BEST PRACTICES IN HYDROGEN FUELING AND MAINTENANCE FACILITIES FOR TRANSIT AGENCIES

Consultant Report

December 2016

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Authority Having Jurisdiction	AHJ
American Fuel Cell Bus	AFCB
American National Standards Institute	ANSI
American Society of Mechanical Engineers	ASME
Compressed Natural Gas	CNG
Diesel Gallon Equivalent	DGE
Department of Defense	DOD
Department of Transportation	DOT
Emeryville Fire Department	EFD
Emergency Shutdown Devices	ESD
Electric Vehicle	EV
Fuel Cell Bus	FCB
Failure Modes Effects and Criticality Analysis	FMECA
Federal Transit Administration	FTA
Fault Tree Analysis	FTA
Hazard and Operability Studies	HAZOP
Hawaii Center for Advancement of Transportation Technologies	HCATT
Hawaii Natural Energy Institute	HNEI
Home Refueling Appliance	HRA
International Code Council	ICC
International Electrotechnical Commission	IEC
Institute of Electrical and Electronics Engineers	IEEE
International Fire Code	IFC
International Organization for Standardization	ISO
Management of Change	MOC
National Electric Code	NEC
National Fuel Cell Bus Program	NFCBP
National Fire Protection Association	NFPA
National Highway Transportation and Safety Administration	NHTSA
National Operations Center	NOC
National Renewable Energy Laboratory	NREL
Original Equipment Manufacturer	OEM
Occupational Safety and Health Administration	OSHA
Preliminary Hazard Analysis	PHA
Renewable Identification Number	RIN
DOT's Research and Innovative Technology Administration	RITA
Society of Automotive Engineers	SAE
Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users	SAFETEA-LU
Transit Investment in Greenhouse Gases and Energy Reduction	TIGGER
Zero Emission Bus	ZEB
Zero Emission Bay Area	ZEBA

Acknowledgments

The authors wish to acknowledge the valuable contributions of the following organizations to the development of this Best Practices Guide:

- Gas Technology Institute
- The California Fuel Cell Partnership
- The U.S. Department of Energy National Renewable Energy Laboratory
- Alameda-Contra Costa Transit
- Sunline Transit Agency
- Stark Area Regional Transit Agency
- Hydrogenics
- Linde
- Ballard
- BAE Systems
- Nuvera
- ITM
- US Hybrid
- Air Products
- Siemens

These organizations served as advisors and/or reviewers as the guide was being developed and have contributed valuable content and guidance. We appreciate their help and support.

Abstract

In 2013, approximately 35% percent of the 21,000 transit buses in the United States were powered with some form of petroleum alternative or advanced technology - natural gas, bioediesel or diesel-electric hybrid powertrains. By contrast, approximately 50 fuel cell buses are currently in service in the USA. While this number may seem small, it represents a significant accomplishment. In fact, fuel cell buses are on a pathway to overcome substantial barriers to widespread comercial adoption. Within the next few years it is anticipated that fuel cell buses will complement other bus powertrain offerings in the United States, China, Europe, and Latin America.

While a great deal of focus to date has been placed on the development and advancement of the technology of fuel cell transit buses, less attention has been paid to the related infrastructure, specifically the development, explanation, and presentation for transit managers of the standards, practices, and rules that govern the development and management of hydrogen refueling stations and bus maintenance facilities. In fact, the importance of creating just such a best practices guide has been acknowledged in efforts funded by the Federal Transit Administration since 2008, including the *East Tennessee Hydrogen Initiative* in December, 2010 (Report No. FTA-TN-26-7033-2011.2) and the *Report on Worldwide Hydrogen Bus Demonstrations* in March, 2009 (Report No. FTA-GA-04-7001-2009.01). Both of these reports recommended the development of a best practices document for transit managers as a crucial next step for the industry.

The anticipated growth of fuel cell bus deployments is a direct result of the Safe, Accountable, Flexible, Efficient, Transportation Equity Act – A legacy for Users (SAFETEA-LU) that focused on fuel cell bus commercialization programs including the Federal Transit Administration National Fuel Cell Bus Program (NFCBP) and the follow-up Low- and No-Emission Bus funding program. Over $90,000,000 in federal funds - matched by industry with another $90,000,000 - resulted in a total of over a $180,000,000 investment in the technology. The projects and the teams that executed the projects were all competitively selected. resulting in a well-balanced portfolio.

Executive Summary: Best Practices in Hydrogen Fueling and Maintenance Facilities for Transit Agencies

Background

This *Best Practices* guide provides an easily digestible resource to help transit properties plan and clearly understand the parameters for refueling and fuel filling; the guidelines for safety; the requirements of maintenance facilities, and the economics of hydrogen facilities.

Objectives

Although the outcomes of this report have merit in their own right, they also help to advance many specific program and performance objectives, including:

- Increasing the public's awareness and acceptance of fuel cell vehicles and fuel cell bus technologies
- Collaborating in the development of design standards for fuel cell bus technologies;
- Developing an understanding of the requirements for market introduction;
- Compiling and maintaining key information on fuel cell bus technology development and needs.

The *Best Practices* guide specifically educates transit agency fleet managers on the basics of designing and operating a hydrogen fueling station. Main topics include:

- The generation or delivery of fuel (including liquid or gaseous hydrogen delivery; onsite refromation of methane; pipeline delivery of hydrogen; onsite electrolysis of water; mobile fueling; or the development of an energy station)
- Options for equipment and site design
- Permits, codes, setbacks, and standards
- Refueling operations and economics
- Equipment sizing
- Capacity expansion considerations
- Operating costs
- Issues specific to fuel cell bus maintenance
- Fueling protocols
- Hydrogen properties and their relationship to facility safety
- Facility upgrade options and costs
- Transit fueling infrastructure case study

Findings and Conclusions

The key finding of this report is that a consolidation of information and best practices regarding the planning, construction, operation, and maintenance of hydrogen fueling stations is needed in order to assist transit agencies with adopting this advanced technology.

CALSTART assembled a project team with the Gas Technology Institute, Air Products, and the Linde Gas Company. Together, the team convened a *Best Practices Advisory Committee* of expert transit properties and industry suppliers throughout the United States who have significant experience in planning and managing the construction of hydrogen refueling stations and maintenance facilities.

The CALSTART team performed specific research on each of the elements by collecting, evaluating, and organizing the existing research in the field. Additional research was conducted to fill in the gaps. The Advisory Committee gave the project team input, experience, and counsel on the key planning elements put forth in the publication. Additionally, they provided the project team with key early research that has been used throughout the process.

The *Best Practices Advisory Committee* includes a broad range of industry suppliers and transit operators. The transit agencies involved, representing varying sizes customer needs preferences, and regulatory requirements, are:

- Alameda Contra Costa
- Stark Area Regional Transit Agency (SARTA)
- SunLine Transit

Benefits

It is of particular concern that this document be made available to the industry's decision-makers. To this end, CALSTART and GTI executed an ambitious outreach campaign to ensure that communities and transit properties nationwide receive and utilize the findings . The team is soliciting additional partnerships with the American Society of Civil Engineers, American Public Transportation Association, various state transit associations, and other industry stakeholders to help distribute the publication and present the findings at targeted industry events.

The advisory committee has assisted in this regard by alerting transit general managers to the publicaiton. The document was previewed at the Fuel Cell Seminar in November 2015, and future conferences and events will serve as additional outlets for dissemination.

Project Information

This research was conducted by Steven Sokolsky of CALSTART. For more information, contact FTA Project Manager, Steven Sokolsky at (626) 744-5604, ssokolsky@calstart.org or Fred Silver at (626) 744-5687, fsilver@calstart.org.

1. Document Purpose and Overview of the National Fuel Cell Bus Program

Background

Recent fuel cell bus developments, demonstrations, and deployments in California have shown fuel cell buses to be reliable and robust. They also offer significant corridor flexibility as compared to other zero emssion bus alternatives. As such, there is anticipation that adoption of fuel cell buses will grow nationwide, both in the number of fleets using fuel cell buses and the number of vehicles in each fleet. This *Best Practices* guide is meant to help transit properties clearly understand the parameters for fueling hydrogen buses, the guidelines for safety, the requirements of maintenance facilities, and the economics of hydrogen facilities.

The FTA National Fuel Cell Bus Program

In Table 1-1, the NFCBP performance objectives identified by the FTA are shown on the left and the achievements to date are on the right. For example, the present generation fuel cells are just now reaching the objective of 20,000 hours in durability and the next generation is expected to exceed 25,000 hours. The tested fuel-economy in operations, while highly dependent on duty cycle and terrain, has consistently exceeded twice the present diesel bus mileage on a gallon equivalent basis. The transportation fuel cell manufacturers that can compete for transit industry fuel cells have doubled, and the supporting suppliers and supply chain has clearly expanded increasing the industry competitiveness.

Table 1-1 NFCB Program Objectives and Achievements to Date

PERFORMANCE OBJECTIVE	STATUS
Less than 5X cost of conventional bus	Cost reductions from > $3.0M in 2006 to ~ $1.3 million in 2016. Plug-in battery dominant bus < less.
Durability 4-6 years or 20,00o – 30,000 for the FCPS	20,000 hours + achieved on FC bus with durability warranties at 10,000 and 12,000
Fuel economy 2X compared to commercial transit bus	Exceed 2X conventional bus, depends on route and bus design
Bus performance equal to or greater than equivalent commercial bus	Operate up to 19 hours/day, good availability, bus miles between road calls at 4,000 (<< than conventional); better acceleration, quieter operation, weight still high
Exceed current emissions standards	Exceeds – zero emissions
Foster competition in FCB technologies	Multiple manufacturers and platforms demonstrating buses
Increase public acceptance for fuel cell bus technologies	Continued progress

The buses operated in the NFCBP, along with those planned for near-term deployment, are listed and described in *Section 9: Compendium of Buses in the National Fuel Cell Bus Program*.

Generation or Delivery of the Fuel

Transit agencies can choose between station configuration options when planning fueling infrastructure.

Table 1-2 provides an overview of hydrogen capacity for station types.

- **Liquid or gaseous hydrogen delivery**: The hydrogen is generated at an off-site location (usually by an industrial gas firm) and delivered by truck to the transit agency's fueling facility. Hydrogen can be delivered in a liquid state which must be stored on-site cryogenically before it is dispensed. It can also be transported in a gaseous state and stored on-site in pressure vessels.

- **On-site reformation of methane**: Approximately 95% of H_2 produced today is made via steam reforming, a process where steam and methane (from natural gas) react at high-temperature to produce CO_2 and H_2. This process can be used at a smaller scale to produce H_2 from pipeline natural gas at the fueling facility.

- **Pipeline delivery of hydrogen**: Though much less common than hydrogen delivery or on-site generation, pipeline delivery of hydrogen is possible through the approximately 700 miles of hydrogen pipelines in the U.S. Generally, the high cost of delivery through hydrogen pipelines limit this mode to fueling facilities proximate to an existing hydrogen pipeline. Pipeline delivery also becomes more practical as the required capacity of a fueling facility increases.

- **On-site electrolysis of water**: Here, electricity is used to split water into hydrogen and oxygen, the hydrogen captured and stored for dispensing. This process requires water purification equipment and consumes high levels of electricity.

- **Mobile fueler**: These portable stations are relatively easy to move and feature on-board fuel storage in need of periodic replenishment. Because they incorporate both storage and dispensing capabilities into one unit, a mobile fueler is a solution for smaller fleets.

- **Energy station**: With the right economics, a delivery system can sometimes be integrated into facility infrastructure to supply reliable electricity on-site. This can provide space heating and even hot water while producing a "slipstream" or by-product of hydrogen that can be used for vehicle fuel.

Table 1-2 Hydrogen Station Type and Typical Dispensing Capacity

General Station Type	Typical Capacity (kg/day)
Liquid Delivery	1,000
Onsite Reformation	100-1,000
Pipeline Delivery*	>1,000
Onsite Electrolysis	30-100
Mobile Fueler	50
Energy Station (CHP)	100-300

*Economics for pipeline delivery are largely based on proximity to existing pipelines

Many factors must be considered in deciding what type of fueling facility is the best fit for a fleet.

- Hydrogen capacity factors
  - Fleet size
  - Available fueling time (fueling in one shift or dispersed throughout the day)
  - Bus hydrogen system (determines max fueling rate)
  - Bus fill receptacle (determines max fueling rate)
- Site parameters
  - Availability
  - Size
  - Access to utilities
- Fuel sourcing
  - Delivery (gas or liquid)
  - Hydrogen pipeline
  - Natural gas pipeline
  - Water supply (electrolysis)
- Asset ownership
- Operations and safety
  - Will size of site allow room for equipment with required separation distances?
  - Emissions permit required (reformer only)
  - Approval for technology from AHJ (Authority Having Jurisdiction)

The economics typically can be broken into up front capital cost (including site permitting, preparation, and equipment installation) and operating cost. (equipment lease and energy costs to produce the hydrogen or a purchased cost for delivered hydrogen)

2. Options for Equipment and Site Design for Hydrogen Refueling Facilities

Time Fill vs Fast Fill

Background

In a *time fil*l (also referred to as slow fill), one or more compressors provides steady overnight (or any time of day when the vehicles are parked) filling, typically over an 8 to10-hour period). This method is generally used by centrally fueled fleets or personal commuters with a home refueling appliance (HRA).

In a fast fill, compressors coupled with compressed gas storage provide fast filling (~5 minutes for a light duty vehicle and ~15 minutes for higher storage volume vehicles, such as trucks and buses) much like a typical gasoline station. This method is typically applied in public access fueling stations and (usually) transit bus fleets.

Fueling Workflow

In a **time fill**:

1. Bus pulls into parking/fueling location
2. Driver connects to time-fill dispensing post
3. Bus is fueled unattended overnight
4. Driver disconnects from dispensing post in the morning

In a **fast fill**:

1. Bus pulls into lot
2. A “fueler” (an individual dedicated to servicing the bus), pulls bus to fueling island and begins fueling
3. Bus is cleaned and inspected while fueling
4. When the bus is filled with fuel, the fueler disconnects from the dispenser
5. Bus pulls away from fueling island (repeat step 1 with next bus)

Equipment

In a **time fill**, fill posts equipped with one or more fill hoses are used. These are simple vertical posts used to support fill hose(s), a hose retractor, and a shut-off valve with vehicle connector. In a **fast fill**, more typical commercial dispenser cabinets are used with one or two hoses, metered display, and an on-off lever or buttons. Primarily due to the internal metering device – sophisticated mass flow meters that measure the hydrogen dispensed into each vehicle -- fast fill dispensers add $20,000 to the cost of the less expensive time fill dispenser. However, these mass flow meters are for transit stations (e.g. if dual use of the station is planned for sale to private light duty vehicles).

Table **2-1** and Figure 2-1 below show more details on time fill and fast fill equipment. Note: Storage can also be a single buffer in place of three banks in a cascade as shown.)

Table 2-1 Equipment for Time and Fast Fill Refueling Stations

Equipment	Time Fill	Fast Fill
Compressor	Small compressor necessary as simultaneous filling occurs over 8+ hrs	Fillings usually occurs sequentially and in minutes, so a larger compressor is required
Gaseous Hydrogen Storage	Small volume of buffer storage required to limit compressor start/stop cycling	Large Buffer storage required to limit compressor start/stop cycling and reduce fill time
Dispenser	One dispensing post required per fueling location	One dispenser for every ~20 buses.
Controls	Controls are very simple for start/stop and safety shutdown	Controls are more complicated to decide whether gas should go to filling bus or filling storage and to determine when to safely terminate the fast fill.

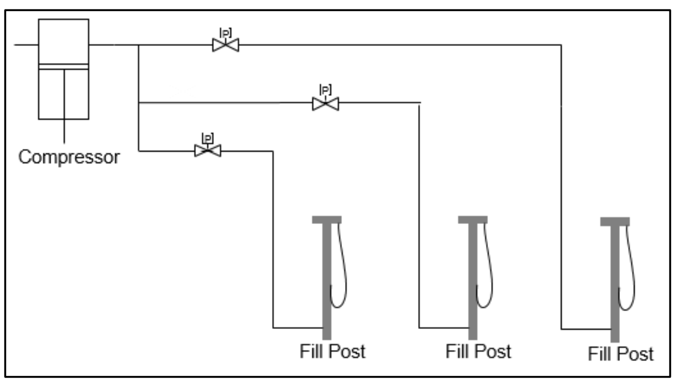

Figure 2-1 Example Time Fill Configuration

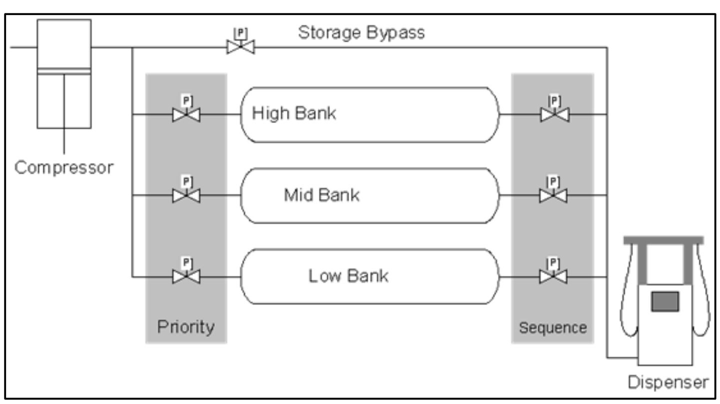

Figure 2-2 Example Fast Fill Configuration (Note: Storage can also be a single buffer in place of three banks in a cascade as shown.)

Connectors

When considering the several connectors on the market, keep in mind that:

- Connector pressure rating must meet or exceed pressure rating of vehicle tank.
- Dispenser nozzle must be compatible with vehicle receptor.

- Fast fills, (up to 7.2kg/min) require a different nozzle with a different standard (ISO 27268:2012 as opposed to the normal SAE J2600 standard) and are permitted for heavy duty vehicles only.

- Fast fill nozzles are designed to prevent a connection between a fast-fill nozzle and a normal-fill receptacle.

In non-communication fast fill, the dispenser is unaware of the temperature inside the vehicle tank. The tank is typically filled more quickly and conservatively and may not fill as fast or provide a 100% fill.

  - Additional information on communication and non-communication fills is available in the fueling protocols discussion in Section 5.

Figure 2-3 Normal Rate Fueling Nozzle from OPW (left) and Fast Fueling Nozzle from WEH (right)

Advantages of Time Fill vs. Fast Fill

- Time Fill:
  - Simple design and control

    - Little or no buffer storage necessary
    - Less severe temperature-rise phenomenon observed than during fast filling hydrogen cylinders (therefore more complete fills conducted)
    - Fills occur unattended: lower labor requirement
- Fast Fill:
    - Easier and quicker fills in a high demand period or after maintenance
    - Fewer dispenser posts required
    - Allows for dual-use station – sale of hydrogen to public consumers

Figure 2-4 Application of Time Fill Fueling (left) Fast Fill at a Bus Fueling Station (right)

Fill Temperature

Hydrogen, like all gases, increases in temperature when compressed into a container. Since hydrogen is less dense at high temperature, and refueling causes an increase in pressure as well as temperature, this results in less hydrogen in the vehicle tank at the end of a fill for a given ending pressure. This partial fill can be significant for fast fills; precooling can be used in fast fills to lower the temperature of the gas going into the tank to ensure a more full fill (although this is usually not yet used in transit applications). In time fills, the longer filling time allows heat to dissipate into the tank wall, so heating is not as significant. More detail on the impact of heating is available in the filling protocol section.

Dual Use Public/Private Transit and Light Duty Vehicle Stations

General

A dual use station is available for fueling by others (i.e., the general public, select pre-arranged users, external fleet fueling) as well as the primary intended purpose for transit bus fueling.

- Additional Required Equipment:
    - Commercial dispenser with certified metering and credit card authorization

    - Fast fill system (if not already available for bus fueling). Additional buffer storage, priority panel, and precooling required to enable quick fueling
    - Because bus applications presently fill to 350bar, and many hydrogen vehicles are capable of filling to 700bar, a dual-use station may require additional infrastructure to reach the 700bar necessary to ensure the public utilization.

- Property: Public-access space is required for maneuvering into and out of position around the dispenser. For site security, a separate lane and a security wall for automobile access may be necessary
- Liability: Additional liability coverage may be needed to protect against incident on site involving the public.
- Public Access may provide the transit property with additional revenues to buy down the cost of operations and the refueling equipment. AC Transit offers public refueling access for hydrogen

Station Equipment Ownership and Fuel Sales

A station can be built, owned and/or managed by either a transit agency or a third party. Here are three options:

- Transit acts as contractor for station construction, ownership and operation of the station. In the case of a dual-use station, the transit company can manage the fuel sales and customer service or hire a third party.
- Transit hires a third party to build and operate fueling station, but retains ownership. This third party will often manage the sales for a dual-use station through a shared revenue arrangement.
- Third parties own and operate a fueling station in exchange for a variety of commercial arrangements, such as, but not limited to: guaranteed minimum fuel sales (at fixed rate, variable rate, indexed rate, etc.), fixed payment schedule (regardless of fuel usage), or a combination of the above with or without shared revenues from a dual use station.

3. Permits, Codes, Setbacks, and Standards

Why be concerned with codes and standards?

Adhering to codes and standards is essential for ensuring user and public safety and confidence in commercial enterprises, particularly for those deploying new technologies.

Definitions

- Code: A document compiling various provisions across a broad subject matter
  - Suitable for adoption into law
  - Incorporates by referencing a range of standards
  - Examples include National Electric Code (NEC), National Fire Protection Association (NFPA), and International Fire Code (IFC).
- Standard: A document covering a narrow subject
  - Some standards, like codes, incorporate by referencing other standards.
  - Examples include CSA America HGV4 - Fuel Dispensing for Hydrogen Gas Powered Vehicles (Figure 3-1), SAE J2600 - Compressed Hydrogen Vehicle Fueling Connection Devices.
- Certification: Determination by a certification organization that a manufacturer has demonstrated the ability to produce a product that complies with the requirements of a specific standard(s).
  - Codes and standards can supplement certification with use of the related terms "approved, listed, and labeled."
  - Compliance by a third party or, in the case of the term "approved," is something that is deemed acceptable to the authority having jurisdiction (AHJ).
  - These terms can apply to individual components or, more broadly, to systems or an entire assembly

Importance of Standards

When listed equipment is unavailable, codes and standards typically require “approval” of the equipment by the AHJ. This places a significant responsibility on AHJs who may lack the resources to support a thorough review, may be unfamiliar with the technology or may be unaware that their review and approval covers unlisted equipment. Therefore, when a listing standard is not available, third-party certification for systems should be sought. Fortunately, standards now exist for dispensers, storage, hoses, breakaways, connectors, compressors, meters, and many other components and pieces of equipment are under development.

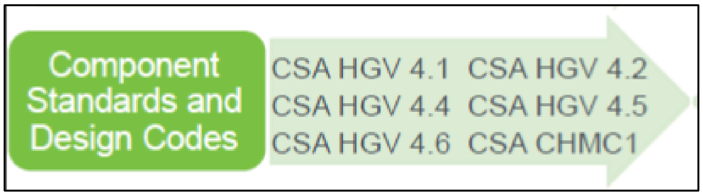

Figure 3-1 Examples of Component Standards

Standard development organizations involved in fueling stations

The following organizations have developed codes and standards which apply to different aspects of the hydrogen fueling station (Table 3-1 Common Codes and Standards for Hydrogen Fueling Stations).

Table 3-1 Common Codes and Standards for Hydrogen Fueling Stations

Construction	H2 Dispensing	FC Vehicle
ICC	SAE	SAE
NFPA	CSA	NHTSA
Local codes		DOT
Electrical	**Storage**	**Fuel Cell Power**
NEC/NFPA	NFPA	ANSI
IEEE	CGA	UL
ANSI	ASME	ISO
UL	ANSI	IEC

Progress on Hydrogen Standards

Historically, primary guidance comes from:

- NFPA 52, Vehicular Gaseous Fuel Systems
- NFPA 55, Compressed Gases and Cryogenic Fluids
- NFPA 853, Installation of Stationary Fuel Cell Power Systems
- NFPA 70, National Electrical Code

With the increased interest in hydrogen as a fuel source, the NFPA Standards Council was petitioned in 2005 to develop an all-encompassing document establishing requirements for hydrogen technologies. In 2011, a Hydrogen Technologies Code (NFPA 2) was introduced. NFPA 2 is meant to provide a single resource to support the design and approval of hydrogen equipment and facilities. The 2013 version of NFPA 52 transferred the responsibility for hydrogen vehicle fueling requirements to the NFPA 2 technical committee. Starting with the 2016 version, NFPA 2 will be the only source for this information. NFPA 2's significance will likely grow since approved changes to the 2015 edition of NFPA 1, Fire Code, and the

International Fire Code will directly refer to NFPA 2 for hydrogen vehicle fueling facility requirements.

Observations

Good progress has been made to make sure available hydrogen expertise has been codified (e.g. gaps within U.S. and international codes are filled, emphasis is placed on educating first responders and AHJs). Thus far, the development of codes and standards has not impeded commercialization, but more education and outreach will help to reduce delays and costs of implementing fueling infrastructure.

Separation Distances for Hydrogen Station Components

NFPA 2 contains minimum separation distances required between hydrogen station equipment and surrounding buildings, property limits or boundaries. These separation distances are dependent on the pressure of the stored hydrogen as well as the size of tubing that is used in the equipment. Figure 3-2 below details separation distances for a 3000-7500 psig hydrogen system with a tubing inside diameter of 0.288”. Shorter distances can be used for smaller tubing. The International Fire Code also contains separation distances for hydrogen equipment, but this code is not as detailed as NFPA 2. The code used can change with different AHJ’s, and it is therefore important to work with the local AHJ to ensure compliance with the correct code. Figure 3-3 below details the additional distances required for liquid hydrogen, although both Figures 3-2 and 3-3 leave out some detail for clarity. Please refer to NFPA 2 directly when planning a station.

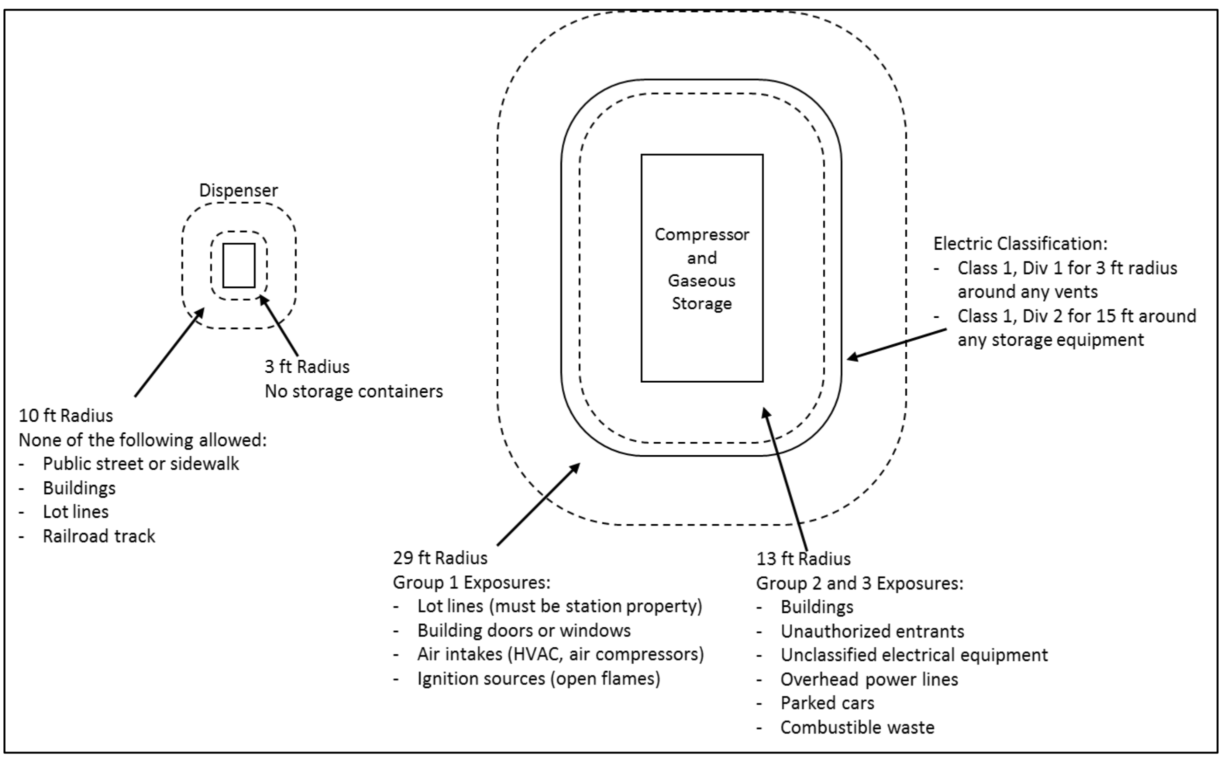

Figure 3-2 NFPA 2 Separation Distances for 350 Bar Hydrogen Equipment with 0.288” ID Tubing

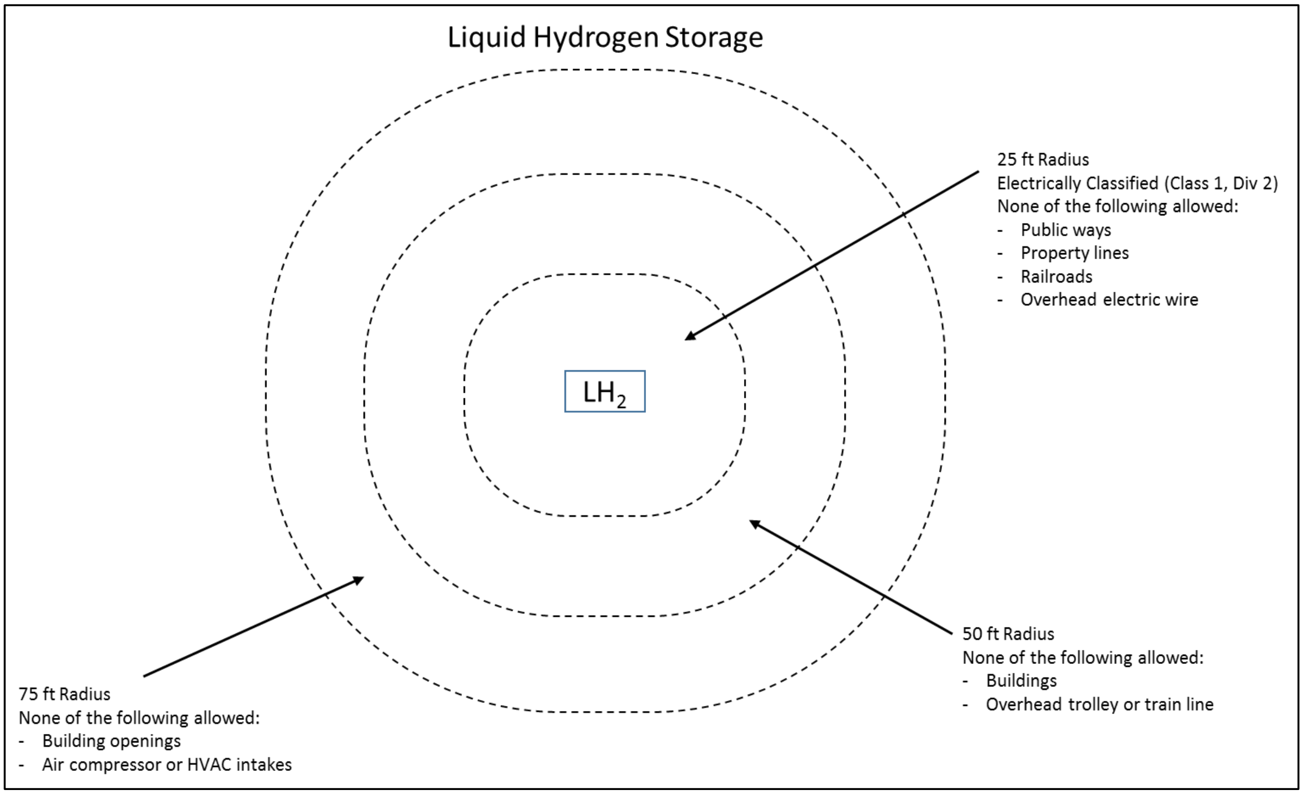

Figure 3-3 NFPA 2 Separation Distances for Liquid Hydrogen (3501-15,000gal)

Figure 3-4 below shows one possible configuration for a transit bus fueling station.

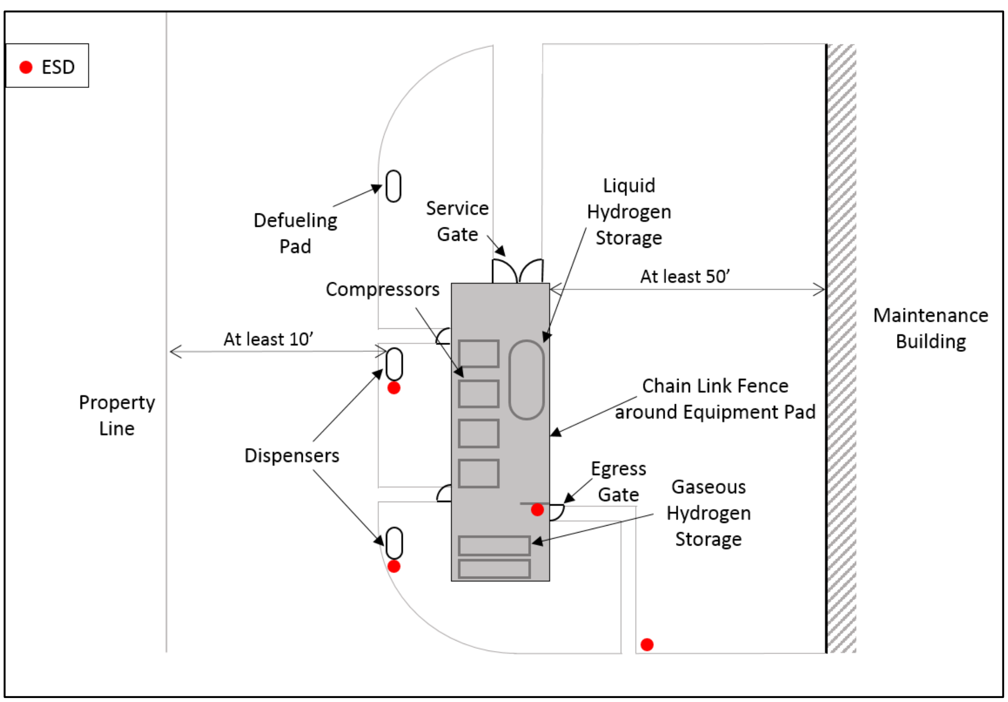

Figure 3-4 Example Transit Bus Fueling Station Configuration

4. Bus/Refueling Operations and Economics

Infrastructure economics and costs

Equipment required vs. fleet size

Representations of the typical equipment required for different sized fleets for both time fill and fast fill configurations are shown below in Table 4-1 and

Table 4-2. Note these tables, created for example only, assume that each bus requires 40kg of hydrogen per day and that the fast fill of a bus is 15 minutes in duration.

- For small fleet sizes (1-4 buses), time fill configurations are more cost-effective than fast fill because they allow for use of smaller compressor capacity and less storage.
- For larger fleet sizes, the required compressor capacity is similar for both time and fast fill.
- Fast fill always requires fuelers to drive each bus to the dispenser, perform the fueling process, and return the bus to the storage area. This labor cost can be partially offset by combining the fueling time with other mandatory maintenance such as bus cleaning, checking fluid levels, and/or emptying the fare box.
- Although time fill posts are much less expensive than fast fill dispensers, locating time fill posts at the parking area for every bus in a large fleet may be very difficult depending on site configurations. For this reason, (and for fueling flexibility), fast filling is usually used for large transit fleets.

Table 4-1 Possible Time Fill Equipment Configurations

# Buses	H2 Fuel Mass (kg/day)	Filling Time (hrs)	Time Fill Rate (kg/hr)	# Compressors	Compressor Size (kg/hr)	Storage Required (kg)	# Time Fill Posts	Fueler Labor (hrs/day)
1	40	10	4	1	4	3	1	0
4	160	10	16	1	16	12	4	0
20	800	10	80	2	40	60	20	0
40	1600	10	160	3	53	120	40	0
80	3200	10	320	6	53	240	80	0

Table 4-2 Possible Fast Fill Equipment Configurations

# Buses	H2 Fuel Mass (kg/day)	Filling Time (hrs)	Time Fill Rate (kg/hr)	# Compressors	Compressor Size (kg/hr)	Storage Required (kg)	# Time Fill Posts	Fueler Labor (hrs/day)
1	40	1	40	1	40	120	1	1
4	160	2	80	2	40	120	1	2
20	800	7	120	2	60	120	1	7
40	1600	7	240	4	60	240	2	14
80	3200	7	480	8	60	480	4	28

Fueling Station Capital Cost

Only a few hydrogen fueling stations have been built for transit applications in North America, all with different configurations meant to validate particular technologies that might be the best fit for a transit application. Therefore, economies of scale have not been realized. Table 4-3 below presents information on five transit fueling stations.

Table 4-3 Transit Fueling Station Configurations

Transit Agency	AC Transit [1]	BC Transit [2]	SunLine [3]	Santa Clara VTA [4]	Columbia, SC [5]	SARTA [6]
H2 Supplier	Linde	Air Liquide	N/A	Air Products	Airgas	Air Products
Hydrogen Source	Liquid Delivery for buses + Electrolyzer for LD cars	Liquid Delivery	Reformer	Liquid Delivery	Gaseous Delivery	Liquid Delivery
Station Dispensing Capacity	600 kg/day	800 kg/day	216 kg/day	Not reported	120 kg/day	300 kg/day
H2 Max Production Rate	65kg/day (electrolyzer only)	No production	216 kg/day	No production	No production	No production
Pressurization Method	Gaseous compressor	Liquid H2 Pumps	Gaseous compressor	Liquid Compression System	Gaseous compressor	Liquid compression system
FCBs in Fleet	12	20	5	3	1	2 (will have 10)
Public Use Available?	Yes	No	Not as of mid-2016. Upgrade planned	No	Yes	Planned
Dispenser Pressure	350/700 bar	350 bar	350 bar (700 bar planned)	350 bar	350 bar	350 bar (700 planned)
Fill Rate*	Fast	Fast	Normal	Fast	Normal	Fast
Active communications	Not reported	Not reported	Not reported	Yes	Not reported	Not reported
Station Capital cost	$10 million	$6 million (CAD)	$750,000 (reformer only)	$640,000	Not reported	$2.2 million
H2 Cost	$9.10/kg 'as dispensed'	$10.55/kg excluding capital	$7.66 to $23.46 depending on use	$9.06/kg delivered $18.19/kg when accounting for boil-off	$9.93/kg + $2,000/month	$4.60 for H2 only
Maintenance costs	$142,000/yr			Included in monthly fee to Air Products		

[1] K. Chandler and L. Eudy, “National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2.”
[2] L. Eudy and M. Post, “BC Transit Fuel Cell Bus Project: Evaluation Results Report.”
[3] L. Eudy and K. Chandler, “SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Fourth Results Report.” and personal communication between T. Edwards and Steven Sokolsky
[4] K. Chandler and L. Eudy, “Santa Clara Valley Transportation Authority and San Mateo County Transit District Fuel Cell Transit Buses: Evaluation Results.”
[5] L. Eudy and K. Chandler, “National Fuel Cell Bus Program: Proterra Fuel Cell Hybrid Bus Report, Columbia Demonstration.”
[6] K. Conrad, personal communication with Fred Silver

As can be seen from Table 4-3, transit fueling stations can have many different configurations and there is limited data available on prices paid for these stations. In some cases, the transit agency owns the fueling facility, in others it does not. In all cases, much of the funding was provided by an external source such federal or state government, and goals have differed depending on the funding agency. For instance, the BC Transit fueling station was designed with approximately double the liquid hydrogen storage as necessary because the liquid hydrogen was to be trucked nearly 3000 miles from Quebec where it is renewably produced via electrolysis using hydropower.

In 2007, the US Department of Transportation's Research and Innovative Technology Administration (RITA) published a study projecting the cost of infrastructure for a 100-bus fuel cell bus fleet. The study concluded that a fueling station for 100 fuel cell hybrid buses would cost $1.7-$4 million and be capable of producing (or purchasing) and dispensing 1,870kg/day [7].

More information has been gathered about light duty hydrogen fueling stations. Although many of the components are the same, there are enough differences to make correlation difficult. For instance, hydrogen compressors for transit applications need only to reach 350 bar pressure, not the 700 bar necessary for most light-duty stations. Also, the dispenser does not require refrigeration or an expensive high accuracy mass flow meter for transit vehicles.

Operating and maintenance costs

Maintenance costs for hydrogen fueling stations are not well documented for transit applications. Often maintenance is handled by the station provider or owner with a service contract. The cost of these contracts is shown in Table 4-3.

For light duty vehicle fueling stations, an NREL project created a Hydrogen Station Cost Calculator which includes maintenance cost estimation (shown in Figure 4-1 below). Although the numbers will vary with transit applications, the scale may be similar. The simplicity of transit applications may lower the costs slightly from what is shown.

---

[7] US Department of Transportation, "Fuel Cell Bus Life Cycle Cost Model: Base Case & Future Scenario Analysis."

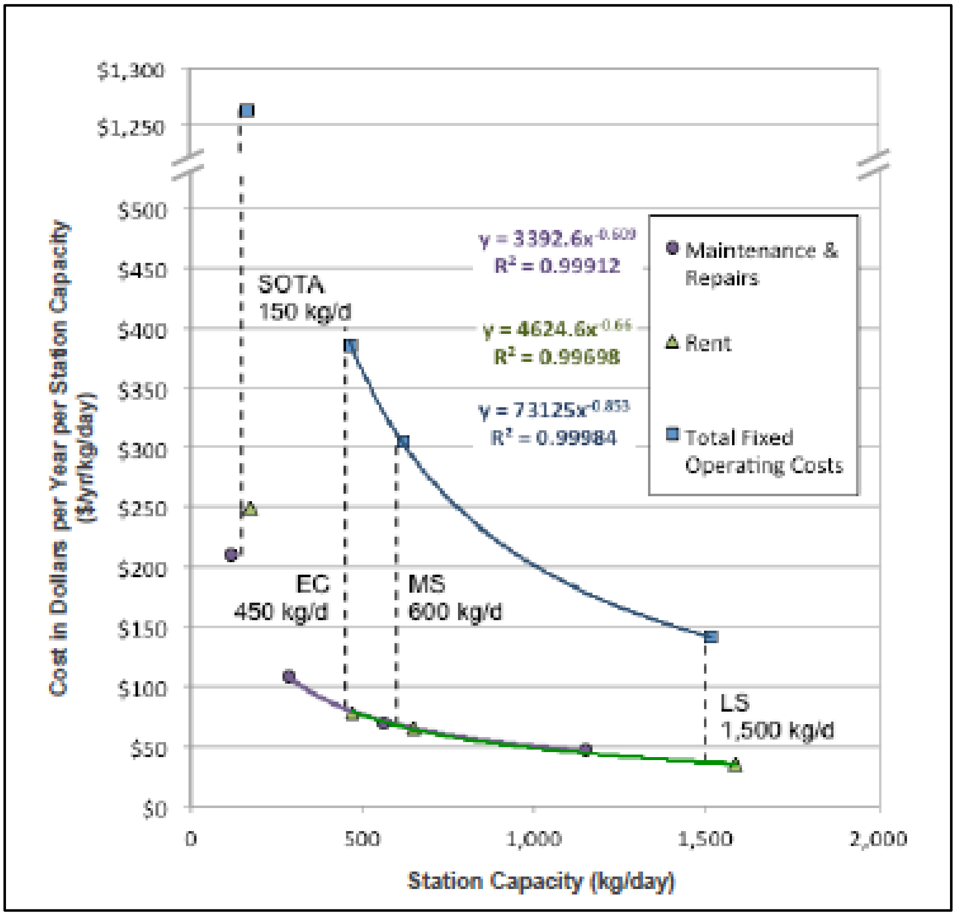

Figure 4-1 Fixed Operating Costs for Hydrogen Stations

Cost of Hydrogen Delivery vs. Generation

Hydrogen can be either delivered to the transit station (via truck as a gas, via truck as a liquid, or via gas pipeline) or generated on site from natural gas or water via reformation or electrolysis, respectively.

A UC Davis study in 2005 examined the differences in operating costs for several hydrogen stations utilizing delivery vs generation technologies [8]. Table 4-4 provides below (both full costs and cost/kg). Although this study is centered on light duty vehicles, general conclusions can be drawn:

- Larger-scale reforming on-site provides the lowest fixed operating cost compared to liquid hydrogen purchases and deliveries.
- Electrolysis requires high capital cost and high levels of electricity, increasing the operating cost.

[8] Jonathan Weinert, "A Near-Term Economic Analysis of Hydrogen Fueling Stations."

- Pipelines can provide cheap hydrogen, but only if the station is a very short distance from an existing pipeline.
- Liquid hydrogen allows for lower capital investment with a similar total hydrogen cost to a reformer (which is much more complicated to install and operate).

Reformer and electrolysis technologies may carry higher risk due to a lack of experience with these technologies at small scales. It should be noted that this study is over 10 years old and does not account for more recent technological advancements (no subsequent comprehensive studies have been conducted). Also, with the hydrogen fueling infrastructure just starting to be deployed, transit agencies should continuously look for recent technological advancements which could benefit their programs.

Table 4-4 Estimated Costs for Various Station Types [9]

Station Type	**Reformer**	**Electrolysis**	**Pipeline Delivered**	**Reformer**	**Liquid H_2 Delivered**
Capacity (kg/day)	100	100	100	1000	1000
Capital and Installation	$1,047,927	$923,039	$583,141	$5,137,202	$2,677,362
Operating Cost	$92,594	$202,558	$79,459	$456,278	$901,007
Cost/kg					
Natural Gas	$1.14			$1.14	
Electricity	$0.36	$8.25	$0.35	$0.36	$0.11
Fixed Operating	$3.84	$3.44	$4.24	$1.13	$5.09
Capital Charge	$5.65	$4.59	$2.70	$3.20	$1.55
Delivery and Installation	$2.30	$2.41	$1.73	$0.70	$0.48
Total	$13.29	$18.69	$9.02	$6.53	$7.23

Additional Considerations

- Hydrogen generated from renewable resources (bio-methane or water + renewable electricity) qualifies for renewable fuel credits referred to as Renewable Identification Numbers (RINs). These RINs can be sold to petroleum refiners which are mandated to attain a certain percentage of renewable fuels in their products. In 2015, RINs were sold for approximately $0.80 per 77,000Btu, equating to approximately $1.20/kg of hydrogen. Note that this price is very volatile and will change significantly over time. So far in 2016, the price has risen to over $0.90 per 77,000Btu.
- Various tax deductions, credits and certifications are available depending on the local government and station configuration. These are fluid and regional in nature and should be investigated prior to finalization of station design to ensure applicability.

[9] Ibid.

- Depending on the arrangement with the gas supplier, it may be necessary to purchase or rent trucks and/or trailers used for delivery of gaseous or liquid hydrogen. This is included in the UCD analysis above.

5. Fueling Protocols and Specifications for Bus Manufacturers and H_2 Storage Tank Suppliers

Fueling Standard

Fueling a vehicle with compressed hydrogen gas presents new issues as compared to refueling with conventional liquid fuels. This is primarily due to: 1) gas heats up when compressed, and 2) the pressure in the tank is dependent on temperature.

- Two standards have been established in the US and internationally for storage vessel technologies. Each hydrogen tank has a normal working pressure of either 350 bar (5,000psig) or 700 bar (10,000psig). Heavy duty hydrogen vehicles use 350 bar hydrogen.
- A ‘full’ tank is defined as the level of hydrogen in the tank at the normal working pressure and with the tank settled at 59°F.
- As a tank is filled, the temperature increases. Gas density decreases with increasing temperature, so the tank will contain less hydrogen than a ‘full’ fill if it is filled to the normal working pressure and the gas is more than 59°F.
- Tanks are allowed to be filled up to 125% of their normal working pressure if the temperature is high. This allows a full fill at elevated temperatures (either because of hot weather conditions, or heat from gas compression that will cool slowly after the fill is complete).
- Dispensers must register the temperature inside the vehicle tank in order to determine at what pressure to stop fueling (referred to as the target fill pressure). The dispenser to can determine the tank temperature through:
    - Measurement (Active Communication). This involves a temperature measurement device on or inside the vehicle tank that communicates with the dispenser through a vehicle communication interface (usually via an infrared device, see Figure 5-1 below).
    - Calculation. The dispenser can also contain an algorithm to calculate an estimated tank temperature, the dispenser then determining an appropriate target fill pressure based on this calculation. Because it is not a direct measurement, this method is less accurate than the communication fill. Therefore, the target fill pressures for non-communication fills are conservative and can leave the vehicle tank partially full depending on the algorithm and control system employed.
- For fast-fills, depending on the vehicle’s tank pressure rating, the hydrogen may need to be pre-cooled down to -20°C or -40°C in order to achieve a full fill. Hydrogen heats up

significantly when compressed. Without pre-cooling, the hydrogen can exceed the high temperature rating of the tanks (85°C). For transit applications, the hydrogen is usually not pre-cooled.

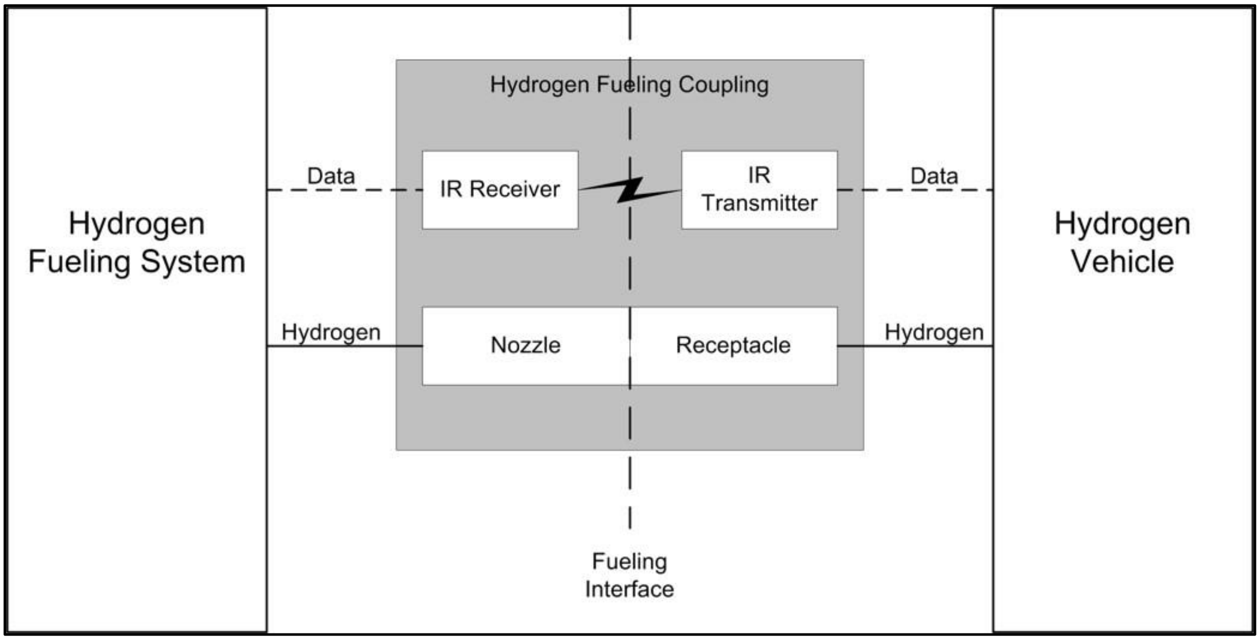

Figure 5-1 Example of a Vehicle Communication Interface [10]

The Society of Automotive Engineers (SAE) has published two standard fueling protocols, SAE J2601 and J2601-2. J2601, for application to light duty vehicles only, details a fueling process for hydrogen tanks which have a maximum storage capacity of 10 kg and a normal working pressure of either 350 bar or 700 bar. J2601 is detailed in its approach to filling vehicle tanks, determining the target fill pressure by using lookup tables. There are different tables for different size tanks, dispenser gas temperatures, and if the fill is communication or non-communication. However, these lookup tables only exist for tanks up to 10 kg capacity and are therefore not applicable for heavy duty hydrogen bus applications.

For larger tanks, J2601-2 is the applicable protocol. Far less detailed a protocol, the fueling algorithm is left to the dispenser manufacturer. While this allows the flexibility for improvements in the fueling algorithm, information about that algorithm will only be available from the dispenser manufacturer. This highlights the need to work with the dispenser manufacturer to ensure the bus/dispenser interface is specified appropriately. Some notable topics in J2601-2 are:

1) Fill speed. The J2601-2 protocol defines three possible fill speeds and the connection standard to be followed for each option. For additional information see Table 5-1 below. The light duty fueling standard (J2601) covers the normal fueling option only.
2) The fast fueling dispenser nozzle is unable to connect with a standard normal fill rate receptacle.

10. SAE J2799

3) The station (dispenser) is responsible for ensuring that the vehicle tank remains below the temperature limit (85°C) and is not subject to over fill. Other limits must be noted as well.
4) Active communication is optional for heavy duty vehicles, and choosing this option is usually based on an economic decision weighing the value of additional complete full fills vs. the cost of the communication equipment.

Table 5-1 Fueling Rate Options for Heavy Duty Vehicles [11]

Category	Application	Connection Standard	Fueling Rate
Fast Fueling - Option A	Fast fill - only allowed for heavy duty vehicles	ISO 27268:2012	≤ 120 g/s (7.2 kg/min)
Normal Fueling - Option B	Normal rate - same rate as light duty vehicle fueling	ISO 27268:2012 or SAE J2600	≤ 60 g/s (3.6 kg/min)
Slow Fueling - Option C	Time fill	ISO 27268:2012 or SAE J2600	≤ 30 g/s (1.8 kg/min)

Bus Specifications

To ensure that a bus is compatible with a fueling station, one must:

- Ensure bus receptacle is compatible with dispenser nozzle
  - Ensure pressure rating of receptacle meets or exceeds rating of nozzle.
  - Ensure fast flow receptacle is used if fast flow nozzle is used.
  - Ensure bus and dispenser/nozzle manufacturers understand requirements for compatibility if communication equipment is desired.
- Ensure pressure drop between receptacle and storage tank(s) is acceptable
  - Fast fueling rates may require larger tubing in the bus fuel system to avoid choke points which would limit fueling rate.
  - A high pressure drop between the receptacle and the tank would result in a slower fill rate and potentially a less than full fill.

Bus Hydrogen Tanks: Although the specific construction is different for hydrogen tanks, the tank types are similar to compressed natural gas (CNG) tanks. There are 4 types (Figure 5-2):

- Type 1: All steel tank. This is low-cost but heavy.
- Type 2: Steel tank hoop-wrapped with composite. This provides some weight savings over type 1 tanks.

[11] "J2601/2: Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles - SAE International."

- Type 3: Metal liner with composite shell. This provides weight savings at higher cost.
- Type 4 (Figure 5-3): Polymer lining with composite shell. This offers the most weight savings since it removes the metal liner.

Most on-vehicle hydrogen storage tanks are either type 3 or 4. Type 1 or 2 are often used for ground storage.

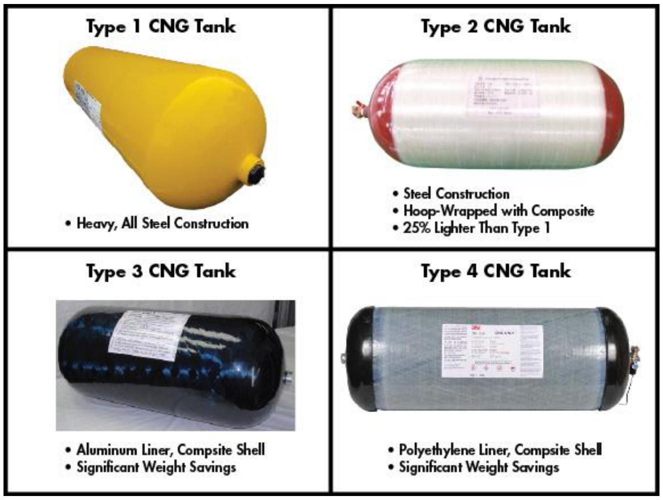

Figure 5-2 CNG and Hydrogen Tank Types [12]

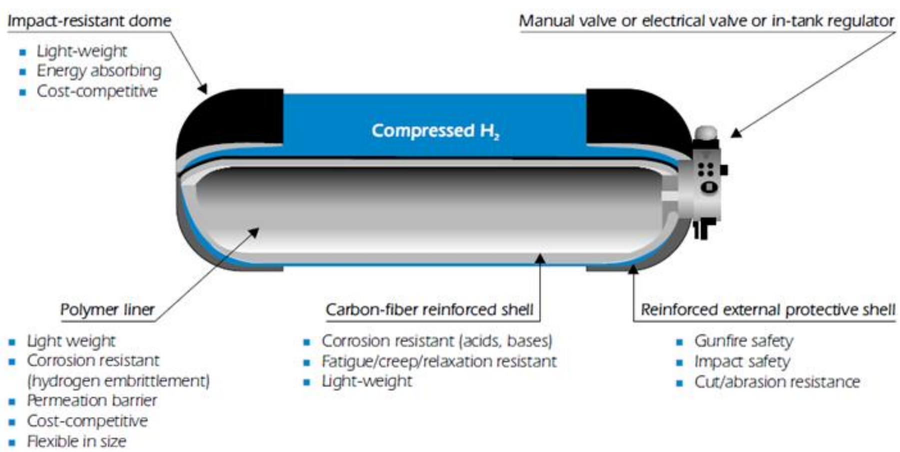

Figure 5-3 Type 4 Hydrogen Tank [13]

[12] CNG Pit Stop, "CNG System Installation Basics - How CNG Works."

[13] Dr. Samy Pal, "Application for Anode Hydrogen Exhaust for a DFC-300 Fuel Cell."

6. Fuel Cell Bus Maintenance Facilities

Background on the Properties of Hydrogen and Fuel Safety

Properties of Hydrogen

Hydrogen is 14 times lighter than air (Figure 6-1). As a result, it rises and disperses quickly in air. Hydrogen is colorless, odorless, tasteless, and non-toxic. Natural gas is odorless but an odorant is added. Because hydrogen disperses so quickly in air, there is no existing odorant light enough to 'travel' with it.

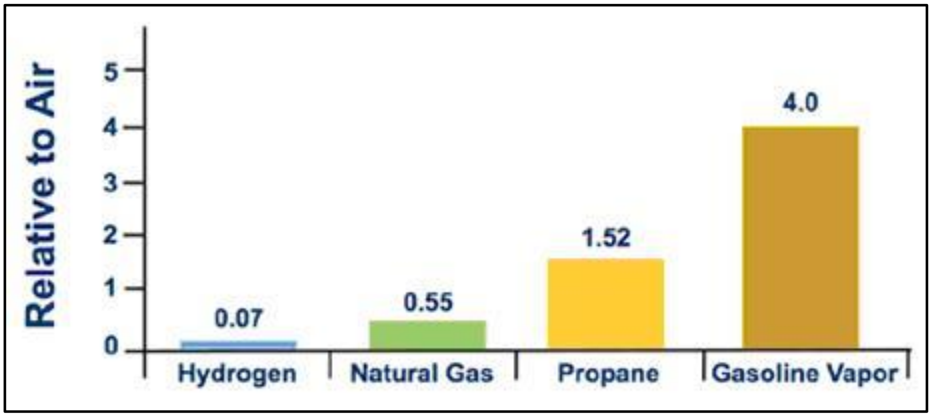

Figure 6-1 Relative Vapor Density of Hydrogen and Other Fuels [14]

Compressed gases also store mechanical energy. An uncontrolled release of pressure such as a vessel rupture can propel the cylinder at speeds capable of causing significant damage and injury. High pressure gas impinging on a surface or skin can also cause damage or injury.

Compared to gasoline, hydrogen gas contains 2.5x the energy per mass. One kilogram of hydrogen contains the equivalent energy of roughly one gallon of gasoline. However, even when compressed to 350 bar, hydrogen requires more than 10x the volume to store the same energy.

Hydrogen has a very large flammability range compared to other fuels (Figure 6-2). Mixtures of 4-75% hydrogen can catch fire and combust. At the optimal combustion condition (29% hydrogen), the ignition energy for the hydrogen mixture is very low (0.02mJ). The ignition energy increases at lower concentrations.

[14] "Best Practices Overview | Hydrogen Tools."

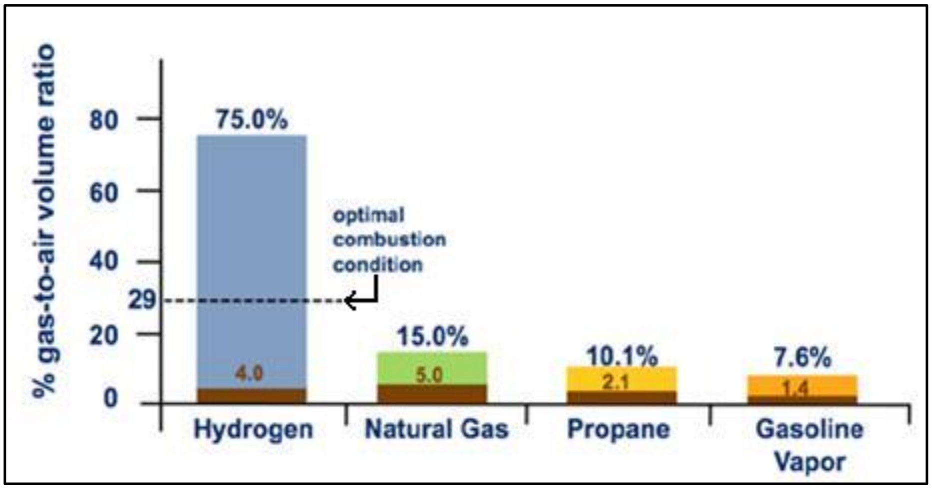

Figure 6-2 Flammability Range of Hydrogen and Other Fuels [15]

Hydrogen burns with a pale blue flame (Figure 6-3, invisible in daylight), infrared cameras often employed for flame detection. It burns rapidly in comparison to other fuels, and In open environments, a hydrogen cloud can burn and release energy quickly. In closed environments this rapid combustion may cause high pressures capable of damaging buildings and injuring people. Also, leaks in pressurized containers will create a jet of gas which may ignite.

Figure 6-3 Hydrogen Flame [16]

Liquid Hydrogen

Liquid hydrogen is normally stored at approximately -423°F, and can therefore cause cryogenic burns or lung damage. It can vaporize and expand to fill an enclosed space. Gaseous hydrogen occupies approximately 850 times the volume of liquid hydrogen. If a small amount of liquid hydrogen is left in an enclosed space, it could vaporize and fill the space, displacing oxygen and acting as an asphyxiant. For this reason, as well as the ignition potential mentioned above, ventilation is necessary when working with hydrogen (gas or liquid) in confined spaces.

[15] Ibid.
[16] "Blewbury Energy Initiative - Hydrogen."

Maintenance Facilities

Maintenance Garage or Barn

The 2016 edition of NFPA 2 Hydrogen Technologies Code has provided requirements for hydrogen vehicle repair garages. Below is a brief summary of highlights - refer to NFPA 2 for more detail.

- Defueling required for all work on the fuel system or all hot works (welding or open flame) within 18” of vehicle fuel supply container.
    - Specific requirements for defueling systems are also included in NFPA 2
- A gas detection system must be provided and ready to activate the following if hydrogen level exceeds 25% LFL.
    - Initiation of audible and visual signals
    - Deactivation of heating systems
    - Activation of the exhaust system (unless the exhaust system operates continuously)
- Open flame heaters or heating equipment with a temperature over 750°F (399°C) are not permitted in areas subject to ignitable concentrations of gas

Additional equipment may be necessary depending on specific applications and local code requirements. For instance, AC Transit’s Oakland Maintenance Facility includes a 2-hour firewall to separate the hydrogen maintenance area from other sections of the building, as well as an ignition free space heating system, high speed roll-up garage doors programmed to open if hydrogen is detected above 20% LFL, and Class 1 Div 2 electrical classification throughout. The upgrade to this facility required a $1.5 million investment and would have cost even more had AC Transit not required buses to depressure fueling systems to 600 psig prior to maintenance.

In contrast, SunLine Transit conducts maintenance on hydrogen buses in what is essentially a canvas tent costing approximately $50,000. By designing the tent to allow hydrogen to escape through large gaps, SunLine avoided the cost associated with a facility upgrade. Gas detection was still required and the lighting is Class 1 Div 1 rated. A structure such as this provides a low-cost option to an agency in warmer climates,

Also, repair garages will usually require a defueling system to empty a vehicle’s fuel storage system to enable repair work to be completed. The defueling system can either transfer the gas from the vehicle tank to a storage tank or vent to the atmosphere (or a combination of both). A summary of maintenance facilities and the associated costs is shown in (Table 6-1) below.

Table 6-1 Summary of Maintenance Facility Upgrades

Transit Agency	AC Transit [17]	BC Transit [18]	SunLine [19]	Santa Clara VTA [20]	Columbia, SC [21]
Facility Cost	$1.5 million	$680,000 (CAD)	$50,000	$4.4 million	Not provided
Type of modification	Partial modification of existing building	Modifications included in design of new facility	New naturally ventilated 'tent' built	New 2-bay maintenance facility and car wash	Added lift to car wash canopy
Defueling Required?	Max 600 psig pressure	Not reported	No	No	No

Refueling islands and canopies

Canopies must be designed to prevent accumulation of hydrogen (sloped canopy roof structure pictured in Figure 6-4). Emergency shutdown devices (ESDs) must be present in two locations, one positioned at the dispenser, and one on a path of egress 25-75ft from the dispenser and generation/compression/storage equipment. The ESD must automatically shut off power to all hydrogen storage, compression and dispensing equipment. Additional requirements for this system are contained in the International Fire Code and NFPA 2.

Figure 6-4 Example Canopy [22]

[17] K. Chandler and L. Eudy, "National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2."
[18] L. Eudy and M. Post, "BC Transit Fuel Cell Bus Project: Evaluation Results Report."
[19] L. Eudy and K. Chandler, "SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Fourth Results Report."
[20] K. Chandler and L. Eudy, "Santa Clara Valley Transportation Authority and San Mateo County Transit District Fuel Cell Transit Buses: Evaluation Results."
[21] L. Eudy and K. Chandler, "National Fuel Cell Bus Program: Proterra Fuel Cell Hybrid Bus Report, Columbia Demonstration."
[22] "Anteater Express | Sustainability."

Safety Systems – Hazard Analysis

NFPA 2 requires a hazard analysis to be completed for all hydrogen fueling stations prior to operation, and because this can force design modifications, it is best to complete the analysis early in the design process. All known hazards are ranked by likelihood and severity of consequences, and the ranking determines if the hazard is acceptable or if additional mitigation measures must be taken. The most common methods of hazard analysis include hazard and operability studies (HAZOPs), failure modes effects and criticality analysis (FMECA), preliminary hazard analysis (PHA), fault tree analysis (FTA), and event tree analysis.

Standard designs analyzed by recognized methodology do not require examination upon every installation. Rather, site-specific elements that are unique to the installation must be reviewed in concert with the analysis performed on the standard system to ensure that the standard design has not been altered in a way that would negatively affect the hazard analysis.

The hazard analysis must be conducted by a qualified engineer with proven expertise in hydrogen fueling systems and installation (consultants are also available to assist).

Safety Systems – Procedures

The following procedures should be developed prior to the operation of the fueling station:

- Emergency response procedure
    - Include operation of the ESD button, emergency contact, evacuation of the station, and assistance to emergency personnel.
- Fueling station startup procedures
    - Startup under normal conditions
    - Startup after emergency shutdown device (ESD button) activation
- Fueling Procedure
- Defueling procedure (for venting gas from vehicle tank(s) prior to maintenance)
- Maintenance procedures or manual (for both vehicles and fueling station)
- Safety equipment testing procedures (should define testing frequency)
    - Calibration of gas monitoring equipment
    - Testing of fire and gas detection equipment
    - Station leak check
- Management of change procedure
- Incident investigation procedure

Safety Systems – Maintenance

All maintenance activities should be conducted in accordance with a written and approved procedure or manual, or have a risk review completed. The risk review details the activities to be performed, the risks associated with those activities, and control or mitigation steps required to minimize the risks.

A maintenance schedule must be completed and implemented. Include safety system testing in maintenance schedule. A maintenance log must be maintained (per NFPA 2). And should detail:

- The maintenance activity performed and the date completed
- The start and stop time of the maintenance work
- Whether the maintenance was scheduled or unscheduled
- If unscheduled, the reason it was performed
- The name of the maintenance inspector
- A list of the components repaired/replaced including serial number and/or certification number of the component

Safety Systems – Management of Change

Components of the hydrogen fueling station are specified and designed according to a particular design plan. Safety, codes, and future expansion issues all play a part in the design process. Seemingly minor modifications to the station can have a large impact on the station and safety. All system changes which are not a 'replacement-in-kind' require completion of a management of change (MOC) procedure. A 'Replacement-in-Kind' is defined by OSHA as any replacement part that meets the design specification of the original part. It is best to consult with the hydrogen station designer and installer on any changes (other than identical part number replacements) to ensure the replacement meets all of the design specifications.

Poor management of change has occurred with hydrogen systems. A common issue is that hydrogen can damage some metals and degrade strength over time, causing failure. It is important to consider the metallurgy of replacement parts in addition to pressure and temperature ratings. This is one reason for the station designer's involvement in changes to the station to determine if a replacement part meets all design criteria.

If it is determined that the change is not a 'replacement-in-kind', the MOC procedure should be initiated. This procedure should include:

- Revisiting the hazard analysis for the station and updating per the changes
- Conducting a hazard analysis on any new hazards that may have been introduced by the change
- Reviewing these documents with the hydrogen station designer and installer
- Preparation of a report that documents changes
- Management approval of the changes
- Updating all affected documents
    - Procedures

- Drawings
- Training documents (fuelers/maintenance personnel/emergency responders)

- Communicating changes and impacts to all affected personnel (may include personnel not employed by transit company)
- Retaining documentation of completed MOC as a record

Safety Systems – Safety Culture

In a strong safety culture, everyone feels responsible for safety and pursues it on a daily basis; employees go beyond "the call of duty" to identify unsafe conditions and behaviors, and intervene to correct them. It is extremely important to have full involvement or "buy-in" from all employees. The pyramid shown below (Figure 6-5) represents the number of safety incidents at various levels recorded (or estimated) for every workplace fatality. Preventing injuries, lost workday cases and even fatalities begin with monitoring and mitigating near misses and at-risk behaviors. A company with a strong safety culture usually experiences fewer at-risk behaviors and consequently fewer injuries, lost workday cases, etc. Additional information on building a safety culture is available on the OSHA website.

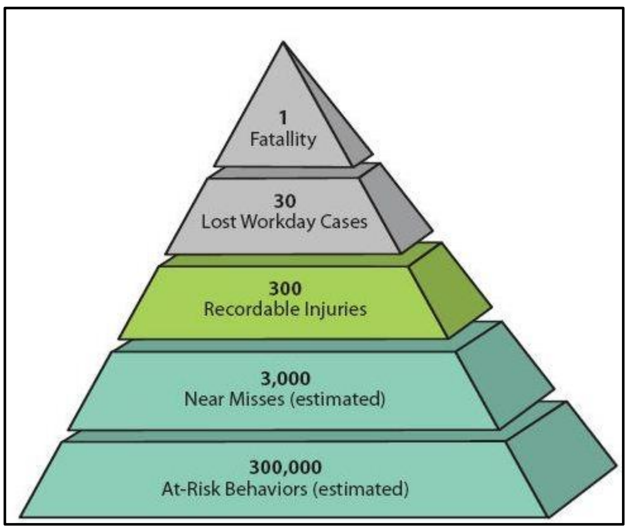

Figure 6-5 Safety Incident Pyramid [23]

Communications

It is important to meet with members of the community early on in the planning process. Many hydrogen station plans have experienced significant resistance from the local community, resulting in delays to the project. Also, the local authority having jurisdiction (AHJ) typically lacks experience with hydrogen station codes and standards, so initiating communications with the AHJ early on will help streamline the planning and permitting processes.

[23] "Workplace Injury Management | Biosymm."

It is wise to involve a variety of stakeholders in the early planning meetings. Representation from the proposed industrial gas supplier, local gas and/or electric utility, vehicle manufacturer, tank manufacturer, station design engineering company/consultant, station equipment suppliers, and others can help to educate the local decision makers.

Training

Relevant personnel must receive training on the properties and hazards of hydrogen, as well as the following specific training:

- Bus Operators: Because they are responsible for the operation of the bus in public transit service, bus operators must have a thorough knowledge of the unique features of the vehicle. Training should include instruction on how to identify emergency situations, how to keep the public safe, and the emergency action plan.
- Bus Maintenance Technician: Hydrogen buses have several components similar to other buses, but the differences (especially the hydrogen system) require additional training to review the tools and procedures used to safely maintain a hydrogen bus fleet.
- Bus Fueling Personnel: Only individuals trained in the differences between a conventional liquid fuel dispenser and a hydrogen dispenser should be permitted to operate the dispenser.
- Fueling Station Maintenance Personnel: This group requires training on the equipment and maintenance procedures used in servicing the fueling station equipment.
- Emergency Personnel: The local fire department, police and/or SWAT teams, and any other first responders require training on the emergency systems and procedures as well as a general understanding of station operation and locations of key equipment.

Drills

Drills should be conducted on a regular basis per a schedule determined during the station design and hazard analysis, and should include all affected employees as well as local emergency response personnel.

Learning from the AC Transit Emeryville Station Incident

Although the situation was handled safely and there were no injuries, a recent incident at a hydrogen fueling station provides an opportunity to improve on the safety and communications systems employed at hydrogen fueling stations. Sandia National Laboratory led an investigation into this incident, the report available on their website and summarized below [24]

On the morning of May 4th, 2012 an incident at the AC Transit hydrogen fueling station in Emeryville, CA began when a pressure relief valve on one of the high pressure gaseous hydrogen storage vessels failed, releasing hydrogen through the vent stack to atmosphere. This hydrogen ignited, producing a jet flame out the vent stack. The failure of the pressure relief valve was linked to improper material selection - only certain types of steel are capable of

[24] Aaron P. Harris and Chris W. San Marchi, "Investigation of the Hydrogen Release Incident at the AC Transit Emeryville Facility (Revised)."

operating in high pressure hydrogen environments without failure. A component in the valve was incorrectly specified with steel that was susceptible to failure in hydrogen service. When that component failed, it caused the release of hydrogen out the vent stack and subsequent fire.

The fire burned for approximately 2.5 hours before it was extinguished by isolating the supply of gas. The initial response was consistent with the available procedure: an AC Transit employee activated the emergency stop and local emergency services were contacted. Shortly after arriving, the Emeryville Fire Department (EFD) contacted the Linde National Operations Center (NOC). The Linde NOC initiated the emergency procedures to respond to the incident, including sending Linde personnel to the site as quickly as possible. However, the Linde NOC did not communicate their ability to remotely monitor the pressure transmitters on the hydrogen storage vessels (the pressure had dropped significantly, indicating the fire was not in contact with the vessels).

Without this information, the EFD had to assume vessel failure was a possibility and proceeded with caution, evacuating a local school and a one block radius, and requesting shelter facilities at a second local school. When Linde personnel arrived, they entered the area with thermal imaging equipment and were able to pinpoint the fire to the vent stack and close the isolation valve on the leaking vent stack, extinguishing the fire.

Several lessons can be learned from this incident. The most obvious is that material selection is very important, especially when dealing with hydrogen. When it comes to communication, it is clearly important that emergency responders receive all relevant information. In this case, direct communication between the Linde NOC and the EFD with regard to the pressures in the storage vessels would have helped the EFD make more informed decisions (although it may not have changed the decisions that were ultimately made due to the lack of ability to verify the readings from the remote system). Guidelines for this communication should be developed in the emergency response procedure for the site. It is also recommended that regular drills with key personnel be performed.

AC Transit

Emeryville

The AC Transit HyROAD Program is focused on accelerated operations of its fuel cell electric buses, leading to major improvements in fuel cell durability and availability at rated performance. AC Transit's fleet of 12 buses are in service up to two shifts per day. Even with an improved average mileage of 7.04 miles per DGE (diesel gallon equivalent) compared to 4.20 miles per DGE for their standard 40-foot diesel transit bus, the individual buses consume 24 to 28 kg of hydrogen per day. This requires a fueling station capable of dispensing over 300 kg/day. Accelerated operations with their fleet resulted in AC Transit and Linde opting for a liquid delivery station type with a high-performance, fast-fill dispensing system. The Linde fueling system uses an IC-50 ionic compressor and high pressure storage is capable of filling the bus hydrogen storage tank system with up to 30 kg of hydrogen at 350 bar in 6 minutes. The total fueling capacity of the system is 360 kg/day [25, 26, 27, 28]

[25] K. Chandler and L. Eudy, "National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2."

The Emeryville hydrogen fueling station is a liquid hydrogen solution and began fueling buses in August 2011. The Emeryville dispensers are shown in Figure 6-6. An important attribute of the new fueling station is the capability to offer light duty vehicle fuel dispensing “outside the fence” for the general public, on the right in Figure 6-6. The bus fuel dispenser is “inside the fence at the Emeryville bus facility, on the left in Figure 6-6.

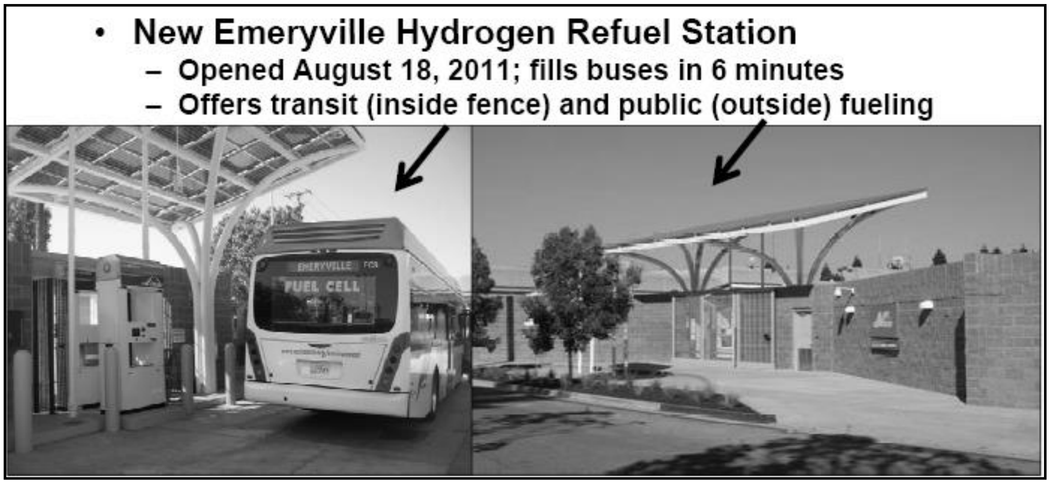

Figure 6-6 AC Transit Emeryville Fueling Station Dispensing Locations

Hydrogen is produced and liquefied at a central production plant and delivered to the Emeryville station for storage and dispensing to the buses. In California, all central plants steam reform natural gas (often referred to as steam methane reformation or SMR). The hydrogen is then cooled to a liquid form and delivered in a tanker truck. The Emeryville station stores the liquid hydrogen in an insulated tank as shown in Figure 6-7. When needed, the station uses ambient air to warm and vaporize the H_2 into a gaseous state. Linde uses an ionic liquid compressor to compress the gas, a process claimed to be more energy efficient and requiring less maintenance than a mechanical piston compressor. Using this method, the system stores up to 360 kg of gaseous H_2 per day. The system dispenses the hydrogen into the fuel tank(s) on the buses providing a fast fueling rate. This rate is crucial to widespread use of fuel cell technology in transit applications allowing for a large bus division to refuel in one shift with increased storage and an appropriate number of dispensers.

[26] AC Transit, Tour of AC Transit Facilities.
[27] Linde, “Linde Industrial Gases.”
[28] ProtonOnSite, “Hydrogen, Nitrogen, and Zero Air Generators.”

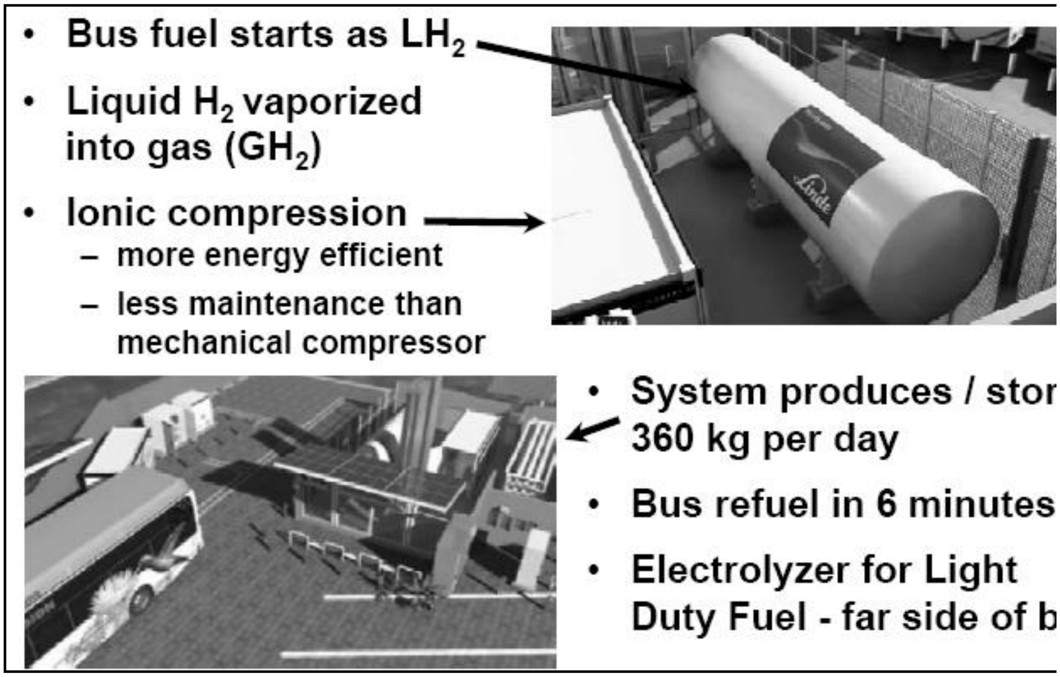

Figure 6-7 AC Transit Liquid H2 Emeryville Station [29]

[29] AC Transit, Tour of AC Transit Facilities.

7. Directory of Infrastructure Equipment Providers

Hydrogen Production

Giner

Manufacturers of hydrolysis units for hydrogen generation, with unit production estimated at 0.33 kg/hr and at pressures up to 50 bar [30]. They also produce advanced fuel cell membranes.

Giner, Inc.
89 Rumford Avenue
Newton, MA 02466
Tel: 781-529-0500
Fax: 781-893-6470
information@ginerinc.com

ITM Power

Self-contained hydrogen generators using electrolysis technology and producing 20 to 500 kg/day [31].

ITM Power Head Office
22 Atlas Way
Sheffield
S4 7QQ
+44 (0)114 244 5111

Praxair

A company that produces and sells a wide variety of industrial gases, including compressed and liquid hydrogen. Praxair also is capable of handling distribution and gas management [32].

Praxair, Inc Worldwide Headquarters
39 Old Ridgebury Rd.
Danbury, CT 06810 USA
1-800-PRAXAIR
info@praxair.com

Proton OnSite

This company specializes in hydrogen generation units in a range of sizes. They make two models, the M1 and the M2, that are at a scale to be useful for fueling stations. The maximum generation of these units is 1000 kg per day, operating at over 400 m^3/hr [33]. The modular design, however, allows for scaling up production by whatever factor is necessary.

Proton OnSite
10 Technology Drive
Wallingford, CT 06492
01.203.678.2000

30. Giner, "Home."
31 ITM Power, "HFuel."
32 Praxair, "Compressed Hydrogen Gas or Liquid Hydrogen (H2)."
33 ProtonOnSite, "Hydrogen, Nitrogen, and Zero Air Generators."

Teledyne Systems

Manufacturer of hydrogen generators, from individual units to whole hydrogen plants (2.8 – 500 NM^3/hr) for on-site generation [34].

Teledyne Systems, Inc.
Corporate Headquarters
10707 Gilroy Road
Hunt Valley, MD 21031
Tel: 410.771.8600
Fax: 410.771.8620
http://www.teledynees.com/

Station Components

PDC Machines

Gas compressor manufacturers with experience in products for use in fuel cell stations. Their instruments are capable of producing gas at a wide range of pressures and flow rates (from 7.2 – 277 kg/hr) [35]. PDC has more than 180 compressors operating in demonstration and commercial fuel cell stations.

PDC Machines Inc.
1875 Stout Drive
Warminster, PA 18974
215-443-9442

Full Stations

Air Products

A company that provides a wide range of services and products relating to industrial gases. For hydrogen fuel, they can provide the entire supply chain from pure hydrogen gas to on-site generators to full fueling stations capable of using a variety of feedstocks [36,37]. They have been involved with fuel cell bus demonstration projects, including during the 2008 Beijing Olympics [38].

Air Products and Chemicals, Inc.
Corporate Headquarters
7201 Hamilton Boulevard
Allentown, PA 18195-1501
1-800-654-4567
gigmrktg@airproducts.com

---

[34] Teledyne Energy Systems, “Product Portfolio.”
[35] PDC Machines, “Diaphragm Compressors: Designed and Constructed for High Reliability and Low Maintenance.”
[36] Air Products, “Hydrogen Energy - Material Handling.”
[37] Air Products, “H2 Energy and Fueling Station.”
[38] Air Products, “Hydrogen Fuel for Transportation.”

Air Liquide

Another large industrial gas company, they have already collaborated on over 60 hydrogen fueling stations, with plans in place to develop a regional network of stations in the northeast of the United States [39]. They are capable of supplying on-site generation, hydrogen transportation, and filling station infrastructure technologies. Past projects have included building the fuel station for the BC Transit fuel cell bus demonstration that took place during the 2010 Vancouver Winter Olympics [40].

Air Liquide USA Inc.
2700 Post Oak Blvd
Suite 1800
Houston, Texas - 77056
+1 877 855 9533

GTI

GTI has over 40 years of experience in the hydrogen fuel industry. They have designed a natural gas to hydrogen system for the DOE [41]. By using natural gas as the source for hydrogen generation, they can leverage existing infrastructure for natural gas transportation and convert the gas to hydrogen on-site. GTI was also the lead partner on the Capital Metro fueling station for the fuel cell bus demonstration in Austin, TX and the integrated biogas-to-hydrogen system at the JBLM military base [42, 43].

GTI Headquarters
1700 S Mount Prospect Road
Des Plaines, IL 60018
847-768-0500
publicrelations@gastechnology.org

H2 Frontier, Inc.

This company has six active hydrogen fuel station projects. Described as providing hydrogen generation, storage, and delivery systems, they work closely with Air Liquide, NREL, the California Energy Commission, and car companies among others [44].

H2 Frontier, Inc.
403 East Gardena Blvd
Suite B
Gardena, California 90248
info@H2Frontier.com
(951) 741 – 3631

[39] Air Liquide USA, “Gases, Technologies & Services for Industry in the U.S.”
[40] Air Liquide USA, “Renewable Energy.”
[41] Leslie Eudy, Kevin Chandler, and Christina Gikakis, “Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012.”
[42] Gas Technology Institute, “Demonstrating Fuel Cell Technology for Public Transit.”
[43] Gas Technology Institute, “Converting Biogas to Hydrogen.”
[44] H2 Frontier Inc, “Hydrogen Generation, Storage & Delivery Systems.”

Hydrogenics

Long-standing hydrogen energy company active in many areas. They offer a standardized and complete hydrogen fueling station, from electrolysis to tank fueling, capable of producing 20 – 130 kg/day [45].

Hydrogenics USA
12707 High Bluff Drive
Suite 200
San Diego, California
USA 92130
Tel: +1.858.794.1473
Fax: +1.905.361.3626
energystorage@hydrogenics.com

Linde

A company capable of supplying all aspects of hydrogen fuel infrastructure, including generation, distribution, storage, and fueling infrastructure for both compressed and liquid hydrogen [46]. They have participated in a number of fuel station projects, mostly based in Europe but with some work in the US, including the California Fuel Cell Partnership.

Linde North America Inc.
575 Mountain Ave
Murray Hill, New Jersey 07974
1-800-755-9277

[45] Hydrogenics, "Hydrogen Fueling Stations."
[46] Linde, "Linde Industrial Gases."

Appendix: Compendium of Buses in the National Fuel Cell Bus Program

In the past decade and a half, many fuel cell buses of different size, design, and strategy have been built and deployed across the United States. A variety of component manufacturers have come together under different integrators to test this technology. Transit agencies have been trained and the public has become familiar with fuel cells wherever they have been tested. A few manufacturers have emerged as the most likely to continue expanding the fuel cell market going forward. Fuel Cell Electric transit buses are offered by the American Fuel Cell Bus (Forty-foot integrated by BAE Systems), New Flyer (Forty and Sixty Foot), and Van Hool (Forty-foot) all are next-generation fuel cell buses in active development. These companies will continue working to mature this technology, by improving efficiency, range, and price.

For this report only those North American hydrogen fuel cell buses (FCB) with ongoing or planned future production will be reviewed. Though there are other FCBs in-use in North America, these designs are not being supported for future production and will not be built again. Since they do not represent viable, purchasable options, we are excluding them from this report. Of the vehicles described below, all are distinct from each other either by chassis or drivetrain architecture.

Existing Buses

BAE Systems/Ballard/El Dorado National-California: "American Fuel Cell Bus" (AFCB)

This vehicle was developed through a partnership between three companies, each of which makes either fuel cells, drivetrains, or bus chassis [47]. The different companies teamed to construct a fuel cell-dominant 40-foot transit bus. El Dorado manufactures the bus chassis, BAE Systems designed the fuel cell dominant hybrid propulsion system, and Ballard is responsible for the fuel cell engine. Although fuel-cell dominant, the bus utilizes a small Lithium-Ion battery for transient propulsion and energy capture. As of February 2015, there are currently three AFCB models in use at SunLine Transit. The first was deployed in January 2012 and the second two deployed in June 2014 and funded through TIGGER (Transit Investments for Greenhouse Gas and Energy Reduction) [[48]]. Many new buses are on-order and currently under construction or in the pre-planning stages. Funding has been awarded for 12 additional AFCBs through 2017-2018 for sites including MBTA (Massachusetts), UC-Irvine, SARTA (Ohio), and others. AFCB specifications are listed below (Table 0-11) and the operational vehicle is shown in Figure 0-1.

[47] CALSTART and US Department of Transportation, "Developing and Demonstrating the Next-Generation Fuel Cell Electric Bus Made in America."
[48] US Federal Transit Administration, "TIGGER Program Overview."

Table 0-1 AFCB Vehicle and Operational Specifications [49] [[50]]

Parameter	Detail
Length	40’
GVWR	34,800 lbs
Fuel Cell	Ballard 150kW
Fuel Storage	50kg @ 350 bar in eight Dynetek tanks
Battery Type & Capacity	A123 Nanophosphate Li-Ion, 11 kWh
Fueling	Fast-fill capable H2 fueling
Consumption	8 MPkg
Range	325 miles
Deployment Locations	Thousand Palms, CA; Irvine, CA
Number Deployed in US as of July 2016	5 (in use), 12 (funded and on order)

Figure 0-1 The AFCB Deployed for SunLine Transit in Thousand Palms, CA [51]

Van Hool/Siemens: A330 Fuel Cell Bus & A300 L “Nutmeg” Fuel Cell Bus

Van Hool, a Belgian company, has partnered with UTC Power fuel cells and Siemens electric motors to produce a fuel cell bus that has been widely tested, improved, and deployed. As part of the National Fuel Cell Bus Program in the United States, Van Hool successfully partnered with AC Transit in Northern California to test three Van Hool model A330 fuel cell buses [52]. From 2006 – 2010, these three buses were deployed across five transit agencies for over 17

[49] BAE Systems, “American Fuel Cell Bus.”
[50] Sunline Transit Agency, “Clean Fuels Fleet.”
[51] Ibid.
[52] Eudy and Post, “Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Third Report.”

hours of operation per day. One bus each of the same model was deployed with SunLine Transit in California and Connecticut Transit; these two vehicles were operated through 2011. This program of accelerated testing led to improvements in design including improved energy storage, less weight, and better integration between OEMs. Because of the success of the program, 12 next-generation A300 L Van Hool buses were deployed across Northern California as part of the Zero Emission Bay Area program, starting in 2011. These buses are primarily in use at AC Transit, but Golden Gate Transit, SamTrans, VTA, and Muni have had access to the vehicles for trials. Connecticut Transit ordered four of the improved Van Hool buses for deployment in early 2011. In April of 2012, one of these buses was transferred to Flint, Michigan for a one-year demonstration with the city's MTA [53]. At the conclusion of the Connecticut Transit project, the remaining three buses were transferred to North Augusta (South Carolina), AC Transit in California (to join the ZEBA program), and US Hybrid (for continued testing) [54,55]. Specifications and pictures for both buses are listed in Table 0-2 and shown in Figure 0-2, respectively.

Table 0-2 Van Hool Fuel Cell Bus Vehicle and Operational Specifications [56, 57, 58,59]

Parameter	**A330**	**A300 L**
Length	40'	40'
GVWR	43,000 lbs	40,000 lbs
Fuel Cell	UTC Power 120 kW	UTC Power 120 kW
Fuel Storage	40kg @ 350 bar in Type III SCI tanks	40kg @ 350 bar in eight Dynetek tanks
Battery Type & Capacity	Nickel Sodium Chloride, 53 kWh	Lithium-Ion, 21 kWh
Fueling	5 kg/min capable	5 kg/min capable
Consumption	7.37 MPkg (8.33 MPGe)	6.4 MPkg (7.4 MPGe)
Range	275 miles	230 miles
Deployment Locations	San Francisco Bay Area, CA; Connecticut; Thousand Palms, CA	San Francisco Bay Area, CA; Connecticut; Thousand Palms, CA; Flint, MI; North Augusta, SC
Number Deployed in US as of July 2016	5	14

[53] Leslie Eudy, Kevin Chandler, and Christina Gikakis, "Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012."
[54] Leslie Eudy and Christina Gikakis, "Fuel Cell Buses in U.S. Transit Fleets: Current Status 2013."
[55] North Augusta City Council, "Regular Meeting Minutes."
[56] Leslie Eudy and Kevin Chandler, "SunLine Transit Agency Hydrogen-Powered Transit Buses: Evaluation Results Update."
[57] US Department of Energy, "AC Transit Demos Three Prototype Fuel Cell Buses."
[58] AC Transit, "Taking the HyRoad...With Zero-Emission Technology."
[59] Van Hool, "Hybrid Fuel Cell Bus."

Figure 0-2 Van Hool Fuel Cell Bus (A300 L) [60]

Near-Term Future Buses

BAE/El Dorado/: Battery-Dominant "American Fuel Cell Bus"

The battery-dominant version of the AFCB is currently under contract with a team, including BAE Systems, that will provide the enhanced battery modules and completing overall assembly of the vehicle. Despite the use of a reduced power fuel cell, the price per net kilowatt may be up to 40% lower than comparable full fuel cell buses [61]. Achieving this improvement is largely due to optimization of the hybrid system and lower component pricing. The build and delivery to the deployment fleet (SunLine Transit) is scheduled for 2017. Specifications for this vehicle are listed below in

Table **0-3**; after assembly, delivery, and testing, more accurate and comprehensive data will be available.

Table 0-3 Battery-Dominant AFCB Vehicle and Operational Specifications [62]

Parameter	Detail
Length	40’
Fuel Cell	Ballard 150kW
Fuel Storage	Luxfer storage tanks
Battery Type	Lithium-Ion, 50 kWh
Deployment Locations	Thousand Palms, CA
Number Deployed in US as of July 2016	In development

[60] Ibid.
[61] CALSTART, “Zero-Emission Battery Dominant Fuel Cell Bus.”
[62] Ibid.

New Flyer/Hydrogenics/Siemens: Xcelsior with "Celerity Plus" Range Extender

New Flyer is currently under contract to provide the bus platform and assembly labor for the first fuel cell bus purpose-built for medium- and heavy-duty commercial vehicles. They have worked closely with Hydrogenics, the fuel cell provider, and Siemens, the electric hybrid drive provider, to ensure that the interfacing between components is seamless [63]. The specifications of this partnership are listed in Table 0-5.

The vehicle design improves upon New Flyer's previous battery-driven Xcelsior model by including a fuel cell for increased range and allowing the bus to operate in all-electric or hybrid fuel cell-electric modes as conditions demand [64]. The goal of this demonstration vehicle is regular deployment for one year with data collection and testing reported at monthly intervals by the operating partner, SunLine Transit.

Table 0-4 New Flyer Xcelsior Fuel Cell Bus Vehicle and Operational Specifications

Parameter	Detail
Length	41'
Curb Weight	32,500 lbs
Fuel Cell	Hydrogenics "Celerity Plus" 60 kW
Fuel Storage	40kg @ 350 bar
Battery Type	Lithium-Ion, 80 kWh
Deployment Locations	Thousand Palms, CA

New Flyer/Ballard/Siemens: Xcelsior 60' Fuel Cell Range Extender Bus

In 2014, New Flyer began developing a 60' articulated battery-dominant fuel cell bus. Much of the architecture will be scaled up from the New Flyer Xcelsior 40' hybrid-electric transit bus. Key fuel cell technology and hydrogen storage will be added to this longer model. The goals of the project are increased reliability and lower purchase and operating costs [65]. AC Transit will receive the bus for this project and utilize the vehicle for demonstration and testing over the course of 22 months of in-service use [66]. Preliminary specifications are listed in Table 0-5 and a picture is shown in Figure 0-3 of a similar style bus.

Table 0-5 New Flyer Xcelsior 60' Fuel Cell Bus Specifications [67]

Parameter	Detail
Length	60'
GVWR	67,890 lbs

[63] Andrew Papson, "Hydrogenics Bus."
[64] Andrew Papson, "New Flyer - Project Narrative."
[65] Lawrence Wnuk, "Fuel Cell Range Extender Projects."
[66] New Flyer, "New Flyer Expands Proven Zero-Emission Product Line to Include a Sixty-Foot Battery-Electric/Fuel Cell Xcelsior® Bus."
[67] Ibid.

Fuel Cell	Ballard
Fuel Storage	4 Front Luxfer H2 Tanks, 4 rear Luxfer H2 Tanks
Battery Type	120 kWh Li-Ion
Consumption	5.3 mi/kg MPGe
Range	300 mi
Deployment Locations	AC Transit, Oakland CA
Number Deployed in U.S.	In development

Figure 0-3 New Flyer Xcelsior 60' Fuel Cell Bus Style [68]

[68] Ibid.

References

Aaron P. Harris, and Chris W. San Marchi. "Investigation of the Hydrogen Release Incident at the AC Transit Emeryville Facility (Revised)." Albuquerque, NM: Sandia National Laboratories, October 2012.

AC Transit. "Taking the HyRoad...With Zero-Emission Technology," 2012. http://www.actransit.org/wp-content/uploads/010912B_HyRoad_web2.pdf.

———. Tour of AC Transit Facilities, 2011.

Air Liquide USA. "Gases, Technologies & Services for Industry in the U.S." *Air Liquide USA*, October 6, 2015. https://industry.airliquide.us/airliquideus.

———. "Renewable Energy," September 30, 2015. https://industry.airliquide.us/renewable-energy.

Air Products. "H2 Energy and Fueling Station." Accessed May 6, 2016. http://www.airproducts.com/industries/Energy/Power/modal-hydrogen-station.aspx.

———. "Hydrogen Energy - Material Handling." Accessed May 6, 2016. http://www.airproducts.com/industries/Energy/Hydrogen-Energy/Material-Handling/product-list/forklifts-material-handling.aspx?itemId=5619F922C30F4238BEA049462915827D.

———. "Hydrogen Fuel for Transportation." Accessed May 6, 2016. http://www.airproducts.com/industries/Energy/Hydrogen-Energy/Transportation.aspx.

Andrew Papson. "Hydrogenics Bus," n.d.

———. "New Flyer - Project Narrative," n.d.

"Anteater Express | Sustainability." Accessed May 6, 2016. http://www.shuttle.uci.edu/about/sustainability/hydrogenbus/.

BAE Systems. "American Fuel Cell Bus," 2011. http://www.hybridrive.com/pdfs/AllAmerFuelC.pdf.

"Best Practices Overview | Hydrogen Tools." Accessed May 6, 2016. https://h2tools.org/bestpractices.

"Blewbury Energy Initiative - Hydrogen." Accessed May 6, 2016. http://www.blewbury.co.uk/energy/hydrogen.htm.

California Energy Commission. "Alternative and Renewable Fuel and Vehicle Technology Program Grant Solicitation PON-14-605 Medium- and Heavy-Duty Advanced Vehicle Technology Demonstration." State of California Natural Resources Agency, June 18, 2015. http://www.energy.ca.gov/contracts/PON-14-605_Revised_NOPA.pdf.

CALSTART. "Zero-Emission Battery Dominant Fuel Cell Bus," n.d. http://www.calstart.org/Libraries/Low_Carbon_Bus_Program_Documents/Battery_Dominant_Fuel_Cell_Hybrid_Bus.sflb.ashx.

CALSTART, and US Department of Transportation. "Developing and Demonstrating the Next-Generation Fuel Cell Electric Bus Made in America." American Fuel Cell Bus Program, February 2012. http://www.nrel.gov/hydrogen/pdfs/nfcbp_fs4_feb12.pdf.

CNG Pit Stop. "CNG System Installation Basics - How CNG Works." *CNG Pit Stop*, 2015. http://www.cngpitstop.com/how-cng-works/.

Colin M. Stewart. "Hydrogen Buses to Debut." *Hawaii Tribune-Herald*, December 27, 2012. http://hawaiitribune-herald.com/sections/news/local-news/hydrogen-buses-debut.html.

Dr. Samy Pal. "Application for Anode Hydrogen Exhaust for a DFC-300 Fuel Cell," July 9, 2012. https://drsamypal.wordpress.com/2012/07/09/application-for-anode-hydrogen-exhaust-for-a-dfc-300-fuel-cell-bit-i-did-for-the-student-hydrogen-design-contest/.

Eudy, Leslie, and Matthew Post. "Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Third Report." National Renewable Energy Laboratory, 2014. http://www.nrel.gov/docs/fy14osti/60527.pdf.

Gas Technology Institute. "Converting Biogas to Hydrogen." Accessed May 6, 2016. http://www.gastechnology.org/Solutions/Pages/Converting-biogas-to-hydrogen.aspx.

———. “Demonstrating Fuel Cell Technology for Public Transit.” Accessed May 6, 2016. http://www.gastechnology.org/Solutions/Pages/Demonstrating-fuel-cell-technology-for-public-transit.aspx.

Giner. “Home.” Accessed May 6, 2016. http://www.ginerinc.com.

H2 Frontier Inc. “Hydrogen Generation, Storage & Delivery Systems.” Accessed May 6, 2016. https://www.google.com/maps/d/viewer?mid=1DAI2aFb_HxPUYDkFLxAd5GZ_0Nw.

Hydrogenics. “Hydrogen Fueling Stations.” Accessed May 6, 2016. http://www.hydrogenics.com/hydrogen-products-solutions/energy-storage-fueling-solutions/hydrogen-fueling-stations.

ITM Power. “HFuel.” *ITM Power*. Accessed May 6, 2016. http://www.itm-power.com/product/hfuel.

“J2601/2: Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles - SAE International.” Accessed May 6, 2016. http://standards.sae.org/j2601/2_201409/.

Jonathan Weinert. “A Near-Term Economic Analysis of Hydrogen Fueling Stations.” Institute of Transportation Studies, UC Davis, 2005. http://pubs.its.ucdavis.edu/download_pdf.php?id=46.

K. Chandler, and L. Eudy. “National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2.” US Department of Transportation, June 2010. http://www.actransit.org/wp-content/uploads/NREL_rept_JUN2010.pdf.

———. “Santa Clara Valley Transportation Authority and San Mateo County Transit District Fuel Cell Transit Buses: Evaluation Results.” National Renewable Energy Laboratory, November 2006. http://www.nrel.gov/hydrogen/pdfs/40615.pdf.

Lawrence Wnuk. “Fuel Cell Range Extender Projects.” n.d.

Leslie Eudy, and Christina Gikakis. “Fuel Cell Buses in U.S. Transit Fleets: Current Status 2013.” National Renewable Energy Laboratory, 2013. http://www.nrel.gov/docs/fy14osti/60490.pdf.

Leslie Eudy, and Kevin Chandler. “SunLine Transit Agency Hydrogen-Powered Transit Buses: Evaluation Results Update.” National Renewable Energy Laboratory, 2007. http://www.nrel.gov/hydrogen/pdfs/42080.pdf.

Leslie Eudy, Kevin Chandler, and Christina Gikakis. “Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012.” National Renewable Energy Laboratory, 2012. http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fceb_status_2012.pdf.

L. Eudy, and K. Chandler. “National Fuel Cell Bus Program: Proterra Fuel Cell Hybrid Bus Report, Columbia Demonstration.” National Renewable Energy Laboratory, n.d. http://www.nrel.gov/hydrogen/pdfs/fta_report_no_0003.pdf.

———. “SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Fourth Results Report.” National Renewable Energy Laboratory, January 2013. http://www.nrel.gov/docs/fy13osti/57560.pdf.

L. Eudy, and M. Post. “BC Transit Fuel Cell Bus Project: Evaluation Results Report.” National Renewable Energy Laboratory, February 2014. http://www.nrel.gov/docs/fy14osti/60603.pdf.

Linde. “Linde Industrial Gases.” Accessed May 6, 2016. http://www.linde-gas.com/en/index.html.

New Flyer. “New Flyer Expands Proven Zero-Emission Product Line to Include a Sixty-Foot Battery-Electric/Fuel Cell Xcelsior® Bus.” *New Flyer - News Releases*, October 13, 2014. http://www.newflyer.com/index/101314-sixty-foot-battery-electric-fuel-cell-xcelsior-bus.

North Augusta City Council. “Regular Meeting Minutes.” North Augusta, South Carolina, 2013. http://www.northaugusta.net/Home/ShowDocument?id=991.

PDC Machines. “Diaphragm Compressors: Designed and Constructed for High Reliability and Low Maintenance.” Brochure. PDC Machines, 2013. pdcmachines.com.

Praxair. “Compressed Hydrogen Gas or Liquid Hydrogen (H2).” Accessed May 6, 2016. http://www.praxair.com/gases/buy-compressed-hydrogen-gas-or-liquid-hydrogen?tab=overview.

ProtonOnSite. “Hydrogen, Nitrogen, and Zero Air Generators.” Accessed May 6, 2016. http://protononsite.com/.
Rich Piellisch. “US Hybrid for Hawaii Hydrogen Plug-In.” *Fleets & Fuels*, June 30, 2014. http://www.fleetsandfuels.com/fuels/hydrogen/2014/06/us-hybrid-for-hawaii-h2-bus/.
Sunline Transit Agency. “Clean Fuels Fleet,” n.d. http://www.sunline.org/clean-fuels-fleet.
Teledyne Energy Systems. “Product Portfolio.” Accessed May 6, 2016. http://www.teledynees.com/products/detail/product-portfolio.htm.
US Department of Energy. “AC Transit Demos Three Prototype Fuel Cell Buses.” Fuel Cell Bus Demonstration Projects, 2006. http://www.nrel.gov/hydrogen/pdfs/39441.pdf.
US Department of Transportation. “Fuel Cell Bus Life Cycle Cost Model: Base Case & Future Scenario Analysis.” Research and Innovative Technology Division: Office of Research Development and Technology, June 2007.
US Federal Transit Administration. “TIGGER Program Overview,” n.d. http://www.fta.dot.gov/12351_11424.html.
US Hybrid. “H2Ride 30 Fuel Cell Plug-In Shuttle Bus,” n.d. http://www.ushybrid.com/documents/PDF/2/H2Ride30.pdf.
———. “H2Ride 32 Fuel Cell Plug-In Shuttle Bus,” n.d. http://www.ushybrid.com/documents/PDF/2/H2Ride32.pdf.
———. “US HYBRID AWARDED CONTRACT TO DELIVER HYDROGEN-POWERED SHUTTLE BUS TO HAWAII COUNTY MASS TRANSIT AGENCY.” *US Hybrid - News and Events*, June 17, 2014. http://www.ushybrid.com/index.php/news/140-us-hybrid-awarded-contract-to-deliver-hydrogen-powered-shuttle-bus-to-hawaii-county-mass-transit-agency.
Van Hool. “Hybrid Fuel Cell Bus,” n.d. http://www.vanhool.be/home%20fr/autocars%20et%20autobus/transport%20public/Europe/Resources/folderFuelCell.pdf.
“Workplace Injury Management | Biosymm.” Accessed May 6, 2016. http://www.biosymm.com.au/.