

AN INVESTIGATION OF MOBILE HYDROGEN AND FUEL CELL TECHNOLOGY APPLICATIONS

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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 in any project could damage public perception of hydrogen and fuel cells. A recent incident involving a hydrogen mobile storage trailer in the United States has brought attention to the potential impacts of mobile hydrogen storage and transport. Road transport of bulk 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 incident, and in support of hydrogen and fuel cell activities in California, 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 trailer transport, 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 paper discusses the results of the HSP's evaluation of hydrogen and fuel cell mobile applications along with recommendations to address relevant safety issues.

1.0 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 hydrogen storage; transport and fueling equipment such as tanks, 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

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.

information to raise the awareness of hydrogen safety to reduce future mobile application incidents involving hydrogen. This paper summarizes the activities and conclusions associated with this effort.

2.0 BACKGROUND

2.1 Hydrogen Safety Panel

The HSP was formed in 2003 by the U.S. Department of Energy (DOE) 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 helping to identify safety-related technical data gaps, best practices, and lessons learned
- Ensuring that safety planning and safety practices are incorporated into hydrogen projects

The HSP's members collectively have over 400 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), the International Organization for Standardization (ISO), the National Fire Protection Association (NFPA), the 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'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 over 339 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

2.2. Hydrogen Mobile Storage Trailer Incident

On the afternoon of 11 February 2018, a fire occurred during the transportation of a fully loaded hydrogen storage trailer from its fill location to a receiving customer site (see Figures 1 and 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 [2].

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



Figure 1. Exemplar CT-250 hydrogen tube trailer [2]



Figure 2. Cylinder ends in open incident trailer with fire-damaged cylinders encircled [2]

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 PRD-activated 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 PRD outlets were arranged to discharge upward and unobstructed to the open air 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	● Severe burning damage, composite caught fire ²¹
PRD actuated = 12 ²²	○ Scorching, surface burns
Vent line ejected = 7	○ Heat discoloration, blistered paint, melted label
Severe fire damage = 11	○ No discoloration, some soot accumulation

Figure 3. Module 430003 inspection summary [2]

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, 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, thereby 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 crosscuts 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.

3.0 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 and fuel cell mobile applications for the study.

- Trailers with high-pressure (>2,800 psig) hydrogen storage cylinders (particularly those of composite construction), including the type of trailer involved in the incident discussed in Section 2.2
- 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
- Seaport and airport remote power and short distance transport cargo (material handling) applications
- Fuel-cell-powered unmanned aircraft systems such as drones



Figure 4. Mobile auxiliary power unit

Task group members conducted structured interviews as the primary method for data collection and designed an interview questionnaire 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: pressures greater than 2,800 psi (190 bar), use in transport, vehicular and accident impacts, manifolding and isolation of storage tanks, enclosure and ventilation, fire exposure, vent stack protection, and limiting hydrogen loss during transport
 - Gaps in codes and standards requirements: approval for mobile applications, fundamental safety considerations in the absence of safety requirements, protocols used in emergencies, travel, arrival, and fueling

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, cylinder/tank 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. 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 paper 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.

4.0 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 tube trailer resupplying, by far the largest category.

Table 1. Interview summary

	Mobile Refueler & H2 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 any relevant DOT 49 CFR requirements)	NFPA 2 & 52 CSA HGV 3.1, 4.1, 4.5, & 4.8 NEC Haz Loc ASME B31.3 SAE J2579	NFPA 2 ISO TR 15916 IEC 60079-10 ASME B31.3 MIL-ST-882-E	SAE J2601 Others	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 Section 2.2. At the other extreme, the mobile hydrogen generators and the unmanned aerial system (UAS) power suppliers interviewed presently were 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 Section 2.2. Most of the pressures listed in Table 1 far exceed the pressures used in more 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 Section 2.2, 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 in the last three columns.

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 and Pipeline and Hazardous Materials Safety Administration [PHMSA] regulations) and various industry standards (e.g., NFPA, the Compressed Gas Association [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 requirements, codes, and standards applicable to their applications. Many interviewees identified situations where the existing standards and regulations are limited or lacking. General regulations are provided under DOT or the safety standards referenced in Table 1 and are applicable to the transportation of hazardous materials; however, standards for the specific applications have not been 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/Tube Trailers

- Mobile trailers carrying high-pressure hydrogen cylinders lack a specific regulation; therefore, the DOT 49 CFR requirements must be met. Special permit applications are reviewed and approved by PHMSA, but often lack explicit requirements for trailer design, construction, and road travel durability.
- Although there are concise ISO standards for refillable composite gas cylinders (ISO 11119 series of standards), there is no corresponding U.S. standard (the requirements are spread throughout DOT 49 CFR and it may be difficult to follow). However, ISO 11515 has been used as the basis for PHMSA special permit applications for composite cylinders that are otherwise not addressed in DOT 49 CFR.
- Hydrogen transfer and fueling standards are inadequate as temperature limitations are not prescribed in current standards for composite cylinders.
- There is limited guidance/requirements regarding how or where hydrogen cylinders for these applications can be filled (e.g., can these be filled on the side of the road or at retail fueling stations that are intended for light duty vehicles).
- Cylinder/PRD vent design specifications are lacking for these types of applications.
- There are no standard emergency response procedures or guidance for mobile trailers.
- There are no vibration and/or crash test requirements for mobile trailers.

Mobile Fuel Cell Power/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.

Mobile Hydrogen Generators

- NFPA 2 requirements for hydrogen generation systems only cover permanently installed generation systems.
- There are currently no certification standards for mobile generation systems.
- 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 making it available for FAA inspection upon request). The regulation on the operator maintaining visual-line-of-sight with the UAS effectively restricts range. If this restriction is eventually lifted, there will be increased incentive to use fuel cell range extenders.
- ASTM F38 Committee Work Item WK60937 will provide specifications for use of fuel cell power systems for UAS, but the working group has limited participation and the standard is not progressing as quickly as envisioned.

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 the permitting of these vehicles will be under the jurisdiction of PHMSA, the National Highway Traffic Safety Administration (NHTSA), or another DOT organization. PHMSA regulates hazardous material transportation and NHTSA regulates fuel containers for mode of transportation. Many of these new applications could fit under 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 the inherent safety features for vessels, piping, valves, and natural ventilation that are almost omnipresent in standard industrial gas tube trailers due to the PHMSA requirements. These new mobile units may have greater quantities at higher pressure compared to existing tube trailers. They present an increased risk over conventional gas transport operations due to the increased pressure; lack of design, operations, and maintenance codes; and lack of standardized designs. The following specific concerns have been identified:

- Potential crash impact zones need to be evaluated for greater protection. Potential vulnerabilities include the following:
 - Valves located less than 42-48 inches above the road, increasing the potential for impact damage
 - Absence of a rear deck that provides a significant barrier to protect valves and manifolds from rear impact
 - Absence of more robust/inherently safe valves, which are less likely to inadvertently open during impact
 - PRDs that are located on the rear end of cylinder/trailer and are located in areas that make them more vulnerable to rear impacts than standard tube trailers
- Enclosed storage vessels may allow leaked hydrogen to accumulate within the transport package.
- Manifoldd PRD vent stacks are not always extended above the height of all onboard cylinders.

- Some equipment lacks a thorough quantitative structural analysis of the trailer and cylinder supports.
- Non-transportation related electrical equipment on some mobile trailers 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.
- Ventilation of the trailers and expansion/contraction of some trailer tube ends need to be better defined from an engineering standpoint.

5.0 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 paper 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.

5.1 Hazard Analysis

- a. 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 by personnel not involved in product development. A hazard analysis can help the equipment providers identify potential safety issues, discover ways to lower 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 (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 of the team needs to be knowledgeable in the specific identification of the safety vulnerability method being used.
2. One member should have detailed knowledge of hydrogen flammability issues and protection measures.
3. One member who was not involved in system development should be included to represent potential users.
4. One member should be experienced in hazardous material regulations.
5. Someone should be identified to maintain the hazard analysis and monitor for changing conditions that require reevaluation of the equipment
6. At a minimum, the hazard analysis should address the following:
 - i. Potential hazard scenarios during the operation, transport, refueling, and storage of the unit
 - ii. Previous incidents and near misses involving similar systems and components
 - iii. Engineering and administrative controls applicable to the hazards and their interrelationships (e.g., the use of hydrogen detectors and emergency shutdown capability)

- iv. Mechanisms and consequences of component failures and failure modes of engineering and administrative controls
- v. 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.

5.2 Regulations and Permitting

- a. A more general method for permitting hydrogen composite cylinder mobile trailers needs 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 newer technology vessels, especially those 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 all currently are built and operate to the requirements within the special permits. These special permits are submitted by numerous companies and have a wide variety of inconsistencies regarding vessel construction, frame design, 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/overpressure protection:
 - i. Protection of storage tubes from fire
 - ii. Protection of valves/instrumentation/components from fire
 - iii. Protection/redundancy of piping joints vent stack design and location
 2. Cylinder and valve vulnerability to impact from crashes and road debris
- b. Tank and trailer manufacturers should be required to provide detailed installation, operating, maintenance, and testing procedures before the cylinders are publicly transported and refueled on public roads. Instructions should include guidance on checking PRDs and PRD vent lines, trailer valve positions, and methods for isolating each tube during transport. There should also be requirements for inspections prior to cylinder and trailer resale and redeployment.
- c. Regulatory and 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 cargo (material handling) vehicles at ports, airports, and other off-road, busy locations
 5. UASs
- d. Additional guidance is needed to clarify whether PHMSA or NHTSA requirements apply to specific applications.

5.3 Design/Codes and Standards

- a. Develop a standard for trailers and mobile applications equipped with hydrogen cylinders. The standard should include rigorous inspection and testing of the crashworthiness³ and fire

³ Verifiable performance testing using analytical methods should be used to prove the adequacy of the design per TB-25, 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”).

resistance of cylinder valves, cylinder support structure, mechanical connections, and housings. The standard should include the following:

1. The use of listed equipment and components whenever possible.
 2. Ensuring that all cylinders, piping, valves, fittings, and supports have been inspected or tested for their response to road vibration, acceleration, and fire conditions. This includes verifying that all fittings have been installed correctly and are not vulnerable to disengagement during transport.
 3. Defining Class 1, Division 2, Group B locations and verifying 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).
 4. Verifying the hydrogen compatibility of all materials that would come in contact with high-pressure hydrogen gas.
 5. Require 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.
 6. Provide an analysis or test results to verify that the trailer vent openings will be adequately sized for credible hydrogen leaks. Specify required ventilation to ensure hydrogen is not trapped in an enclosure around the cylinders and piping during leakage or a larger release from a broken valve or fitting. If there is a roof on the cylinder enclosure, hydrogen detection should be provided to alert operators, and avoid having them open a door to a flammable mixture.
 7. Verifying that the appropriately rated PRDs or TPRDs are installed on all cylinders and providing an analysis or testing to demonstrate that the vent stack and piping supports (including compression fitting attachments) used to vent releases will be able to handle the forces developed during a release event. The analysis/testing should also determine if the relief system is designed for potential impacts while the trailer is in transport.
 8. Consider a requirement for an interlock to ensure that the hydrogen tank valves are closed/isolated when the trailer is in transport.
 9. Require a formal management of change process to address any changes to the original design during maintenance.
 10. Consistently apply regulations such as CGA-TB25, "Design Considerations for Tube Trailers," to define safety factors necessary to ensure failure modes are understood and addressed.
 11. Define the end-of-life process for tanks (tanks can be redeployed [eBay, etc.]).
- b. Expand the NFPA 2 chapter on hydrogen fueling stations to include mobile stations and other temporary or fixed vehicle-related applications. Similarly, review and expand the ISO TS 19880 standard on hydrogen fueling stations to include mobile stations and heavy-duty vehicles. The new or expanded chapters in these standards should account for the following considerations identified above for the mobile trailer certification: i, ii, iii, iv, v, vii, and x. It is also recommended that a breakaway feature or immobilization device be incorporated into transfer operations to interrupt the transfer, should the trailer unintentionally move.
 - c. Expedite the completion of the ASTM F38 Committee Work Item WK60937 on specifications for use of fuel cell power systems for UASs. Review the draft standard for completeness relative to the NFPA, SAE, CSA, and UL fuel cell standards for stationary applications and for vehicle fueling including fuel-cell-powered industrial trucks.
 - 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” [7].

5.4 Operations and Maintenance

- a. Encourage mobile refueler 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. The operating procedures should identify who is authorized to operate and/or maintain the equipment. Operating procedures should also define what personal protective equipment must be worn when operating the equipment.
- b. Encourage mobile fuel system developers, users, and independent system service and inspection organizations to review safety-related maintenance procedures during maintenance activities.

5.5 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. Hydrogen mobile trailer 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 web site 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 including information specifically for hydrogen applications.

6.0 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 paper should be considered by agencies/organizations involved in the use and regulation of mobile hydrogen applications to ensure that safety is adequately incorporated.

Note that this paper was written before the HSP Mobile Application Task Group completed its anticipated activities. Additional activities may include meeting with DOT to discuss these issues further and working with a relevant industry organization to consider and address the gaps and recommendations.

7.0 ACKNOWLEDGMENTS

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