



HYDROGEN
Safety Panel

Safety of Mobile Hydrogen and Fuel Cell Technology Applications

An Investigation by the
Hydrogen Safety Panel

PNNL-29341

Original: October 2019

Revision 1: November 2023

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, **makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.** Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof. Additionally, the report does not provide any approval or endorsement by the United States Government, Battelle, or the Hydrogen Safety Panel of any system(s), material(s) or equipment discussed in the document.

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by

BATTELLE
for the

UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Abstract

Safe practices in the production, storage, distribution, and use of hydrogen are essential for the widespread acceptance of hydrogen and fuel cell technologies. A significant safety incident could damage public perception of hydrogen and fuel cells. Recent incidents involving multi-cylinder hydrogen transport vehicles in the United States have brought attention to the potential impacts of mobile hydrogen storage and transportation. Road transportation of bulk gaseous hydrogen presents unique hazards that can be very different from those for stationary equipment, and new equipment developers may have less experience and expertise than seasoned gas providers.

In response to the aforementioned incidents, and in support of hydrogen and fuel cell activities in California specifically, the Hydrogen Safety Panel (HSP) has investigated the safety of mobile hydrogen and fuel cell applications (mobile auxiliary/emergency fuel cell power units, mobile fuelers, multi-cylinder transport vehicles, unmanned aircraft power supplies, and mobile hydrogen generators). The HSP examined the applications, requirements, and performance of mobile applications that are being used extensively outside of California to understand how safety considerations are applied. This report discusses the results of the HSP's evaluation of hydrogen and fuel cell mobile applications along with recommendations to address relevant safety issues.

Acknowledgements

The funding for this study was provided by the California Energy Commission and the US Department of Energy through the Hydrogen and Fuel Cell Technologies Office (HFTO). The Hydrogen Safety Panel gratefully acknowledges the guidance and assistance provided by Jean Baronas and Sebastian Serrato of the California Energy Commission. The Panel also thanks the study's participants for sharing invaluable information and insight to help broaden our understanding about safety of hydrogen mobile applications and fuel cell technologies.

The accuracy of the information and the views presented in this report are the responsibility of the authors and do not necessarily represent the opinion of the California Energy Commission or of any individuals or stakeholder groups.

Acronyms and Abbreviations

| | |
|-------|--|
| ASME | American Society of Mechanical Engineers |
| CEC | California Energy Commission |
| CFR | Code of Federal Regulations |
| CGA | Compressed Gas Association |
| CSA | CSA Group |
| CT | composite trailer |
| DOT | U.S. Department of Transportation |
| FAA | Federal Aviation Administration |
| HAZOP | hazard and operability analysis |
| HGV | heavy goods vehicle |
| HHO | hydrogen generator |
| HSP | Hydrogen Safety Panel |
| MEGC | Multi element gas container |
| NFPA | National Fire Protection Association |
| NHTSA | National Highway Traffic Safety Administration |
| NTSB | National Transportation Safety Board |
| IEC | International Electrotechnical Commission |
| ISO | International Organization for Standardization |
| PHMSA | Pipeline and Hazardous Materials Safety Administration |
| PRD | pressure relief device |
| PRV | pressure release valve |
| SAE | Society of Automotive Engineers |
| TPRD | thermally-activated pressure release device |
| UL | Underwriters Laboratories |

Table of Contents

| | |
|--|------------|
| DISCLAIMER | III |
| ABSTRACT | III |
| ACKNOWLEDGEMENTS | IV |
| ACRONYMS AND ABBREVIATIONS | V |
| TABLE OF CONTENTS | VI |
| A. INTRODUCTION | 1 |
| B. BACKGROUND | 1 |
| HYDROGEN SAFETY PANEL..... | 1 |
| THE CALIFORNIA HYDROGEN MOBILE STORAGE TRAILER INCIDENT | 2 |
| C. SCOPE AND APPROACH | 5 |
| D. FINDINGS | 7 |
| MOBILE FUELERS/MULTI-CYLINDER TRANSPORT VEHICLES..... | 9 |
| MOBILE FUEL CELL POWER AND LIGHTING | 10 |
| MOBILE HYDROGEN HHO GENERATORS..... | 10 |
| UNMANNED AERIAL SYSTEMS | 10 |
| FUEL-CELL-POWERED SPECIAL-MATERIAL-HANDLING VEHICLES | 11 |
| OTHER FINDINGS FOR MOBILE REFUELERS AND TUBE TRAILERS | 11 |
| E. RECOMMENDATIONS | 12 |
| HAZARD ANALYSIS | 12 |
| REGULATIONS AND PERMITTING | 13 |
| DESIGN/CODES AND STANDARDS | 13 |
| OPERATIONS AND MAINTENANCE..... | 15 |
| EMERGENCY PROCEDURES..... | 15 |
| F. CONCLUSION | 15 |
| G. REFERENCES | 15 |
| APPENDIX A – MOBILE APPLICATION INTERVIEW QUESTIONNAIRE | 17 |

Safety of Mobile Hydrogen and Fuel Cell Technology Applications: An Investigation of by the Hydrogen Safety Panel (HSP)

A. Introduction

Safe practices in the production, storage, distribution, and use of hydrogen are essential for the widespread acceptance of hydrogen and fuel cell technologies. A catastrophic failure in any hydrogen project could damage public perception of hydrogen and fuel cells. Given the nascent nature of the mobile hydrogen applications, incidents involving mobile equipment can have detrimental impacts for the public as well as stakeholders and project proponents who are committed to hydrogen's use as a safe alternative energy resource.

In support of the California Energy Commission (CEC), the Hydrogen Safety Panel (HSP) investigated safety practices of hydrogen mobile applications and fuel cell technologies that have been extensively used in the United States. The investigation covered mobile applications, including bulk gaseous hydrogen storage; transport and fueling equipment such as vessels, trailers, and mobile fuelers; and fuel cells used in ground support vehicles and aerial vehicles (e.g., hydrogen-powered unmanned drones).¹ Based on interviews with individuals from the hydrogen suppliers, research and development organizations, and mobile application and fuel cell manufacturers, the HSP identified common safety gaps and vulnerabilities in mobile applications. In addition, the HSP identified some observations and recommendations regarding additional activities and actions for developing guidance as well as information to raise the awareness of hydrogen safety to reduce future mobile application incidents involving hydrogen. This report summarizes the activities and conclusions associated with this effort.

The rest of the report is presented as follows. In Section 2, we first describe the mission, role, and capability of the HSP, whose members conducted the interviews with select individuals from the hydrogen industry, for the purpose of highlighting the technical rigor in the investigation approach, analyses, and findings. We also provide background information regarding a 2018 hydrogen multi-cylinder trailer incident that precipitated the need for a systematic investigation of safety practices of mobile hydrogen equipment and applications. In Section 3, we describe the method used in the investigation. In Section 4, we present the analyses and findings based on the interview data. In Section 5, we conclude by discussing potential activities and actions the CEC and other interested stakeholders can take to mitigate the safety gaps and improve hydrogen mobile application safety in the near- and long-term.

B. Background

Hydrogen Safety Panel

The HSP was formed in 2003 by the U.S. Department of Energy to help develop and implement practices and procedures that would ensure safety in the operation, handling, and use of hydrogen and hydrogen systems. The HSP's primary objective is to enable the safe and timely transition to hydrogen and fuel cell technologies. This is accomplished by:

- Providing expertise and recommendations and assisting with identifying safety-related technical data gaps, best practices, and lessons learned.
- Ensuring that safety planning and safety practices are incorporated into hydrogen projects.

¹ Léon [1] makes a distinction between mobile applications (e.g., internal combustion engines, fuel cell vehicles, and storage tanks) and portable applications (e.g., fuel cells). In this report, we maintain the conceptual distinction between the two classes of technologies without referring to fuel cells as portable applications.

The HSP's members collectively have over 700 years of experience and represent a cross-section of expertise from the commercial, industrial, government, and academic sectors. HSP members participate in a variety of standards development organizations including the American Society of Mechanical Engineers (ASME), CSA Group (CSA), International Organization for Standardization (ISO), National Fire Protection Association (NFPA), Society of Automotive Engineers (SAE), Compressed Gas Association (CGA), and Underwriters Laboratories (UL). HSP members also contribute to peer-reviewed literature and trade magazines on hydrogen safety and present at national and international forums.

The HSP's diverse expertise has been applied to emphasize the importance of continuous attention to safety in all aspects of a broad project portfolio—research, technology development, and market deployment. Since 2003, the HSP has played an integral role in supporting the deployment of hydrogen and fuel cell technologies by raising safety consciousness directly at the project level and has reviewed hundreds of projects covering vehicle fueling stations, auxiliary power, backup power, combined heat and power, industrial truck fueling, portable power, mobile applications, and research and development activities. The HSP will continue to enable the safe and timely transition to hydrogen and fuel cell technologies by broadly sharing project learnings and recommendations pertaining to handling and use of hydrogen.²

The California Hydrogen Multi-Cylinder Transport Trailer Incident

On the afternoon of 11 February 2018, a fire occurred during the transportation of a fully loaded multi-cylinder hydrogen transport trailer from its fill location to a receiving customer site (see Figure 1 and Figure 2). The trailer consisted of a chassis-mounted hydrogen storage module containing 25 composite, fully wrapped, carbon-fiber-reinforced, aluminum-lined cylinders. The cylinders were manufactured and operated per a U.S. Department of Transportation (DOT) special permit. The trailer and cylinders had completed their first 5-year requalification approximately 6 weeks prior to the incident.

Local emergency responders, a hazardous materials team, and emergency response personnel from the motor carrier also responded to the incident. The U.S. National Transportation Safety Board (NTSB) investigated the incident and reported that there were no injuries, but local officials estimated that approximately 1500-2000 people from surrounding businesses and residential areas were involved in an evacuation.³



Figure 1. Exemplar CT-250 hydrogen tube trailer (from NTSB report)

² For additional information on the HSP, visit <https://h2tools.org/hsp>.

³ National Transportation Safety Board, Investigator-in-Charge Factual Report, February 11, 2018, Tube Trailer Module Hydrogen Release and Fire, Diamond Bar, California, NTSB Report No. HMD18FR001, <https://dms.nts.gov/pubdms/search/document.cfm?docID=465882&docketID=61458&mkey=96772>.



Figure 2. Cylinder ends in open incident trailer with fire-damaged cylinders encircled (from NTSB report)

During the incident, pressure relief devices (PRDs) activated on 12 of the cylinders, releasing 120 kg of hydrogen, which was consumed in the fire. One cylinder was out of service. The 12 remaining cylinders containing 120 kg of hydrogen were vented as part of the incident response after the fire was extinguished and prior to removal of the trailer from the incident location. The investigation confirmed that none of the vessels lost mechanical integrity and that the vessels did not contribute to the cause, or perpetuation, of the incident.

In accordance with DOT requirements, each vessel was equipped with a PRD on each end, for a total of 50 PRDs on the trailer module. The design PRDs were a type CG-5 and consisted of a 10,000-psig copper rupture disk in contact with the vessel contents, backed by a fusible metal plug rated at 212 °F. The vessels themselves had a service pressure rating of 7,500 psig with a burst pressure rating in excess of 25,000 psig. The PRD outlets were arranged to discharge upward and unobstructed to the open air in accordance with DOT requirements to prevent escaping gas from impinging on the vessels, piping, or personnel.

Figure 3 identifies the positions of the actuated PRDs and detached vent tubes.

| | | | | |
|--|-------------------------|--|---|--|
| 21 ● | 22 ● PRD actuated | 23 ● PRD actuated Vent line ejected | 24 ● PRD actuated Vent line ejected | 25 ● PRD actuated Vent line ejected |
| 16 ● | 17 ● | 18 ● PRD actuated | 19 ● PRD actuated Vent line ejected | 20 ● PRD actuated Vent line ejected |
| 11 ● Incorrect front and rear PRD | 12 ● | 13 ● PRD actuated | 14 ● PRD actuated Vent line ejected Incorrect rear PRD | 15 ● PRD actuated Vent line ejected |
| 6 ○ | 7 ○ | 8 ● | 9 ● PRD actuated | 10 ● PRD actuated |
| 1 ○ | 2 ○ | 3 ● | 4 ● PRD actuated (2/4/18) Incorrect front PRD | 5 ● |

Viewed from the Rear

Incorrect PRD = 4
 PRD actuated = 12²²
 Vent line ejected = 7
 Severe fire damage = 11

● Severe burning damage, composite caught fire²¹
 ● Scorching, surface burns
 ● Heat discoloration, blistered paint, melted label
 ○ No discoloration, some soot accumulation

Figure 3. Module 430003 inspection summary (from NTSB report)

The NTSB report [2] described post-incident actions taken by the vehicle operator and cylinder inspection company to prevent future incidents involving underrated PRDs and improperly attached cylinder vent tubes.

Based on the evidence found during the root cause analysis and NTSB investigation, it was concluded that several incorrectly set PRDs were installed during the trailer's DOT-mandated requalification. One of these PRDs, set at 5,833 psig instead of the design set pressure of 10,000 psig, was on the rear end of a vessel located within the storage module. The PRD did not immediately activate when the trailer was put in service due to support provided to the rupture disk from the fusible metal located downstream and behind the disk. During its 6 weeks in service, the rupture disk began to crack and eventually activated on the afternoon of 11 February 2018 while in transit. The thrust force and pressure of the gas flowing from the activated PRD ejected part of the vent tubing from a compression fitting elbow on the vent line.

From evidence and measurements of the compression fitting after the incident, it was determined that the compression fitting and tubing had been incompletely assembled during original manufacture of the trailer module. The ferrules were not fully swaged onto the mating tubing. Due to the failure of the vent system, hydrogen jets impinged on adjacent cylinders instead of being vertically vented from the open top of the trailer as intended by the design. Hydrogen ignition was likely caused by the shock wave from the sudden release and/or impact of the ejected tubing with surrounding equipment. The released hydrogen continued to burn within the trailer module, exposing other vessels to fire. Eleven additional PRDs on other vessels activated when exposed to the fire. Six of these also resulted in ejected vent tubing and five were properly vented per the vent system design.

Since safety cuts across all areas of hydrogen technology and is of paramount importance for the adoption and acceptance of hydrogen as a viable alternative energy carrier, the California incident increased public

scrutiny of the potential safety impact of hydrogen transportation and mobile applications. It also highlighted the growing need to understand the prevailing safety practices in the nascent industry of high-pressure hydrogen mobile applications and fuel cell technologies. It is important to identify safety gaps and vulnerabilities, develop strategies to address the gaps and mitigate vulnerabilities, help raise public awareness of hydrogen safety, and positively shape public perception of hydrogen and hydrogen-based technologies.

C. Scope and Approach

In the wake of the incident, the CEC asked the HSP to conduct an exploratory study to assess the current state of safety practices and vulnerabilities in mobile hydrogen application and fuel cell technology. The goal of the study was to identify safety gaps and provide comments and recommendations to mitigate these gaps.

The HSP formed a six-member Mobile Applications Task Group for this project. The task group's first decision was to select the types of mobile applications to be included in the study. The group decided to focus on new hydrogen and fuel cell mobile applications with which emergency responders and perhaps regulators have limited experience and familiarity. This ruled out conventional, widely used, hydrogen tube trailers and liquid hydrogen tankers. Likewise, most hydrogen-fueled vehicles, including cars, buses, industrial trucks, and road trucks, were considered familiar enough to be removed from the project scope.

The task group selected the following new hydrogen transportation and fuel cell mobile applications for the study.

- Trailers with high-pressure (over 2,800 psig) hydrogen storage cylinders, particularly those of composite construction, including the type of trailer involved in the incident discussed in the previous section
- Mobile auxiliary power and emergency power hydrogen fuel cell systems, including lighting power supplies (Figure 4)
- Mobile hydrogen generators, such as a truck-mounted electrolyzer (Figure 5)
- Seaport and airport remote power and short distance transport cargo (material handling) applications (Figure 6)
- Fuel-cell-powered unmanned aircraft systems such as drones (Figure 7)



Figure 4. Mobile auxiliary power unit



Figure 5. Truck mounted hydrogen generator



Figure 6. Material handling hauler



Figure 7. U.S. Naval Research Laboratory fuel-cell-powered unmanned aerial vehicle

Task group members conducted structured interviews as the primary method for data collection and designed an interview questionnaire (Appendix A) to solicit input from interviewees. The questionnaire had three key components:

- Summary characterization of the mobile applications (e.g., maximum fill pressure, minimum and maximum design temperatures, and capacity)
- General safety topics regarding approaches to hazard identification, safety reviews, risk acceptance criteria, safety resources, safety requirements, and safety training

- Specific safety topics
 - Specific vulnerabilities in design and operations for pressures greater than 2,800 psig (190 bar) that include:
 - Mobile application use while in transport
 - Vehicular accident impacts
 - Manifolding and isolation of storage vessels
 - Enclosure and ventilation
 - Fire exposure
 - Vent stack design and protection
 - Hydrogen loss during transport
 - Gaps in codes and standards requirements that include:
 - Approval for mobile applications
 - Fundamental safety considerations in the absence of clear safety requirements
 - Protocols used in emergencies
 - Transport and re-filling of the equipment with hydrogen

The HSP identified an initial set of applicable companies and cognizant individuals and recruited them for interviews. Between May and June 2018, HSP members conducted structured interviews with 18 individuals representing 12 diverse hydrogen-related organizations to understand the safety considerations in design, operation, permitting, and maintenance of these mobile application systems. The organizations included hydrogen industrial gas suppliers, vessel manufacturers, trailer manufacturers, fuel cell system manufacturers, and some vehicle suppliers or contractors.

For each interview, two HSP members interacted with one to three individuals from an organization over the telephone. The interviews lasted about 90 minutes on average. Some interviewees emailed supplemental information to the HSP interviewers. The HSP interviewers documented and consolidated the responses to the questionnaire (Appendix B). After each interview, the HSP interviewers also documented learnings, issues, gaps, and recommendations based on the responses. To protect confidentiality, interviewee names and organizational affiliations are excluded from this report and any related publications unless the interviewee granted permission to make such information public.

It is worth emphasizing that due to the limited sample size and the sampling approach used, and the evolving nature of new and curtailed mobile applications, the results of the investigation are exploratory and do not necessarily represent the entire hydrogen and fuel cell mobile applications industry. Further, since the 15 interviews were conducted by different HSP members, some variability was observed in the information obtained from participants. Therefore, interested readers are encouraged to be cautious about generalizing the results below to potentially modified applications and new mobile system designs.

D. Findings

Table 1 lists the number of organizations interviewed for the five different mobile application categories, and the hydrogen and fuel cell parameters as reported during the Task Group interviews. Some organizations were involved in multiple application categories. There were eight organizations involved in various types of mobile refueling and hydrogen transportation, by far the largest category.

Table 1. Interview summary

| | Mobile Refueler & H ₂ Supply Tube Trailers | Mobile Fuel Cell Power & Lighting | Mobile Hydrogen Generators | Unmanned Aerial System Power | Power for Special Material Handling Vehicle |
|--|--|--|---|---|---|
| Number of Organizations Interviewed | 8 | 3 | 1 | 1 | 2 |
| Amount of Hydrogen Onboard (kg) | 100 to 950 | Not Specified | 0.75 | 0.43 to 0.8 | TBD |
| Type of Cylinder or Tank | Type 3/Type 4 or Not Specified | Not Specified | Hydride | Not Specified | Not Specified |
| Maximum Pressure (bar) | 294 to 950 | 350 to 700 | 138 | 400 | TBD |
| Type of PRD | Pressure Release Valve (PRV), Fusible Links, Thermally-activated Pressure Release Device (TPRD) | TPRD, PRV | Not Specified | TBD | TBD |
| Max Power (kW) | NA | 25 to 100 | NA | 0.6 to 1.2 | 25 to 100 |
| Consensus Safety Standards Implemented (in addition to meeting relevant DOT 49 CFR and Special Permit requirements) | <ul style="list-style-type: none"> • NFPA 2 & 70 • CSA HGV 3.1, 4.1, 4.5, & 4.8 • NFPA 110 • ASME B31.3 • SAE J2579 • CGA TB-25 and C-29 • ISO 11515 & 11119 • CGA S-1.1 • 49 CFR | <ul style="list-style-type: none"> • NFPA 2 • IEC 60079-10 • ASME B31.3 • MIL-ST-882-E | <ul style="list-style-type: none"> • Not Specified | ASTM F2910, new ASTM draft standard for fuel cell UAS | Not Specified |

Mobile refueling and high-volume transport applications carried the largest amounts of onboard hydrogen, up to 950 kg, which is about four times as much hydrogen as was on the trailer involved in the incident described in the previous section. At the other extreme, mobile hydrogen generators and unmanned aerial systems (UAS) are presently carrying less than 1 kg onboard (although other applications that were not part of this study may involve larger quantities). The range of hydrogen maximum pressures shown in Table 1 is similar to the range of pressures for the hydrogen cylinders involved in the incident described in the previous section. Most of the pressures listed in Table 1 far exceed the pressures commonly found in conventional tube trailers.

As indicated in Table 1, various types of PRDs are used or are anticipated for use in the different mobile applications. Since inadvertent actuation of an improperly rated PRD was the initiating event in the incident described in the Section B, a review of PRD reliability and susceptibility to improper installation could benefit these mobile applications as well as other applications that use PRDs.

The last row in Table 1 shows the many different consensus safety standards currently being followed, with NFPA 2 and ASME B31.3 being the most prevalent. However, only one or two standards were reported as being followed for smaller and newer applications such as the mobile generators, aerial systems, and material handling equipment.

The interviews also included questions on how the organizations performed internal and external safety reviews. Only five organizations indicated that their applications or components of their applications have undergone external safety reviews (e.g., by government agencies, independent/neutral safety reviewers, or third-party certifying bodies). Across the interviewees, corporate internal review processes, pertinent government regulations (e.g., DOT Pipeline and Hazardous Materials Safety Administration [PHMSA] regulations) and various industry standards (e.g., NFPA, CGA, and ASME) were referenced as the key risk acceptance criteria used in assessing safety of the mobile applications and fuel cell technologies. In addition, reliance on internal resources for safety evaluations was the dominant practice across many of the organizations included in the study.

Most interviewees demonstrated familiarity with the codes and standards that were applicable to their applications. Many interviewees identified situations where the existing standards and regulations are limited or lacking. Regulations applicable to the transportation of hazardous materials are provided by DOT PHMSA. While these regulations provide transportation requirements, additional standards may be needed (protection of the vessels and vent stacks during transport, for example). Safety standards referenced in Table 1 provide additional guidance; however, standards for specific applications beyond hazardous material transportation have not yet been fully developed. This is understandable as the speed at which the technology and applications are evolving significantly outpaces the development of new regulations. The existing pertinent regulations, standards, and issues are described below on an application-by-application basis. Gaps are provided for separate applications.

Mobile Fuelers/Hydrogen Transport Trailers

- Trailers carrying high-pressure hydrogen cylinders lack a specific design regulation; therefore, DOT 49 CFR requirements must be met. Special permit applications are reviewed and approved by PHMSA, but often lack explicit requirements for trailers, the integration and mounting of vessel support structures with the chassis, design of piping and components, vent stack(s), trailer ventilation, construction, road travel durability, accident protection of the equipment and vehicle, protection from internal or external fire, and limiting loss of hydrogen during transport.
- Although there are ISO standards such as ISO 11119 and ISO 11515 for the design and manufacture of composite gas cylinders, there is no specification for composite cylinders within PHMSA regulations. However, these standards along with the CFFC standard for Fully Wrapped Carbon-Fiber Reinforced Aluminum Lined Cylinders have been used as the basis for many PHMSA special permit applications and approvals.
- Hydrogen transfer, fueling, and fire protection standards are inadequate as temperature limitations are not clearly or consistently prescribed in current standards for composite cylinders.
- There is limited guidance and requirements for how or where hydrogen vessels for these applications can be filled (e.g. whether these can be filled on the side of the road or at retail fueling stations that are intended for light duty vehicles).
- PRD and vent design requirements are lacking for these types of applications. Special permits will often address this equipment, but not with detail or consistency. 49 CFR requires that vents be oriented vertically upward similar to stationary systems. However, many vehicle types have PRD vents that are directed downward, particularly those used for mobile applications. This discrepancy may be

related to differences between National Highway Traffic Safety Administration (NHTSA) and PHMSA regulations, which govern different industries, applications, and markets.

- The existing NFPA 2 code provides limited direction for mobile hydrogen refueling and for storage and use of hydrogen within mobile applications.
- There are no standardized emergency response procedures or guidance for these high pressure mobile applications, generic or otherwise, except for what is provided within the PHMSA Emergency Response Guidelines. The ERG Guide 115, which is applicable to both liquid and gaseous hydrogen transportation, is generic to all flammable gases and cryogenic liquids, many of which have widely varying properties. Specific guidance is not provided for hydrogen and the equipment required to meet these rapidly developing applications.
- There are no vibration and/or crash test requirements for these trailers.

Mobile Fuel Cell Power and Lighting

- Although there are two standards for portable fuel cell power systems (CSA FC 3 and IEC 62282-5), it is not clear that these standards cover the new types of emergency power supplies and lighting applications pertinent to this mobile application. They may not include adequate constraints for the fuel cell package frame impact and vibration resistance.
- There may be a gap in the vibration and crash resistance requirements for these fuel cell mobile power applications.
- There are differences of opinion as to the applicable cylinder requirements. Some consider these applications to be PHMSA regulated as hazardous material transportation while others consider these cylinders to be regulated by NHTSA as vehicle fuel tanks.

Mobile Hydrogen HHO Generators

- Vehicular on-board hydrogen generation (HHO) systems electrochemically generate a low-pressure mixture of hydrogen and oxygen from a water-based caustic electrolyte for immediate injection into internal combustion engines, with the intent of improving diesel/gasoline fuel economy and emissions.
- HHO generators are aftermarket add-ons, not provided by vehicle original equipment manufacturers. Various manufacturers provide retrofits and do-it-yourself hobby kits.
- There typically is no gas storage in the system other than the hydrogen within the HHO generation device.
- There are currently no certification standards for HHO mobile generation systems.
- Mobile HHO generators are not to be confused with pure hydrogen gas generation systems using water electrolysis technology, manufactured for industrial, laboratory, and hydrogen fueling stations. Product certification standards such as ISO 22734 and UL 2264 only apply to stationary hydrogen gas generators. NFPA 2 requirements for hydrogen generation systems only cover stationary pure hydrogen generators.
- DOT and other regulatory agencies must decide which branch or agency has jurisdiction over these mobile systems.

Unmanned Aerial Systems

- Federal Aviation Administration (FAA) Regulation 107 on UASs is silent on power supply and airworthiness, other than a requirement to make it available for FAA inspection upon request. The regulation for an operator to maintain visual-line-of-sight with the UAS effectively restricts range. If this restriction is eventually lifted, there will be increased incentive to use hydrogen-powered fuel cell range extenders.
- ASTM F38 Committee Work Item WK60937 will provide specifications for use of fuel cell power systems for UASs. The working group has made progress and the standard is expected to be issued in 2024.

Fuel-Cell-Powered Special-Material-Handling Vehicles

- National and international consensus standards for hydrogen-fueled vehicles are primarily for light-duty vehicles. There are no such standards available for special-material-handling vehicles.
- DOT regulations are unclear regarding requirements for hydrogen-fueled special cargo material handling vehicles, particularly if these vehicles are intended for off-road use at ports and airports. It is not clear if approvals for these vehicles will be under the jurisdiction of PHMSA, NHTSA, or other regulatory bodies. PHMSA regulates hazardous material transportation and NHTSA regulates vehicles and their fuel systems when used for various modes of transportation. Many of these new applications could fit within the jurisdiction of either organization.

Other Findings for Mobile Refuelers and Tube Trailers

Some of the hydrogen refueler and tube trailer designs do not incorporate inherent safety features for vessels, piping, valves, and natural ventilation that are almost universally used on standard industrial gas tube trailers due to PHMSA requirements. These units may have comparable or much larger quantities, and at much higher pressure when compared to existing tube trailers. The HSP believes that these applications present an increased risk over conventional gas transport operations due to the increased pressure, lack of standardized designs, and lack of design, operations, maintenance codes and standards. Listed below are some of these concerns for some of the mobile transport and application trailers.

- Storage vessels that are located within enclosures, allowing leaked hydrogen to accumulate within the transport package. Determination that adequate ventilation is provided in both enclosed and partially enclosed spaces is critical to prevent overpressure events. Special Permits have inadequate and inconsistent guidance to address the hazards of enclosures.
- Lack of bulkheads or walls that separate leak prone areas from the storage area can result in internally generated fire exposure of the vessels.
- Valves that are located less than 42 to 48 inches above the road, increasing the potential for impact damage.
- The absence of a rear deck that provides a significant barrier to protect valves and manifolds from rear impact.
- The absence of more robust/inherently safe valves, which are less likely to inadvertently open during impact.
- PRDs which are often located in exposed areas, making them vulnerable to external impact, especially when at the rear or front of the vehicle.
- Manifolder PRD vent stacks that do not necessarily extend above the height of all onboard cylinders and/or are not piped in adequately designed piping systems with supports that can withstand the pressures and forces involved with PRD activation.
- Some equipment lacks a thorough quantitative structural analysis of the trailer and vessel supports.
- Non-transportation-related electrical equipment on some mobile equipment may be located within classified electrical areas (and not having a Class 1, Division 2, Group B rating), making them potential ignition sources for leaked hydrogen, especially during deliveries or operation of the mobile applications.
- Crash impact zones need additional engineering evaluation of the provided protection.
- Ventilation of the trailers and expansion/contraction of some trailer vessel ends need to be better defined from an engineering and safety standpoint.
- Current placarding requirements maybe be insufficient since they had not anticipated current, lighter vessel technology as well as the deployment of mobile applications where they can be perceived to not apply.
- Insufficient guidance for the integration of vessels and support structures with the vehicle chassis design to ensure resilient and safe packaging.

E. Recommendations

Compared to hazards associated with stationary equipment, mobile hydrogen applications present new safety challenges to system developers, users, and public safety officials. There also appears to be a lack of specific requirements and much uncertainty over who is responsible for the development and implementation of safety requirements for these new mobile applications. Earlier sections of this report described current safety practices, gaps, and issues in hydrogen mobile applications and fuel cell technologies. Based on the identified safety gaps, the following recommendations are provided to help address prevalent safety issues and unique safety challenges associated with mobile applications and fuel cell technologies.

Hazard Analysis

A hazard analysis should be performed for mobile hydrogen equipment to help ensure that all potential hazards have been considered and mitigated. The analysis should include all hazards associated with the operation, transport, refueling, and storage of the unit. A hazard analysis can help the equipment providers identify potential safety issues, discover ways to reduce the likelihood of an occurrence, and minimize the associated consequences. Also, since it is possible that persons with little hydrogen experience could use certain mobile hydrogen equipment (through a purchase or lease), ensuring that all potential hazards are considered and mitigated should be top priority, with emphasis on engineering controls rather than operator actions and administrative controls. The following guidance is provided to assist the project in conducting a hazard analysis.

The hazard analysis should be conducted by a team with sufficient collective expertise in all aspects of the work to be performed. At least one team member should have experience and knowledge specific to the set of processes, equipment, control system, and facilities being evaluated. Also, the team should include the following expertise:

1. One member knowledgeable in the specific identification of the safety vulnerability method being used
2. One member with detailed knowledge of hydrogen flammability issues and protection measures
3. One member who was not involved in system development to represent potential users.
4. One member experienced in hazardous material regulations
5. One member to maintain the hazard analysis and monitor for changing conditions that require reevaluation of the equipment

At a minimum, the hazard analysis should address the following:

1. Potential hazard scenarios during the operation, transport, refilling, and storage of the unit
2. Previous incidents and near misses involving similar systems and components
3. Engineering and administrative controls applicable to the hazards and their interrelationships (e.g., the use of hydrogen detectors and emergency shutdown capability)
4. Mechanisms and consequences of component failures and failure modes of engineering and administrative controls
5. A qualitative evaluation of a range of the possible safety and health effects resulting from failure of controls

While there are a variety of hazard analysis processes, the HSP recommends a hazard and operability analysis (HAZOP) be used to evaluate this equipment. A HAZOP is a structured and systematic tool for analyzing the potential for component failures and unintended use and operating conditions in all system setup and operating modes.

Regulations and Permitting

- a. Specific regulations for hydrogen trailers, tube bundles, multi-element gas containers (MEGC) and mobile applications within 49 CFR for equipment with storage pressures over 2,800 psig need to be developed instead of relying on the current approach for DOT PHMSA special permits. These new high-pressure applications use a wide variety of new technologies that do not comply with current specifications, especially vessels made with composite materials. PHMSA has not formally adopted a specification to which these vessels can be built. As such, they are not 49 CFR “specification” vessels, and currently all are manufactured and operated within the requirements of special permits. Numerous companies submit these special permits and have a variety of inconsistencies regarding vessel construction, frame design, pressure protection, interconnecting piping, fire protection, and operating procedures. The general design review should include all potential hazard scenarios during the operation, transport, refueling, and storage of the unit, including:
 1. Fire and overpressure protection:
 - i. Protection of storage vessels from internal and external fire
 - ii. Protection of valves/instrumentation/components from fire
 - iii. Protection/redundancy of piping joints vent stack design and location
 - iv. Vent system design and location
 - v. Selection of appropriate PRD types and installation
 2. Vessel and valve vulnerability to impact from vehicle accidents and road debris
 3. Pull away protection to prevent loss of hydrogen containment upon inadvertent movement of the vehicle
 4. Integration of the vessels, mounting frames, and chassis to ensure robustness of the entire vehicle design
- b. Vessel and trailer manufacturers should be required to provide detailed installation, operating, maintenance, and testing procedures before the mobile equipment is transported on public roads and refueled at public facilities. Instructions should include guidance on checking trailer and vessel condition, PRDs and PRD vent lines and supports, trailer valve positions, and methods for isolating each tube during transport. There should also be requirements for inspections prior to vessel and trailer resale and redeployment.
- c. Regulatory authority, permitting jurisdictions, and procedures need to be determined for the following new mobile fuel cell power and hydrogen generation and refueling applications:
 1. Emergency power supplies
 2. Temporary power and lighting
 3. Hydrogen roadway refueling
 4. Special material handling vehicles at ports, airports, and other off-road, busy locations
 5. UAS
- d. Additional guidance is needed to clarify whether PHMSA, NHTSA, or other requirements apply to specific applications.

Design/Codes and Standards

- a. Develop a standard for vehicles and mobile applications equipped with hydrogen vessels. The standard should include rigorous inspection and testing of the crashworthiness⁴ and fire resistance of cylinder valves, cylinder support structure, piping support, PRD'sT, vent systems and supports, mechanical connections, and enclosures. The standard should include the following:

⁴ Verifiable performance testing using analytical methods should be used to prove the adequacy of the design per TB-25 and CGA C-29, new or current CFR (49 CFR Part 393.86, “Rear impact guards and rear end protection,” and it shall be designed, constructed, labeled, and maintained in accordance with 49 CFR Part 571, Standard No. 223, “Rear impact guards” and Standard No. 224, “Rear impact protection”).

1. Requirements for the vehicle chassis and its integration with the vessels and vessel support frames.
 2. Requirements that the vessels, pipe, and components are protected from vehicular impact.
 3. The use of listed equipment and components whenever possible.
 4. Methods to ensure that all vessels, vehicle chassis, piping, valves, fittings, and supports have been inspected or tested for their response to road vibration, acceleration, and fire conditions. This includes verification that all fittings have been installed correctly and are not vulnerable to disengagement during transport.
 5. Definition of Class 1, Division 2, Group B locations and verification that electrical devices are rated for these areas or are electrically isolated during hydrogen loading, offloading, or its intended use (e.g., hydrogen powering an onboard application).
 6. Verification of the hydrogen compatibility of all materials that would come in contact with high-pressure hydrogen gas.
 7. Requirements for an evaluation of hydrogen tank performance in response to a localized fire or the effects of an external exposure fire (other vehicle fuel, tires, etc.), since the PHMSA regulations do not address impingement fires.
 8. Analysis or test results to verify that the trailer ventilation openings are adequately sized for credible hydrogen leaks. Require ventilation to minimize the probability of hydrogen from leakage or failure of equipment being trapped within enclosures surrounding cylinders or piping.
 9. Requirements for a fire protection system. Where the TPRD's are required as part of a fire protection system, an analysis or test should be required to verify that vent stacks and associated piping supports are adequate to resist the pressure and thrust forces from the gas being released. The vent system should also be analyzed or tested to determine its capability to withstand expected impacts during transportation.
 10. Walls, bulkheads or other means to protect cylinders from fire exposure from hydrogen leakage or release internal to the vehicle.
 11. Consideration of a requirement for an interlock to ensure that the hydrogen tank valves are closed/isolated when the trailer is in transport.
 12. Requirements for a formal management of change process to address any changes to the original design during maintenance.
 13. Application of regulations such as CGA TB-25 and C-29 to define safety factors necessary to ensure failure modes are understood and addressed.
 14. Development of the end-of-life process for cylinders.
 15. Specification for ventilation when hydrogen equipment is within an a full or partial enclosure to minimize probability of developing a flammable environment.
 16. Detection equipment to alert operators of a flammable environment prior to opening an enclosure.
- b. Expand the NFPA 2 chapters on hydrogen fueling stations to include additional specific requirements for mobile equipment and other temporary or stationary vehicle-related applications. Similarly, review and expand the ISO 19880 standards for hydrogen fueling stations to include mobile stations and heavy-duty vehicles
 - c. It is also recommended that a breakaway feature or immobilization device be incorporated into equipment design to interrupt hydrogen transfer should the vehicle unintentionally move.
 - d. Review the consensus standards for portable fuel cell power systems (CSA FC 3 and IEC 6228-1) to determine whether they adequately cover mobile fuel cell power systems for emergency power and temporary lighting. If so, make the developers of these new mobile fuel cell power systems aware of these standards and their requirements. If not, revise the standards accordingly.
 - e. Expand the NFPA 2 chapter on hydrogen generation systems to cover mobile platform hydrogen generation systems, including hydride-based systems.
 - f. Mobile application developers and standards writers should define the specific hazardous location zones per IEC 60079-10-1, "Explosive atmospheres – Part 10-1: Classification of areas – Explosive gas atmospheres."

- g. Conduct a study to evaluate the effectiveness of PRD or TPRDs. A prior DOT study, “Test Report Hydrogen Tube Trailer Engulfing Fire Test,” published 28 July 2010 may be a valid starting point for the evaluation. There are various opinions as to the effectiveness of PRDs versus their potential failures, which should be assessed.

Operations and Maintenance

- a. Encourage mobile fueler developers to provide filling and offloading instructions that encompass both normal operation and emptying of storage vessels in the case of an emergency or incident.
- b. The operating procedures should identify who is authorized to operate and maintain the equipment. Operating procedures should also define what personal protective equipment must be worn when operating the equipment.
- c. Encourage mobile fuel system developers, users, and independent system service and inspection organizations to review safety-related maintenance procedures during maintenance activities.
- d. Encourage inspections of the trailer, tubes, and piping components prior to each trip.

Emergency Procedures

- a. Fire service organizations such as the International Association of Firefighters and the International Association of Fire Chiefs should encourage their members to become familiar with hydrogen-related releases.
- b. Mobile fueler and equipment users should ensure that emergency responders have a readily identifiable contact they can reach in an emergency. This may be as simple as posting a phone number on the vehicle that can be seen from a distance.
- c. The H2Tools.org website and emergency responder training tools should include information on mobile trailers and refuelers.
- d. Documents such as the DOT PHMSA Emergency Response Guidelines should consider revision of Guide 115 or development of a new Guide including information specific for hydrogen applications.

F. Conclusion

Developers of new mobile equipment may have less experience and expertise than seasoned gas providers. Given the nascent nature of the mobile hydrogen applications, incidents involving mobile equipment can have detrimental impacts for the public as well as stakeholders and project proponents who are committed to hydrogen’s use as a safe alternative energy resource. The issues and recommendations identified in this report should be considered by agencies/organizations involved in the use and regulation of mobile hydrogen applications to ensure that safety is adequately incorporated. Recent incidents within the industry have continued to demonstrate the need for improvements with current standards and regulations as described in this report.

G. References

Fichtner, Maximilian. 2008. Scientific Scope, in *Hydrogen Technology: Mobile and Portable Applications*, Léon Aline (ed.), pp. 625-636.

International Electrotechnical Commission, “Explosive atmospheres – Part 10-1: Classification of areas – Explosive gas atmospheres,” IEC Standard 60079-10-1, 2015.

Léon, Aline. 2008. *Hydrogen Technology: Mobile and Portable Applications*, Springer-Verlag Berlin, Heidelberg.

Macbride, Mellissa, and Marc Cota-Robles. 2018. "Evacuation order lifted after explosion on semi-truck carrying hydrogen tanks in Diamond Bar." ABC7 Eyewitness News, 2/12/2018. Retrieved on Dec 17, 2018 from <https://abc7.com/evacuation-lifted-after-hydrogen-tank-explosion-on-semi-truck/3068078/>

National Transportation Safety Board. 2018a. *Investigator-in-Charge Factual Report. February 11, 2018, Tube Trailer Module Hydrogen Release and Fire, Diamond Bar, California*. HMD18FR001. <https://dms.nts.gov/pubdms/search/document.cfm?docID=465882&docketID=61458&mkey=96772>

National Transportation Safety Board. 2018b. *Preliminary Report: Hazardous Materials High-Pressure Hydrogen Gas Cylinder Fire During Transportation. Diamond Bar, California*, February 11, 2018. HMD18FR0001. <https://www.nts.gov/investigations/AccidentReports/Reports/HMD18FR001-preliminary.pdf>

Appendix A – Mobile Application Interview Questionnaire

In support of hydrogen and fuel cell activities in California, the Hydrogen Safety Panel (HSP) is evaluating the safety of mobile hydrogen and fuel cell applications (mobile auxiliary power units, mobile fuelers, multi-cylinder trailer transport, refrigeration units, etc.). The activity will examine the applications, requirements and performance of mobile applications that are being used extensively outside of California to understand how safety considerations are applied. A report summarizing the HSP’s activities and conclusions/recommendations will be provided to the California Energy Commission later this summer.

Background on the HSP: The HSP was formed in 2003 by the U.S. Department of Energy to help develop and implement practices and procedures that would ensure safety in the operation, handling and use of hydrogen and hydrogen systems. The primary objective is to enable the safe and timely transition to hydrogen and fuel cell technologies. This is accomplished by:

- Providing expertise and recommendations and assist with identifying safety-related technical data gaps, best practices, and lessons learned, and
- Ensuring that safety planning and safety practices are incorporated into hydrogen projects.

The HSP’s members collectively have over 700 years of experience and represent a cross-section of expertise from the commercial, industrial, government, and academic sectors. HSP members participate in a variety of standards development organizations including the American Society of Mechanical Engineers (ASME), CSA Group (CSA), International Organization for Standardization (ISO), National Fire Protection Association (NFPA), Society of Automotive Engineers (SAE), and Underwriters Laboratories (UL). HSP members also contribute to peer-reviewed literature and trade magazines on hydrogen safety and present at national and international forums. The HSP has reviewed over 325 projects covering vehicle fueling stations, auxiliary power, backup power, combined heat and power, industrial truck fueling, portable power, mobile applications, and research & development activities.

| | |
|---|--|
| Date | |
| HSP Interviewer(s) | |
| Company Name | |
| Interviewee Name | |
| Interviewee Phone | |
| Interviewee Email | |
| Summary of the Application | |
| Can you provide pictures or a diagram of the application? | |
| Maximum fill pressure of unit | |
| Minimum design temperature | |
| Maximum design temperature | |
| Capacity of hydrogen (kg) | |
| | |

| General Topics | Response/Conclusion |
|--|---------------------|
| What is your company's approach for identifying potential and unique hazards (vulnerabilities) for new applications? | |
| What organizations have reviewed the mobile system from a safety perspective? What was the scope and focus of this review? | |
| What criteria are applied to assess for acceptable risk for identified hazards? | |
| What resources and people do you use? | |
| What process(es) is/are utilized to ensure and maintain safety? | |
| What safety requirements, codes, and standards are applied? Please be specific to the part of the design that each safety requirements, codes, and standards is applied? | |
| How are the drivers and operators trained? | |
| | |
| Specific Topics | |
| How have these vulnerabilities been addressed in the design and operation of your mobile hydrogen application: | |
| <ul style="list-style-type: none"> • Higher pressures (>2800 psi) | |
| <ul style="list-style-type: none"> • Use in transport - acceleration, vibration and suitability of pipe fittings, etc. | |
| <ul style="list-style-type: none"> • Potential vehicle and accident impacts | |
| <ul style="list-style-type: none"> • Manifolding and isolation of storage tanks | |
| <ul style="list-style-type: none"> • Enclosed compartments/unique ventilation issues | |
| <ul style="list-style-type: none"> • Potential exposure fires | |
| <ul style="list-style-type: none"> • Vent stack protection from accident and safe location for H2 venting | |
| <ul style="list-style-type: none"> • Limiting the loss of hydrogen during transport | |
| Have fire protection devices been used? How? | |
| Have overpressure devices been used? How? | |
| What Storage tank performance and system-level safety integration issues for hydrogen fueling tanks when used for other than light-duty vehicles (mobile applications) have been considered? | |
| What Fueling protocols and safety implications for refueling nonstandard equipment at existing stations have been considered? | |

| | |
|---|--|
| What gaps in codes and standards requirements exist? If there are existing requirements, are they comprehensive enough to suit these types of designs? | |
| <ul style="list-style-type: none"> • What is needed to get mobile applications approved for use (certifications, examinations, etc.)? | |
| <ul style="list-style-type: none"> • If necessary requirements are not available, what fundamental issues (specific attributes or safety features) could be identified (and support development of future requirements)? | |
| What DOT permit are these units being transported? | |
| How are affected H2 cylinders/tanks offloaded if an incident occurs? | |
| Has Safe disposal of damaged cylinders/tanks and equipment been considered? | |
| If electrical components are used, how have the electrical issues for hydrogen been addressed? | |
| How will grounding occur? | |
| What emergency protocols are in place? | |
| What safety protocols/checks are in place for assuring safe travel and arrival for use? | |

The **Hydrogen Safety Panel** was formed in 2003 by the U.S. Department of Energy to help develop and implement practices and procedures that would ensure safety in the operation, handling and use of hydrogen and hydrogen systems. The primary objective is to enable the safe and timely transition to hydrogen and fuel cell technologies. This is accomplished by:

- Providing expertise and recommendations and assist with identifying safety-related technical data gaps, best practices, and lessons learned, and
- Ensuring that safety planning and safety practices are incorporated into hydrogen projects.

The 24-member panel has over 700 years of combined experience and is comprised of a cross-section of expertise from the commercial, industrial, government, and academic sectors. Panel members participate in a variety of standards development organizations including the ASME, CSA, ISO, NFPA, SAE, and UL. Panel members also contribute to peer-reviewed literature and trade magazines on hydrogen safety and present at national and international forums. The Panel has reviewed hundreds of projects covering vehicle fueling stations, auxiliary power, backup power, combined heat and power, industrial truck fueling, portable power, mobile applications, and R&D activities.

If you have interest in utilizing the expertise of the Panel, contact the program manager at 509-371-7894 or by email at hsp@h2tools.org.



HYDROGEN
Safety Panel