk than conventional refueling station. This paper presents a quantitative risk assessment (QRA) of a high pressure hydrogen refueling station in an urban area with a large population and high congestion between the instruments and equipment. The results show that leaks from the tube-trailer and dispenser as well as potential explosion of the tube-trailer are the main risks. For the safety of the station operator, customers and people surrounding the refueling station, additional mitigation plans such as adding additional safety barrier system have to be implemented on the compressor and dispenser in order to prevent continuous release of hydrogen from an accident.

Development of safety standard for mobile hydrogen refueling facilities in China

Zhiyong Li, Xiangmin Pan, Ke Sun, Wei Zhou, Dingyun Gao, Shaojun Liu, Jianxin Ma

Abstract: With the progress of fuel cell vehicle demonstrations in the past ten years, a number of hydrogen refueling infrastructures have been built in China including both stationary and mobile facilities. To facilitate the development of hydrogen infrastructure, the National Technical Committee on Hydrogen Energy of Standardization Administration of China (SAC/TC309) has made a lot of efforts in the development of regulations, codes and standards associated with hydrogen technologies. One of the achievements related to hydrogen infrastructure is the GB50516-2010 Technical Code for Hydrogen Fuelling Station, which is targeting at stationary hydrogen fuelling facilities while the mobile hydrogen fuelling facilities are not included. As a supplementary document to Technical Code for Hydrogen Fuelling Station, a new standard, Safety Technical Regulations for Mobile Hydrogen Refueling Facility, is now under drafting. This paper introduces the development of this new standard and addresses its highlights. Safety experience learned from engineering practice is integrated into the safety specifications. Safety studies on mobile hydrogen refueling facilities are also applied to the development of the safety standard. Highlights of the specifications and the progress of the draft are summarized in terms of technical safety requirements, operation management and other special provisions. Finally, future perspectives on the development of standards for mobile refueling facilities are proposed.

Fire Protection Engineering Design Brief Template: Hydrogen Refueling Station

A. Chris LaFleur, Alice B. Muna and Katrina M. Groth

Abstract
Building a hydrogen infrastructure system is critical to supporting the development of alternate fuel vehicles. This report provides a methodology for implementing a performance-based design of an outdoor hydrogen refueling station that does not meet specific prescriptive requirements in NFPA 2, The Hydrogen Technologies Code. Performance-based designs are a code-compliant alternative to meeting prescriptive requirements. Compliance is demonstrated by comparing a prescriptive-based fueling station design with a performance-based design approach using Quantitative Risk Assessment (QRA) methods and hydrogen risk assessment tools. This template utilizes the Sandia-developed QRA tool, Hydrogen Risk Analysis Models (HyRAM), which combines reduced-order deterministic models that characterize hydrogen release and flame behavior with probabilistic risk models to quantify risk values. Each project is unique and this template is not intended to account for site-specific characteristics. Instead, example content and a methodology are provided for a representative hydrogen refueling site which can be built upon for new hydrogen applications.

Risk analysis on mobile hydrogen refueling stations in Shanghai

Ke Sun, Xiangmin Pan, Zhiyong Li, Jianxin Ma

To better understand the hazards and risks associated with the mobile hydrogen refueling stations, a risk analysis was preformed to improve the safety of the operation. The risks to the station personnel and to the public were discussed separately. Results show that the stationary risks of the mobile stations to the personnel and refueling customers are lower than the risk acceptance criteria over an order of magnitude, so the occupational risks and the risks to customers are completely acceptable. The third party risks can be acceptable as long as the appropriate mitigation measures, especially well designed parking area and operation time, are implemented. Leak from booster compressors is the main risk contributor to the stationary risks due to the highest failure rates according to the generic data and the worst harm effects based on the consequence evaluations. However, the failure of the tube storages will result in the largest financial loss, though the likelihood of this scenario is much less than that of failure from booster compressors. As for the road risks of the mobile stations, they can be acceptable as long as the appropriate mitigation measures, especially well-planned itinerary and transport time, are implemented.

Impact of hydrogen SAE J2601 fueling methods on fueling time of light-duty fuel cell electric vehicles

Krishna Reddi, Amgad Elgowainy, Neha Rustagi, and Erika Gupta

Hydrogen fuel cell electric vehicles (HFCEVs) are zero-emission vehicles (ZEVs) that can provide drivers a similar experience to conventional internal combustion engine vehicles (ICEVs), in terms of fueling time and performance (i.e. power and driving range). The Society of Automotive Engineers (SAE) developed fueling protocol J2601 for light-duty HFCEVs to ensure safe vehicle fills while maximizing fueling performance. This study employs a physical model that simulates and compares the fueling performance of two fueling methods, known as the "lookup table" method and the "MC formula" method, within the SAE J2601 protocol. Both the fueling methods provide fast fueling of HFCEVs within minutes, but the MC formula method takes advantage of active measurement of precooling temperature to dynamically control the fueling process, and thereby provides faster vehicle fills. The MC formula method greatly reduces fueling time compared to the lookup table method at higher ambient temperatures, as well as when the precooling temperature falls on the colder side of the expected temperature window for all station types. Although the SAE J2601 lookup table method is the currently implemented standard for refueling hydrogen fuel cell vehicles, the MC formula method provides significant fueling time advantages in certain conditions; these warrant its implementation in future hydrogen refueling stations for better customer satisfaction with fueling experience of HFCEVs.

Evaluating uncertainty in accident rate estimation at hydrogen refueling station using time correlation model

Mahesh Kodoth, Shu Aoyama, Junji Sakamoto, Naoya Kasai, Tadahiro Shibutani, Atsumi Miyake

Hydrogen, as a future energy carrier, is receiving a significant amount of attention in Japan. From the viewpoint of safety, risk evaluation is required in order to increase the number of hydrogen refueling stations (HRSs) implemented in Japan. Collecting data about accidents in the past will provide a hint to understand the trend in the possibility of accidents occurrence by identifying its operation time However, in new technology; accident rate estimation can have a high degree of uncertainty due to absence of major accident direct data in the late operational period. The uncertainty in the estimation is proportional to the data unavailability, which increases over long operation period due to decrease in number of stations. In this paper, a suitable time correlation model is adopted in the estimation to reflect lack (due to the limited operation period of HRS) or abundance of accident data, which is not well supported by conventional approaches. The model adopted in this paper shows that the uncertainty in the estimation increases when the operation time is long owing to the decreasing data. A partial listing of the accidents considered in this model is provided below:

No.	***Description***
1	Hydrogen leakage from filling hose
2	Hydrogen leakage at hydrogen station
3	Explosion of hydrogen at hydrogen station
4	Hydrogen leakage at hydrogen station
5	Hydrogen leakage in compressed hydrogen gas
6	Hydrogen leakage from filling hose during filling operation
7	Inhalation of hydrogen station, hydrogen leakage from discharge valve mounting part
8	Hydrogen leakage from dispenser joint due to earthquake
9	Hydrogen leakage from the cap nut of the connection part of the card
10	Hydrogen leakage from hydrogen station pressure gauge
11	Leakage from hydrogen station dispenser and hose attachment
12	Leakage from valve mounting part of hydrogen stand
13	Hydrogen leakage from the valve connection
14	Hydrogen leakage from the check screw ground thread portion of compressor discharge
15	Hydrogen leakage from the accumulator base valve
16	Leakage from liquid hydrogen receiving lower valve at hydrogen station
17	Leakage from overflow preventing valve connection of hydrogen station
18	Hydrogen leakage from the shutoff valve
19	Hydrogen leakage from filling hose after completion of filling test
20	Hydrogen leakage from the connecting part of the compressor unit
21	Explosion during inspection of opening of accumulator
22	Rupture of hydrogen filled hose during filling test

Best Practices

Hydrogen Station Permitting Guidebook
Best practices for planning, permitting and opening a hydrogen fueling station
Governor's Office of Business and Economic Development

Developing a hydrogen station can be time intensive, especially for the first station in a community. Permitting requirements will differ from station to station depending on the site characteristics, station type, and the local jurisdiction's unique processes. In California, local governments have the ultimate authority to approve or deny any project. A design approved in one community does not guarantee approval of the same design in another community (although it often helps). This section of the guidebook is designed to minimize the research required to permit a station from perspectives of the Authorities Having Jurisdiction (AHJs, or reviewing entities—often a city or county) and the station developer by offering insight and tools from past experiences and general recommendations for streamlining the permitting process. The intent of this guidebook is to provide consistent application of these Title 24 requirements throughout the state, as they relate to hydrogen stations. This guidebook is not intended to create, explicitly or implicitly, any new requirements

A major piece of the station permitting process is dedicated to ensuring stations are built to current codes and standards. The following text provides references to California codes and guidance, which can be amended by local jurisdictions in certain circumstances. The California Building Code gives authority to each AHJ's chief building official to be the final authority on the code interpretation in their jurisdiction. Previous experiences have shown that code requests can vary widely with different interpretations from one AHJ to another.

Code requirements are developed and implemented to provide for the safety of people and property, as well as minimize the environmental impacts associated with project development. The California Building Standards Code provides uniform requirements for buildings throughout the state. These requirements are contained in Title 24 of the California Code of Regulations (CCR). Title 24 applies to all building occupancies and related features and equipment throughout the state. It contains requirements for a building's structural, mechanical, electrical, and plumbing systems, in addition to measures for energy conservation, sustainable construction, maintenance, fire and life safety, and accessibility. Specific areas within Title 24 directly relate to hydrogen stations, such as:

- California Building Code, Part 2, Title 24
- California Electrical Code, Part 3, Title 24
- California Energy Code, Part 6, Title 24
- California Fire Code, Part 9, Title 24

Cities and counties in California are required by state law to enforce Title 24 building standards. However, cities and counties can, and regularly do, adopt local laws (also called "ordinances") to modify these state building standards to address local climatic, geological, or topographical conditions, and generally are more restrictive. This means that a city or county may have local ordinances that modify or add to the provisions of Title 24 for any section that impacts hydrogen stations.

Performance-Based Approach to Siting Hydrogen Refueling Stations

Chris LaFleur

Impacts of demonstrating performance-based design option

• Increase options for industry in siting hydrogen fueling stations
• Increase confidence in the performance-based approach for station design
• Reduce effort required by industry to use the PB approach by providing template and test case
• Provide path for international harmonization of the PB approach to station design
• Lay groundwork (establish precedence) for similar PB approach for other alternate fuels (i.e. CNG and LNG)

NFPA 2 (Hydrogen Technologies Code) Chapter 5 allows performance-based designs for hydrogen facilities.
Performance-based designs (PBD) enable alternate specifications that do not conform with the prescriptive code requirements, while ensuring equivalent safety through the use of performance criteria.

- Performance-based design solutions have not been developed for hydrogen applications due to:
  - Perceptions that PBD is cost prohibitive
  - Uncertainty surrounding acceptance by Authorities Having Jurisdiction (AHJs)
  - Lack of validated methodology

A Near-Term Economic Analysis of Hydrogen Fueling Stations
Jonathan Weinert

There is growing interest in hydrogen as a transportation fuel in California. Plans are underway to construct a “Hydrogen Highway” network of stations across the state to stimulate fuel cell vehicle deployment. One of the key challenges however in the planning and financing of this network is determining the costs of the stations. The purpose of this thesis is to examine the near-term costs of building stations and answer the fundamental question, ‘how much would new hydrogen stations cost now?’ The costs for seven different station types are analyzed with respect to size, siting factors, and operating factors. The first chapter of the thesis reviews the existing body of knowledge on hydrogen station costs. In the second chapter, I present hydrogen station cost data in a database, the Compendium of Hydrogen Refueling Equipment Costs (CHREC), created to organize and analyze data collected from equipment suppliers, existing stations and literature. The third chapter of the report presents the Hydrogen Station Cost Model (HSCM), an engineering/economic model also created as part of this thesis, to analyze the cost of stations. In the final chapter of the report, the HSCM model is applied to the case of the proposed California Hydrogen Highway Network to indicate the costs of different hydrogen infrastructure options.

Based on these cost analyses, I conclude the following:

- Existing hydrogen station cost analyses tend to under-estimate true station costs by assuming high production volume levels for equipment, neglecting station installation costs, and omitting important station operating costs.
- Station utilization (i.e. capacity factor) has the most significant impact on hydrogen price.
- Hydrogen fuel costs can be reduced by siting stations at strategic locations such as government-owned fleet yards and facilities that use hydrogen for industrial purposes.
- Hydrogen fuel costs ($/kg) are higher at small stations (10-30 kg/day) that are burdened with high installation costs and low utilization of station infrastructure.
- Energy stations that produce electricity for stationary uses and hydrogen for vehicles have the potential for low-cost hydrogen due to increased equipment utilization. Costs of energy stations are uncertain because few have been built.
- The Hydrogen Station Cost Model is a flexible tool for analyzing hydrogen station costs for a variety of conditions and assumptions

Investing in Alternative Fuel Infrastructure: Insights for California from Stakeholder Interviews

Marc Melaina, Matteo Muratori, Joyce McLaren, and Paul Schwabe

ABSTRACT

Increased interest in the use of alternative transportation fuels, such as natural gas, hydrogen, and electricity, is being driven by heightened concern about the climate impacts of gasoline and diesel emissions and our dependence on finite oil resources. A key barrier to widespread adoption of low- and zero-emission passenger vehicles is the availability of refueling infrastructure. Recalling the "chicken and egg" conundrum, limited adoption of alternative fuel vehicles increases the perceived risk of investments in refueling infrastructure, while lack of refueling infrastructure inhibits vehicle adoption.

In this paper, we present the results of a study of the perceived risks and barriers to investment in alternative fuels infrastructure, based on interviews with industry experts and stakeholders. We cover barriers to infrastructure development for three alternative fuels for passenger vehicles: compressed natural gas, hydrogen, and electricity. As an early-mover in zero emission passenger vehicles, California provides the early market experience necessary to map the alternative fuel infrastructure business space. Results and insights identified in this study can be used to inform investment decisions, formulate incentive programs, and guide deployment plans for alternative fueling infrastructure in the U.S. and elsewhere.

3.3.2 Barriers to Hydrogen Refueling Station (HRS) Infrastructure Development

Interviewees noted several current barriers to the development of HRS infrastructure:

Lack of Connection between Hydrogen Producers and Retail Stations.

Permitting, Codes, and Standards.

Demand Uncertainty

Length of Time To Develop Infrastructure. Oesult of losing site-owner support.

Lack of Information for Retail Station Owners.

Impact of Hydrogen Refueling Configurations and Market Parameters on the Refueling Cost of Hydrogen

Krishna Reddi, Amgad Elgowainy, Neha Rustagi, and Erika Gupta

Abstract
The cost of hydrogen in early fuel cell electric vehicle (FCEV) markets is dominated by the cost of refueling stations, mainly due to the high cost of refueling equipment, small station capacities, lack of economies of scale, and low utilization of the installed refueling capacity. Using the hydrogen delivery scenario analysis model (HDSAM), this study estimates the impacts of these factors on the refueling cost for different refueling technologies and configurations, and quantifies the potential reduction in future hydrogen refueling cost compared to today's cost in the United States. The current hydrogen refueling station levelized cost, for a 200 kg/day dispensing capacity, is in the range of \$6–\$8/kg H2 when supplied with gaseous hydrogen, and \$8–\$9/kg H2 for stations supplied with liquid hydrogen. After adding the cost of hydrogen production, packaging, and transportation to the station's levelized cost, the current cost of hydrogen at dispensers for FCEVs in California is in the range of \$13–\$15/kg H2. The refueling station capacity utilization strongly influences the hydrogen refueling cost. The underutilization of station capacity in early FCEV markets, such as in California, results in a levelized station cost that is approximately 40% higher than it would be in a scenario where the station had been fully utilized since it began operating. In future mature hydrogen FCEV markets, with a large demand for hydrogen, the refueling station's levelized cost can be reduced to \$2/kg H2 as a result of improved capacity utilization and reduced equipment cost via learning and economies of scale.

Two-tier pressure consolidation operation method for hydrogen refueling station cost reduction

Krishna Reddi, Amgad Elgowainy, Neha Rustagi and Erika Gupta

Abstract
An operation strategy known as two-tier "pressure consolidation" of delivered tube-trailers (or equivalent supply storage) has been developed to maximize the throughput at gaseous hydrogen refueling stations (HRSs) for fuel cell electric vehicles (FCEVs). The high capital costs of HRSs and the consequent high investment risk are deterring growth of the infrastructure needed to promote the deployment of FCEVs. Stations supplied by gaseous hydrogen will be necessary for FCEV deployment in both the near and long term. The two tier pressure consolidation method enhances gaseous HRSs in the following ways: (1) reduces the capital cost compared with conventional stations, as well as those operating according to the original pressure consolidation approach described by Elgowainy et al. (2014) [1], (2) minimizes pressure cycling of HRS supply storage relative to the original pressure consolidation approach; and (3) increases use of the station's supply storage (or delivered tube-trailers) while maintaining higher state-of-charge vehicle fills.

Liquid Hydrogen Release Risk and Behavior Modeling: State-of-the-Art, Knowledge Gaps, and Research Needs for Refueling Infrastructure Safety

Isaac W. Ekoto, Ethan Hecht, Chris San Marchi, Katrina M. Groth, A. Christine LaFleur, Nitin Natesan, Mike Ciotti and Aaron Harris

Executive Summary

As demand for hydrogen fuel increases with the introduction of fuel cell electric vehicles (FCEV), there will be increased pressure to minimize fueling station footprints and lower costs while maintaining safety and performance. The DOE Energy Efficiency and Renewable Energy Fuel Cell Technology Office (EERE FCTO) supports the initial build-out of hydrogen fueling stations through the development of tools needed to implement a risk-informed approach to station design and siting. Transformational EERE investments have previously supported the successful implementation of fire safety codes for compressed gaseous hydrogen systems (e.g., NFPA 55 and 2) using a risk-informed approach.

Bulk liquid hydrogen storage has the benefit of a higher storage potential that enables greater station throughput over similarly sized gaseous systems. However, data for model development and validation of liquid hydrogen releases — critical information needed for risk-based strategies — is unavailable due to a lack of adequate science-based test platforms with full control over release boundary conditions. Accordingly, current prescriptive liquid hydrogen bulk-storage separation distances are based on subjective expert opinion, and may be overly conservative relative to similar bulk gaseous hydrogen storage system requirements. In practice, current liquid hydrogen separation distances have become a major impediment to fueling station deployments.

This work summarizes the current scientific consensus and knowledge gaps regarding cryogenic releases. Quantitative risk assessment (QRA) is presented as a means of informing fire safety codes, underscoring the need for validated, reduced-order models as a backbone for this approach. A review of the data and detailed modeling of cryogenic releases in the scientific literature is presented, with a noticeable dearth of validated models, or appropriate data to validate these models. The state-of-the-art in reduced-order hydrogen behavior modeling is described, which is advanced for gaseous releases, but requires development for liquid releases. Challenges associated with modeling cryogenic hydrogen releases largely stem from the multiphase flows and phase change behaviors encountered during these releases.

Finally, this work describes a new capability being developed for controlled cryogenic hydrogen releases that can be used to improve and validate deterministic liquid hydrogen release models. The basic approach will follow a template used previously to characterize high-pressure gaseous hydrogen releases. The concept is to integrate a novel dual-stage heat-exchanger into the existing Turbulent Combustion Laboratory infrastructure to reduce supply gaseous hydrogen flows to the desired temperature — potentially creating mixed-phase flows — with the hydrogen exiting through a custom nozzle. High-fidelity Rayleigh scatter imaging diagnostics will be used to measure relevant release phenomena. Data developed from this effort will advance the creation of release models for low-temperature hydrogen leaks, which will enable risk-informed approaches to liquid hydrogen bulk storage safety.

Analyzing the sensitivity of hydrogen vehicle sales to consumers' preferences

David L. Greene, Zhenhong Lin, Jing Dong

The success of hydrogen vehicles will depend on consumer behavior as well as technology, energy prices and public policy. This study examines the sensitivity of the future market shares of hydrogen-powered vehicles to alternative assumptions about consumers' preferences. The Market Acceptance of Advanced Automotive Technologies model was used to project future market shares. The model has 1458 market segments, differentiated by travel behavior, geography, and tolerance to risk, among other factors, and it estimates market shares for twenty advanced power-train technologies. The market potential of hydrogen vehicles is most sensitive to the improvement of drive train technology, especially cost reduction. The long-run market success of hydrogen vehicles is less sensitive to the price elasticity of vehicle choice, how consumers evaluate future fuel costs, and the importance of fuel availability and limited driving range. The importance of these factors will likely be greater in the early years following initial commercialization of hydrogen vehicles.

California Hydrogen Infrastructure Project

Principal Investigator: Edward C. Heydorn

Air Products and Chemicals, Inc. has completed a comprehensive, multiyear project to demonstrate a hydrogen infrastructure in California. The specific primary objective of the project was to demonstrate a model of a “real-world” retail hydrogen infrastructure and acquire sufficient data within the project to assess the feasibility of achieving the nation’s hydrogen infrastructure goals. The project helped to advance hydrogen station technology, including the vehicle-to station fueling interface, through consumer experiences and feedback. By encompassing a variety of fuel cell vehicles, customer profiles and fueling experiences, this project was able to obtain a complete portrait of real market needs. The project also opened its stations to other qualified vehicle providers at the appropriate time to promote widespread use and gain even broader public understanding of a hydrogen infrastructure. The project engaged major energy companies to provide a fueling experience similar to traditional gasoline station sites to foster public acceptance of hydrogen.

Work over the course of the project was focused in multiple areas. With respect to the equipment needed, technical design specifications (including both safety and operational considerations) were written, reviewed, and finalized. After finalizing individual equipment designs, complete station designs were started including process flow diagrams and systems safety reviews. Material quotes were obtained, and in some cases, depending on the project status and the lead time, equipment was placed on order and fabrication began. Consideration was given for expected vehicle usage and station capacity, standard features needed, and the ability to upgrade the station at a later date.

In parallel with work on the equipment, discussions were started with various vehicle manufacturers to identify vehicle demand (short- and long-term needs). Discussions included identifying potential areas most suited for hydrogen fueling stations with a focus on safe, convenient, fast-fills. These potential areas were then compared to and overlaid with suitable sites from various energy companies and other potential station operators. Work continues to match vehicle needs with suitable fueling station locations. Once a specific site was identified, the necessary agreements could be completed with the station operator and expected station users. Detailed work could then begin on the site drawings, permits, safety procedures and training needs.

Permanent stations were successfully installed in Irvine (delivered liquid hydrogen), Torrance (delivered pipeline hydrogen) and Fountain Valley (renewable hydrogen from anaerobic digester gas). Mobile fueling stations were also deployed to meet short-term fueling needs in Long Beach and Placerville. Once these stations were brought online, infrastructure data was collected and reported to DOE using Air Products’ Enterprise Remote Access Monitoring system. Feedback from station operators was incorporated to improve the station user’s fueling experience.

Fire Protection Engineering Design Brief Template: Hydrogen Refueling Station

A. Chris LaFleur, Alice B. Muna & Katrina M. Groth

Abstract

Building a hydrogen infrastructure system is critical to supporting the development of alternate fuel vehicles. This report provides a methodology for implementing a performance-based design of an outdoor hydrogen refueling station that does not meet specific prescriptive requirements in NFPA 2, The Hydrogen Technologies Code. Performance-based designs are a code-compliant alternative to meeting prescriptive requirements. Compliance is demonstrated by comparing a prescriptive-based fueling station design with a performance-based design approach using Quantitative Risk Assessment (QRA) methods and hydrogen risk assessment tools. This template utilizes the Sandia-developed QRA tool, Hydrogen Risk Analysis Models (HyRAM), which combines reduced-order deterministic models that characterize hydrogen release and flame behavior with probabilistic risk models to quantify risk values. Each project is unique and this template is not intended to account for site-specific characteristics. Instead, example content and a methodology are provided for a representative hydrogen refueling site which can be built upon for new hydrogen applications

Driver Response to Hydrogen Fuel Cell Buses in a Real-World Setting Study of a Northern California Transit Bus Fleet

Timothy E. Lipman, Ananda L. Gray-Stewart, and Jeffrey Lidicker

This study examined bus drivers’ acceptance of fuel cell electric buses in Alameda–Contra Costa Transit in the San Francisco Bay Area of California. Of the 145 surveys issued, 47 drivers completed a written survey, for a 32% response rate. The study focused on a key attribute for potential success of alternative urban bus technology: the driver acceptance factor. Technology performance flaws that are undesirable or annoying to the bus drivers may also be disruptive to passengers. Furthermore, because of using the buses throughout their full duty cycle, drivers are in a unique position to identify key opportunities to improve the new technology options as they emerge and evolve. The study found that drivers, in general, rated the hydrogen fuel cell buses to be at the same or better performance than diesel buses for handling, ride quality, acceleration, and braking. For quiet operation, the drivers rated the new buses as excellent. When asked how they liked the experimental hydrogen fuel cell buses, drivers responded at just above neutral, with the most common response being “the same” as diesel buses followed by “much better.” Those drivers who said that they considered fuel economy when purchasing a vehicle liked the fuel cell buses more. Older drivers preferred the diesel buses, and male drivers preferred the new fuel cell buses. Perceptions of safety were mixed, with some drivers expressing safety concerns independent of how much training they had received

Feasibility Study Zero Emissions Fleet Initiative- Infrastructure Safety Study
HTEC

This document summarizes the overall requirements for the safe and successful construction of a permanent hydrogen fueling station to fill Fuel Cell Electric Vehicles (FCEVs) within the Capital Regional District (CRD). Excerpts related to permitting and the importance of early public engagement, as well as the practicality of mobile refueling are provided below.

b. Temporary Installations

The subject of temporary installations, moving stored hydrogen, and mobile refuellers as an option to permanent installations reveals that the overall permitting and safety requirements are similar at best, and in the case of mobile refuellers much more complex (see Appendix B for a discussion of mobile refueling in California).

Moving stored hydrogen in Canada requires special Transport Canada permits, while moving a temporary fueling station simply requires the station to be completely purged of any hydrogen, essentially making it an inert assembly of equipment.

Installing a temporary fueling station has few precedents and by all indications would need to meet all of the codes and regulations set out for a permanent station. A temporary installation might fall under the category of a short-term event, and each municipality may have less stringent requirements for foundations and structures, however it is unlikely the requirements around siting, setbacks, and related safety equipment will be any different from a permanent station.

From Appendix B

As more FCEVs take the road and the hydrogen station network expands, mobile refuelers will be able to provide additional capacity in the case of station repair, or other unforeseen needs. With a hydrogen compressor, storage and dispenser on-board, mobile refuelers have capability to travel to designated locations and fill vehicles.

Mobile refuelers require specific approvals. Tanks on the mobile refueler will need to meet U.S. Department of Transportation (DOT) standards for moving flammable gases, either as pre approved DOT tanks or special permit tanks. (The primary relevant regulation is 49 CFR 173.301.)

The Compressed Gas Association TB25 “Design Considerations for Tube Trailers,” which has been incorporated by reference into 49 CFR 173.01, offers a solid starting point for planning to comply with DOT regulations. It should be used for performing analysis or performance testing. For composite tanks commonly used to store hydrogen, DOT standards require a full range of testing to verify integrity. Prior to testing, it is recommended that manufacturers of mobile refuelers contact the Pipeline and Hazardous Materials Safety Administration (PHMSA) at DOT to ensure tests and methods meet all requirements.

The California Fire Code and International Fire Code do not contain guidance on mobile fueling, but, depending on the site, there is information on mobile refueling in NFPA 2. Manufacturers of mobile refuelers should review NFPA 2 to ensure project compliance

Hydrogen fuel cell electric vehicle performance and user-response assessment: Results of an extended driver study

Timothy E. Lipman*, Matthew Elke, Jeffrey Lidicke

This study examined driver acceptance and performance of hydrogen fuel cell electric vehicles as tested in real-world conditions over a two-year period. The study sample was a volunteer group of “n = 54” drivers who drove the vehicle for a month-long trial period. Each driver took ‘before’ and ‘after’ surveys regarding their driving experience. Drivers drove an average of 1400 miles per month, and either witnessed and/or performed vehicle refueling 3e10 times during their test period.

Key findings from the study include that: 1) 80% of study participant drivers found that the fuel cell vehicle (FCV) performance “exceeded” or “greatly exceeded” their expectations; 2) 98% of study participant drivers view hydrogen as a fuel for vehicles as being “as safe” or “safer” than gasoline as a fuel for vehicles; and 3) 94% of participants view the process of fueling a vehicle with hydrogen to be “as safe” or “safer” than gasoline fueling. Other findings include that 85% of study participants who performed their own fueling described hydrogen fueling to be “somewhat” or “very” simple. Of the participants, 62% percent had to forgo at least one trip due to lack of hydrogen fuel, although vehicle range was rated by 75% of participants as entirely or mostly adequate. If fueling infrastructure availability was not an issue, and fuel cost per-mile was at parity with gasoline, 75% of participants would be willing to pay $40,000 or less for an FCV.

Review of transportation hydrogen infrastructure performance and reliability,

Jennifer Kurtz, Sam Sprik, Thomas H. Bradley,

Abstract: Hydrogen infrastructure for fueling vehicles has progressed in the last decade from stations with restricted access and limited operating hours to customer-friendly retail stations open to the public. There are now 121 retail hydrogen stations around the world. In California, the number of public retail hydrogen stations has increased from zero to more than 30 in less than two years, and the annual amount of hydrogen dispensed by retail stations has grown from 27,400 kg in 2015 to nearly 105,000 kg in 2016 and more than 440,000 kg in 2017—an increase of about four times year over year. For more than a decade, government, industry, and academia have studied many aspects of hydrogen infrastructure, from renewable hydrogen production to retail hydrogen station performance. This paper reviews the engineering and deployment of modern hydrogen infrastructure, including the costs, benefits, and operational considerations (including safety, reliability, availability), as well as challenges to the scale-up of hydrogen infrastructure. The results identify hydrogen station reliability as a key factor in the expense of operating hydrogen systems, placing it in the context of the larger reliability engineering field.

Connected Vehicle Technologies for Efficient Urban Transportation
Ajay Prasad

Connected vehicle technology is employed to optimize the vehicle's control system in real-time to reduce congestion, improve fuel economy, and reduce emissions. This project's goal was to develop a two-way communication system to upload vehicle data to a server at the Traffic Management Center (TMC) or to other servers in real-time, and download traffic information from TMC or other sources to the vehicle. To pursue this task, a computational optimization model was developed in order to send the optimal control strategies to the vehicle. The model's results were analyzed to evaluate reductions in traffic congestion and improvements in vehicle efficiency and fuel economy. The optimization module was integrated with an on-board control system to maximize fuel efficiency based on real-time traffic inputs and navigational guidance. Durability was also added to the optimization model to improve the lifetime of fuel cell system. The ultimate goal is to implement an intelligent power management system to optimize fuel consumption, emission and durability all at the same time leveraging real-time traffic information.

From page 8

The University of Delaware has been conducting a very successful Fuel Cell Hybrid Bus Program since 2005 to research, build and demonstrate fuel cell powered buses and hydrogen refueling stations in Delaware. Under funding from the Federal Transit Administration we have successfully demonstrated two 22-ft fuel cell buses with a 140-mile range on our campus since 2007. The buses transport students across campus as part of the UD shuttle bus system. One larger 40-ft advanced fuel cell hybrid bus was added to the University of Delaware's fleet in December 2015. We have also successfully demonstrated a hydrogen refueling station for our bus program since 2007. The buses have been shown to be reliable, safe, and efficient while producing zero emissions.

Connecticut Transit Fuel Cell Transit Bus: Second Evaluation Report

K. Chandler and L. Eudy

This report describes operations at Connecticut Transit (CTTRANSIT) in Hartford for one prototype fuel cell bus and three new diesel buses operating from the same location. The evaluation period in this report (January 2008 through February 2009) has been chosen to coincide with a UTC Power propulsion system changeout that occurred on January 15, 2008. After this changeout of the propulsion system, the operation of the fuel cell bus was increased as much as the technology would allow. UTC Power reported that this change of the power system incorporated many of the lessons learned from operation including previous early power-loss issues. In this report, the fuel cell bus is considered to be prototype technology that is in the process of being commercialized. The analysis and comparison discussions regarding standard diesel buses help baseline the progress of the fuel cell bus technology. **There is no intent to consider this implementation of fuel cell buses as commercial (or full-revenue transit service).** This evaluation focuses on documenting progress and opportunities for improving the vehicles, infrastructure, and procedures.

Table ES-1 provides a summary of results for several categories of data presented in this report. During the evaluation period, the fuel cell bus accumulated 12,115 miles, and the fuel cell systems accumulated 2,049 hours. These numbers indicate an overall average operating speed of 5.9 mph, which is significantly less than the average service at **CT**TRANSIT (12 mph) and the Star route (10 mph). Note that the maintenance costs are high for the fuel cell bus because of the amount of participation by the **CT**TRANSIT mechanics in fuel cell and hybrid propulsion maintenance.

Table C-1. Fuel Cell and Diesel Bus System Descriptions

Vehicle System	Operation from Hartford Division	
	Fuel Cell Bus	Diesel Bus
Number of Buses	1	3
Bus Manufacturer and Model	Van Hool A330 Low Floor	New Flyer DL 40
Model Year	2005	2007
Length/Width/Height	40 ft./102 in/139 in	40 ft./102 in/111 in
GVWR/Curb Weight	43,240 lb./36,000 lb.	43,850 lb./28,850 lb.
Wheelbase	228 in	293 in
Passenger Capacity	30 seated or 26 seated and 2 wheelchairs; 15 standing	38 seated or 28 seated and 2 wheelchairs; 61 standing
Engine Manufacturer and Model	UTC Power PureMotion[1] 120 Fuel Cell Power System	Cummins ISL
Rated Power	Fuel cell power system: 120 kW Two Electric Drive Motors: 170 kW total (continuous)	280 hp @ 2,200 rpm 900 lb.-ft. @ 1,300 rpm
Accessories	Electrical	Mechanical
Emissions Equipment	None	Active DPF
Transmission/Retarder	Gearbox/Flenders Regenerative braking	Allison B400R/retarder
Fuel Capacity	50 kg hydrogen	125 gal
Bus Purchase Cost	$2.4 million	$337,000

Development and demonstration of fuel cell vehicles and supporting infrastructure in China

Robert K. Dixon, Xi Wang, Michael Q. Wang, Ju Wang and Zhihong Zhang

The demand for urban transportation in China, including cars, motorbikes, buses, and trains, is growing substantially. China's transportation fleet is projected to expand from 16 to 94 million vehicles between 2000 and 2020, with liquid and electricity transport fuel demand growing from about 5 Quadrillion British Thermal Units (Quads) to over 20 Quads in 2035. In response to energy security, economic growth and environmental protection needs, Chinese government agencies, academia and the private sector have organized their programs and investments to advance development and demonstration of sustainable alternative transportation systems. This analysis surveys historic development of fuel cell vehicle (FCV) including fuel cell buses (FCB) technology in China, summarizes recent efforts to scale-up FCV development and associated infrastructure in major Chinese cities, and briefly addresses future directions in Chinese fuel cell and hydrogen energy technology development. Since the late 1990's, Chinese universities, government institutions and the private sector have implemented research, development, demonstration and deployment programs for electric (EV), fuel cell (FCV), and hybrid electric vehicles (HEV). These efforts have advanced the feasibility of FCVs to be a part of sustainable urban transportation system, including technical performance, infrastructure, and customer acceptance. Three generations of FCVs, START I, START II and START III have been developed, demonstrated and deployed. Similarly, several generations of FCBs have been developed and demonstrated. Collectively, these efforts have demonstrated and deployed over 1,000 FCBs and FCVs in several Chinese cities. Large-scale, intensive-use FCV and FCB demonstration trials, including those during the 2008 Beijing Olympics and the 2010 Shanghai World Exposition (EXPO), have been successfully built and operated. Infrastructure, such as hydrogen production facilities, fuelling stations, and maintenance stations have been constructed and operated to support the fleets of FCBs and FCVs. Experiences learned from these FCV research, development, and demonstration activities are the foundation for scaling up infrastructure and fleet trials in a growing number of cities in eastern and western China. An aggressive research and development vision and 2020 technology performance targets provide a foundation for the next generation of EVs, FCVs and HEVs, and, options for China's efforts to develop a portfolio of sustainable transportation systems.

Table 6 Technical specifications of fuel cell bus (FCB) operator of the 2010 Shanghai EXPO

Overall Dimensions (Length x Width x Height)	**12 x 2.5 x 3.5 M**
Gross Weight	**14,500 kg**
Wheel Base	**5.9 m**
Max Speed	**70 km/hr**
Acceleration	**0 – 100 km/hr in 15 sec**
Seating Capacity	**53 persons**
Fuel Range	**220 km**

Assembly Bill No. 739

CHAPTER 639

An act to add and repeal Section 25722.11 of the Public Resources Code, relating to vehicular air pollution.

[Approved by Governor October 10, 2017. Filed with Secretary of State October 10, 2017.]

LEGISLATIVE COUNSEL'S DIGEST

AB 739, Chau. State vehicle fleet: purchases.

Existing law requires all new state fleet purchases made by the Department of General Services and other state entities of certain passenger vehicles and light-duty trucks to meet the fuel economy standard established by the department, in consultation with the State Energy Resources Conservation and Development Commission. Existing law requires the Secretary of Government Operations, in consultation with the department and other state agencies, to develop and implement a plan to improve the overall state fleet's use of alternative fuels, synthetic lubricants, and fuel-efficient vehicles by reducing or displacing the consumption of petroleum products by the state fleet.

This bill would, except as provided, require, beginning December 31, 2025, at least 15% of newly purchased vehicles with a gross vehicle weight rating of 19,000 pounds or more purchased by the department and other state entities for the state fleet to be zero emission, and beginning December 31, 2030, at least 30% of those vehicles to be zero emission. The bill would require, if the department finds, in a public hearing on or after December 31, 2026, that it cannot meet the needs of the state while meeting this requirement, the department to disclose this finding at the hearing and to the Legislature. The bill would require, upon disclosure of this finding, the department to take certain steps to address the issues preventing the department and other state agencies from meeting this state fleet requirement. The bill would require, after a specified time period, if the department finds, in a public hearing, that it still cannot meet the needs of the state after taking those steps, the department to disclose this finding at the hearing and to the Legislature. The bill would provide that the requirement would be inoperative on the latter date on which the department notifies the Legislature.

The people of the State of California do enact as follows:

SECTION 1. Section 25722.11 is added to the Public Resources Code, to read:

25722.11. (a) Beginning December 31, 2025, at least 15 percent of newly purchased vehicles with a gross vehicle weight rating of 19,000 pounds or more purchased by the Department of General Services and other state entities for the state fleet shall be zero emission. Beginning December 31, 2030, at least 30 percent of newly purchased vehicles with a gross vehicle weight rating of 19,000 pounds or more purchased by the Department of General Services and other state entities for the state fleet shall be zero emission.

(b) This section does not apply to vehicles that have special performance requirements necessary for the protection of public safety, as defined by the Department of General Services.

(c) If, on or after December 31, 2026, the Department of General Services, in a public hearing, finds that it cannot meet the needs of the state while meeting the requirements of this section, the department shall disclose that finding at the hearing and shall notify the Legislature of the finding in compliance with Section 9795 of the Government Code.

(d) Upon disclosure of a finding pursuant to subdivision (c), the Department of General Services shall take the following steps:

(1) While meeting the requirements of this section to the maximum extent practicable, the department, in consultation with the State Air Resources Board, shall conduct a technological assessment of zero-emission vehicle technology for vehicles with a gross vehicle weight rating of 19,000 pounds or more. The technological assessment shall include a plan to address the issues preventing the department and other state entities from meeting the requirements of this section.

(2) The department shall implement the plan developed pursuant to paragraph (1) for a period of at least one year.

(3) If, after the one-year period specified in paragraph (2), the department, in a public hearing, finds that it still cannot meet the needs of the state while meeting the requirements of this section, the department shall disclose that finding at the hearing and shall notify the Legislature of the finding in compliance with Section 9795 of the Government Code.

(e) This section is inoperative on the date on which the Department of General Services notifies the Legislature pursuant to paragraph (3) of subdivision (d) and is repealed on January 1 of the following year.

O

List of Potential Mobile Refueler Vendors

Air Products
Allentown, PA

Electricore, Inc
Valencia, CA

Hydrogen Technology & Energy Corporation (HTEC)
Vancouver, British Columbia

Gas Technology Institute
Des Plaines, IL

Power Tech Labs
Surrey, British Columbia

Luxfer GTM Technologies
Riverside, CA

Note: While all of the above vendors may have the expertise to build a 70 MPa refueler, only Electricore is actually fabricating a unit, based on the information available as of this writing.

Contacts

The following individuals / Agencies were contacted to gather information for this investigation. A brief summary of the outcome is provided.

US Department of Energy

James. Alkire, US Department of Energy, Ph (720) 356.1426, James.Alkire@ee.doe.gov

Summary

1. I contacted Mr. Alkire, who in turn referred me to Sara Odom, the Principal Investigator for Electricore. Ms Odom is on family leave and referred me to Spencer Quong, the developer of the mobile refueler
2. Summary of conversation with Spencer Quong on July 30:
    a. Caltrans had already been in contact with him earlier in the month
    b. Electricore only had one fueler built of this date
    c. Discussed a performance based design approach for siting hydrogen stations. Spencer indicated stations are first sited following NFPA-2. A performance based approach is used only if the location cannot meet NFPA-2.
    d. Southern California was being investigated as the location for the demonstration phase of the agreement rather than the Northeast United States as originally planned. The Southern California market is better suited for implementation at this time.
    e. The current Agreement with Department of Energy expires December 31, 2020

California

Timothy E. Lipman, Ph.D., Co-Director, Transportation Sustainability Research Center, University of California-Berkeley, Berkeley, CA. 94704, 510.642.4501, telipman@berkeley.edu

Summary of discussion regarding his work on hydrogen vehicles / refuelers

1. Successfully demonstrated a 70 MPa refueling station at the Richmond Field Station, which is part of the University of California, Berkeley Campus.
2. Suggested other manufacturers that could supply a mobile refueler.
3. Suggested Caltrans lease rather than purchase a mobile refueler for the State
4. Felt the permitting process for a mobile refueler would not be as involved as for a permanent station
5. Long-term costs of a mobile refueler could be significant

Jane Berner, Staff, California Energy Commission, Sacramento, CA, 916.651.9077, jane.berner@energy.ca.gov.

A. Summary of discussion regarding the hydrogen mobile refueler under development by GTI

1. GTI has a grant to develop a mobile refueler for the State of California.
2. GTI has requested additional funding (~$500,000) and time (6 mo) to deliver a mobile refueler. Caltrans Division of Equipment has requested additional funds from the Division of Research to complete the project and deliver a hydrogen mobile refueler. Jane thought that might include evaluation by GTI once implemented, but unsure.
3. GTI maybe objecting to taking research funds due to intellectual property (IP) issues.
4. Regarding permitting, Jane was under the impression the permitting process would be less involved if Caltrans were to keep the mobile unit at a Maintenance Yard as opposed an undeveloped site.

B. Follow-up conversation with Ms Berner on July 29:

1. She confirmed the California Energy Commission and GTI had agreed to mutually terminate their agreement. However the equipment purchased under the Agreement was available to the State.
2. One H2, a subcontractor may be interested in finishing the project. (Tried contacting them, but no response).
3. The Hydrogen Safety Panel had been retained to investigate the recent Santa Clara incident (June) and possibly the February 2018 Diamond Bar incident.

Iowa

Shauna L. Hallmark Director, Institute for Transportation, Iowa State University, Ames, IA., Ph 515-986-4226, shallmar@iastate.edu.

Summary

1. Mobile refueler present a good opportunity to seed a market
2. Iowa's interest at this time is wind and ethanol (corn).
3. No plans to investigate hydrogen at this time.

Jing Dong, Professor, Depart of Civil and Environmental Engineering, Iowa State University, Ames, IA., Ph 515-294-3957, jingdong@iastate.edu.

Summary

1. Prof Dong was previously at Oak Ridge National Laboratory before joining the faculty at ISU.
2. Her work focuses more on the economics of hydrogen vehicles and refueling.
3. Aware that Oak Ridge was developing a mobile refueler and suggested I contact James Alkire.

Pennsylvania

Edward C. Heydorn, Hydrogen Energy Systems Group, Air Products and Chemical, Inc, 7201 Hamilton Blvd., Allentown, PA., Ph 610-481-7099,heydorec@airproducts.com

Call to Mr Heydorn on August 07 to ascertain his (Air Products) interest in providing one or more 70 MPa hydrogen fueler for the California Department of Transportation.

1) Summary of call follows:
   a) Yes, Air Products would be interested
   b) Based on Caltrans requirements, Air Products would develop the fueler using internal funds, thus eliminating any intellectual property (IP) issues.
   c) Once Caltrans agreed the fueler met the terms of the Agreement, Air Products would fabricate / deliver the fueler(s) using Caltrans funds.
   d) Ed felt there could be significant savings if multiple units (3-5) were purchased, as opposed to just one.
   e) Ed was agreeable to consider the equipment available from the GTI Agreement, but cautioned Air Products design philosophy is probably different from GTI.
   f) Once an executed agreement was in place it would take at least 12 mo to deliver the first unit.
   g) The street / road sweeper Caltrans is considering purchasing is a 35 MPa system, which can be fueled using the HF-150.
   h) Ed Hardiman from Div of Equipment is discussing fueling the sweeper with Brian Bonner of Air Products.
   i) Fuelers without US DOT certification cannot carry hydrogen while on public streets / highways.
   j) A Caltrans Yard maintaining a fueler would have to meet the setback / clearance requirements as defined by NFPA-2
2) If the sweeper is only a 35 MPa system, should Caltrans consider purchasing a mix of 35 and 70 MPa systems?
3) Air Products would consider a Long-Term lease Agreement for the fuelers - say five (5) years.

Washington

Nick Barilo, Hydrogen Safety Program Manager, Pacific Northwest National Laboratory (PNNL), Richland, WA, 509.371-7894, nick.barilo@pnnl.gov

Summary of discussion regarding safety of hydrogen mobile refuelers:

1. Codes and standards regulating the design and fabrication of mobile refuelers are weak. Significant research is needed in this area to improve the codes and standards.
2. The mobile refueler currently presents a vulnerability for the industry.
3. Many companies entering the market to develop mobile applications do not have a strong background in hazard analysis processes and thus may not be well equipped to identify and address vulnerabilities.
4. Tank configuration and enclosure on the trailer is a potential area of weakness. Federal government requirements pertain to the protection of storage tanks for their transportation on a highway. However, they may not adequately address the final configuration of the tanks for mobile applications.
5. The PNNL Hydrogen Safety Panel (HSP) is preparing a report on mobile hydrogen applications. The report is being developed for the California Energy Commission in response to the February 11, 2018 mobile refueler incident at Diamond Bar, CA. He agreed to provide a copy when available for release. [This was confirmed by Ms Berner at the California Energy Commission.]
6. The NTSB report from the February 11, 2018 incident is included as Attachment II.
7. As a neutral third-party, the HSP is available to assist Caltrans in the review of hydrogen mobile refueler specifications and designs and can provide input to the development of codes and standards to operate and maintain such devices.

List of Attachments

Attachment I

Innovative Advanced Hydrogen Mobile Fueler
Electricore Inc
Sara Odom (Primary Contact)
Spencer Quong
27943 Smyth Drive, Suite 108
Valencia, CA 91355
Phone: (661) 607-0260
Email: sara@electricore.org

DOE Contract Number: DE-EE0007275
Contract Expiration: December 31, 2020
DOE Manager: James Alkire
Phone: (720) 356-1426
Email: James.Alkire@ee.doe.gov

Overall Objectives

- Design and build an Advanced Hydrogen Mobile Fueler (AHMF).
- Deploy AHMF to support a network of hydrogen stations and vehicles in the United States.
- Gather and analyze fueling data for the National Renewable Energy Laboratory Technology Validation Team.

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Attachment II

NATIONAL TRANSPORTATION SAFETY BOARD

February 11, 2018, Tube Trailer Module Hydrogen Release and Fire

Diamond Bar, California

Report # HMD18FR001. Date: July 30, 2018

Number of pages in document: 49