Air Products and Chemicals, Inc. Tube Trailer Module Hydrogen Release and Subsequent Fire
Diamond Bar, California
February 11, 2018

Incident Report

NTSB/HZM-19/02
PB2019-101398

National Transportation Safety Board

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Hazardous Materials Incident Report

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National Transportation Safety Board

490 L'Enfant Plaza, S.W.
Washington, D.C. 20594

National Transportation Safety Board. 2019. *Air Products and Chemicals, Inc. Tube Trailer Module Hydrogen Release and Subsequent Fire, Diamond Bar, California, February 11, 2018*. Hazardous Materials Incident Report NTSB/HZM-19/02. Washington, DC: NTSB

Abstract: On February 11, 2018, at 1:15 p.m. Pacific standard time, a release of compressed hydrogen and subsequent fire occurred during the transportation of an Air Products and Chemicals, Inc. 2014 Mack CXU613 truck tractor in combination with a 2015 Cheetah Chassis Corporation chassis, with a mounted CT-250 tube trailer module. The tube trailer module contained 25 non-US Department of Transportation specification fully wrapped carbon filler reinforced aluminum-lined cylinders, 24 of which were fully loaded with 240 kilograms of compressed hydrogen. The module caught fire on Golden Springs Drive in Diamond Bar, California. Pressure relief devices, which actuate on 12 of the cylinders, released about 120 kilograms of hydrogen that was likely consumed in the fire. Los Angeles County Fire Department estimated about 1,400 to 2,000 people were evacuated from the adjacent business district and a nearby residential area. Equipment damages were estimated at $175,000. As a result of this investigation, the National Transportation Safety Board is making safety recommendations to the Pipeline and Hazardous Materials Safety Administration; the US Department of Energy, Pacific Northwest National Laboratory; and the Compressed Gas Association.

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Acronyms and Abbreviations

Air Products	Air Products and Chemicals, Inc.
Atlas	Atlas Machining and Welding, Inc.
BASIC	Behavior Analysis and Improvement Categories
CDL	Commercial Driver's License
CFFC	carbon fiber reinforced aluminum-lined cylinders
CFR	*Code of Federal Regulations*
CGA	Compressed Gas Association
DOE	US Department of Energy
DOT	US Department of Transportation
ERG	*Emergency Response Guidebook*
FCEV	fuel cell electric vehicle
FIBA	FIBA Technologies, Incorporated
FMCSA	Federal Motor Carrier Safety Administration
kg	kilograms
LACoFD	Los Angeles County Fire Department
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
PRD	pressure relief devices
psi	pounds per square inch
psig	pounds per square inch, gauge
RSPA	Research and Special Programs Administration

SCI/Worthington	Structural Composite Industries, subsidiary of Worthington Industries
Sherwood	Sherwood Valve, LLC
UN	United Nations

Executive Summary

On February 11, 2018, at 1:15 p.m. Pacific standard time, a release of compressed hydrogen and subsequent fire occurred during the transportation of an Air Products and Chemicals, Inc. 2014 Mack CXU613 truck tractor in combination with a 2015 Cheetah Chassis Corporation chassis, with a mounted CT-250 tube trailer module. The tube trailer module contained 25 non-US Department of Transportation specification fully wrapped carbon fiber reinforced aluminum-lined cylinders, 24 of which were fully loaded with 240 kilograms of compressed hydrogen.[1] The module caught fire on Golden Springs Drive in Diamond Bar, California. Pressure relief devices, which actuated on 12 of the cylinders, released about 120 kilograms of hydrogen that was likely consumed in the fire. The Los Angeles County Fire Department estimated about 1,400 to 2,000 people were evacuated from the adjacent business district and a nearby residential area. Equipment damages were estimated at $175,000.

The postincident inspection found that an incorrect pressure relief device in cylinder No. 14 actuated during normal conditions to transportation. The force of high-pressure hydrogen releasing from the cylinder caused the pressure relief device vent tubing to eject from its fitting and allowed a hydrogen field fire to develop inside of the module. The vent tubing was designed to direct pressure relief gases in a safe direction up and away from the module, but because separated tubing directed gas into the interior of the module, the resulting fire impinged on adjacent cylinders. The fire damaged 21 of the cylinders and resulted in six additional pressure relief device vent tubes being ejected from improperly secured compression fittings, which vented more gas into the interior of the module.

Prior to the incident in December 2017, the tube trailer module gas cylinders had been subjected to a required 5-year requalification inspection and pressure test. Testing facility technicians installed four incorrect pressure relief devices that were designed to activate at almost one-half the required operating pressure of 10,000 pounds per square inch. The incorrect pressure relief devices shipped from the manufacturer were inadvertently commingled in the facility's inventory and went unnoticed by the inspector. Additionally, the pressure relief device vent tubing attached by compression fittings to seven of the module's cylinders had not been sufficiently secured when manufactured. Although the vent tubing could have been secured at the time of the requalification inspection, technicians did not inspect the fittings for securement.

The National Transportation Safety Board initiated this investigation to evaluate the safety of mobile hydrogen tube trailer modules used as fueling stations for hydrogen fuel cell electric vehicles. Automakers expect to make thousands of additional fuel cell electric vehicles available to California consumers, and the state is working to ensure that hydrogen is easily available to drivers. As of April 25, 2018, the California Fuel Cell Partnership reported that the state had 36 open retail and nonretail hydrogen fueling stations, with another 28 stations in various stages of construction and planning.

[1] Cylinders used in the tube trailer were manufactured and operated under the terms of US Department of Transportation special permit DOT-SP 14576, which sets forth alternative requirements, or variances, to the requirements in the Hazardous Materials Regulations.

This report focuses on the following safety issues:

- **Emergency responder awareness:** The Los Angeles County Fire Department emergency responders lacked familiarity with hydrogen tube trailer modules. Emergency responders did not immediately recognize the presence of hazardous materials, had difficulty estimating the likelihood for severe outcomes, and had not received guidance about appropriate mitigating actions needed to reduce the potential for catastrophic gas cylinder failures.

- **Tube trailer requalification and inspection requirements:** The carrier and the requalification inspector missed opportunities to prevent this incident. The carrier failed to conduct external fittings acceptance inspections at the time it received the tube trailer module from the manufacturer, and the requalification facility personnel did not check pressure relief device compatibility and vent line securement as they inspected and tested the tube trailer module cylinders 6 weeks before the incident. The Pipeline and Hazardous Materials Safety Administration special permits and existing regulatory requirements pertinent to qualification and maintenance of cylinders do not require operators and requalification inspectors to verify that the correct pressure relief device model was installed and that venting equipment has been properly assembled and secured before placing the equipment in service.

- **Hydrogen tube trailer component design criteria**: The lack of pressure relief device vent system design requirements that consider factors such as the force of venting gas and materials of construction may leave vent systems for cylinders and tube trailers vulnerable to unexpected failure during an incident. Furthermore, the appearance of the pressure relief devices appropriate for the cylinders involved in this incident are easily confused with similar pressure relief devices with incorrect operating pressure. Seven incorrect pressure relief devices shipped from the manufacturer became commingled into the requalification facility's supply and were inadvertently installed on tube trailer modules, including the incorrect device that actuated during normal transportation and began the sequence of events that led to the fire.

The National Transportation Safety Board determines that the probable cause of the February 11, 2018, tube trailer module fire in Diamond Bar, California, was the requalification technician's installation of an incorrectly rated pressure relief device in cylinder No. 14, which actuated during normal transportation and released high-pressure hydrogen, and the tube trailer module assembly contractor's failure to sufficiently tighten compression fittings on the pressure relief device vent lines that disassembled under the pressure of escaping gas allowing a fire to develop inside the module and impinge on adjacent cylinders. Contributing to the incident was a lack of a requirement for requalification inspectors to verify the pressure relief device pressure rating and to inspect for vent line assembly securement.

1. The Incident

On February 11, 2018, at 1:15 p.m. Pacific standard time, a release of compressed hydrogen and subsequent fire occurred during the transportation of an Air Products and Chemicals, Inc. (Air Products) 2014 Mack CXU613 truck tractor in combination with a 2015 Cheetah Chassis Corporation chassis, with a mounted CT-250 tube trailer module. The tube trailer module contained 25 non-US Department of Transportation (DOT) specification fully wrapped carbon fiber reinforced aluminum-lined cylinders (CFFC), 24 of which were fully loaded with 240 kilograms (kg) of compressed hydrogen. The module caught fire on Golden Springs Drive in Diamond Bar, California. (See figure 1.) Pressure relief devices (PRD), which actuated on 12 of the cylinders, released about 120 kg of hydrogen that was likely consumed in the fire. The Los Angeles County Fire Department estimated about 1,400 to 2,000 people were evacuated from the adjacent business district and a nearby residential area. Equipment damages were estimated at $175,000.

Figure 1. Aerial view of the incident location, Diamond Bar, California.

1.1 Events Preceding the Incident

The Air Products driver reported to duty at the Santa Fe Springs terminal on February 11, 2018, at 4:45 a.m. After delivering a similar tube trailer module that morning, the driver picked up the incident tube trailer module from the Air Products Wilmington, California, hydrogen filling station and conducted a pretrip inspection. The driver connected the module to the filling

stanchion and found that although the cylinders were pressurized to 7,855 pounds per square inch, gauge (psig) (temperature-corrected loading pressure), the pressure had reduced to 7,300 psig with cooling. The driver advised the Air Products dispatcher the module was already full and then proceeded with his trip to deliver it to the South Coast Air Quality Management District headquarters fuel cell electric vehicle (FCEV) fueling station in Diamond Bar.

About 1:15 p.m., the incident occurred after the driver came to a stop at a traffic signal on Golden Springs Drive at Brea Canyon Road, near his destination. The driver was unaware of any unusual occurrences during the module movement from Wilmington to Diamond Bar that might have precipitated the incident. The driver told National Transportation Safety Board (NTSB) investigators that when he stopped, he heard a loud pop and saw flames coming from the front of the module. He immediately exited his vehicle and told others in the area to evacuate.

1.2 Motor Carrier

Air Products is headquartered in Allentown, Pennsylvania, and has been in the business of transporting industrial gases and cryogenic liquids to customers worldwide for about 75 years. Air Products is registered with the Federal Motor Carrier Safety Administration (FMCSA) as a private motor carrier of liquids, chemicals, and compressed gases and has been issued US DOT No. 101263. The company only transports its own hazardous material products. The FMCSA conducted its most recent compliance review of Air Products on May 10, 2010, resulting in a satisfactory rating for the carrier.[2] At the time of this incident, Air Products had no alerts in any of the FMCSA Behavior Analysis and Improvement Categories (BASIC).[3]

1.3 Air Products Driver

At the time of the incident, the driver held a valid California Class A Commercial Driver's License (CDL). The driver had an endorsement for hauling double and triple trailers, a combination endorsement for tanks and hazardous materials, and had no CDL restrictions. According to the driver's qualification file, the driver had a medical certificate that was valid until July 22, 2018.[4] The driver was not subject to postaccident substance and alcohol testing requirements since there was no collision with injury, death, or disabling damage to the vehicle. Air Products required their drivers to use an automatic onboard recording device to record the driver's hours of service. The driver's records showed no violations of the hours of service regulations for the 7 days prior to the incident.

[2] For further information, see the Motor Carrier Factors factual report and Air Products Motor Carrier Management Information System report in the docket for this incident.

[3] The FMCSA BASIC Categories consist of unsafe driving, hours of service, driver fitness, controlled substances and alcohol, vehicle maintenance, hazardous materials, and crash indicators.

[4] See Title 49 *Code of Federal Regulations* (*CFR*) 391.51 for information about general requirements for driver qualification files.

1.4 Tube Trailer Module

Air Products tube trailer module number 430003, was a 2015 Cheetah Chassis Corporation 24-feet drop frame container chassis, on which was mounted a Structural Composite Industries, subsidiary of Worthington Industries (SCI/Worthington) model CT-250 composite gas cylinder module. The CT-250 tube trailer module consisted of 25 horizontal neck-mounted Worthington Type 3 model ALT1015 carbon fiber composite cylinders arranged in a 5 x 5 array.[5] Each cylinder contained 10 kg of hydrogen when full. The entire module had a hydrogen capacity of 250 kg.

Design criteria and operational requirements under special permit DOT-SP 14576 include but are not limited to:

- Service pressure limited to 7,500 psig at 70°F.
- Test pressure of 12,500 psig.
- Minimum cylinder burst pressure of 25,500 psig, or a safety factor of 3.4.
- Cylinder service life is limited to 15 years.
- Each cylinder must be requalified once every 5 years by a qualified person holding a valid DOT requalification identification number using a hydraulic or pneumatic pressure proof test.
- Cylinders must be manifolded in accordance with the requirements of Title 49 *Code of Federal Regulations* (*CFR*) 173.301(g).
- All cylinders must be operated and maintained in accordance with the Structural Composites Industries Cylinder Component Operations Manual.

Each "Hazmat employee," as defined in 49 *CFR* 171.8, who performs a function subject to this special permit must receive training on the requirements and conditions of this special permit in addition to the training required by 49 *CFR* 172.700 through 172.704. SCI/Worthington advertises that its Type 3-cylinder features include light weight, no gas permeation, impact and heat tolerance, and a designed leak-before-burst fatigue failure mode. ALT1015 cylinders are constructed with a seamless 6021 aluminum liner surrounded by 23 layers of carbon fiber reinforcement wrapped in either a circumferential or helical continuous filament winding pattern. The composite fiber wrap constitutes the predominant pressure bearing element. The exterior layers of fiberglass and white exterior epoxy provide added abrasion and damage protection. The tube trailer cylinders had been in service for 5 years, and the cylinders had 10 years of remaining authorized service life.

[5] Pressure vessels for compressed natural gas and hydrogen fuel tanks are classified in four categories by the CSA/ANSI NGV2 standard for compressed natural gas vehicle fuel containers. Type 3 cylinders are seamless and gas-tight metal-lined cylinders with full exterior composite reinforcement.

Air Products contracted FIBA Technologies, Incorporated (FIBA) to inspect and requalify tube trailer module number 430003 on December 29, 2017. The module was subjected to 22 hydrogen fill-and-discharge cycles and deliveries after the requalification inspection. The incident occurred during the module's 23rd postrequalification delivery.

1.5 Pressure Relief Devices

Title 49 *CFR* 173.301(f) requires that cylinders offered for transportation be equipped with one or more PRDs sized and selected as to type, location, and quantity, and tested in accordance with the Compressed Gas Association (CGA) S-1.1 and CGA Pamphlet S-7.[6] The PRD must be capable of preventing rupture of the normally filled cylinder under fire conditions. In accordance with 49 *CFR* 173.301(g) and Table 3 CGA S-1.1, the PRDs are required at both ends of horizontally mounted cylinders. The gas cylinders used in incident tube trailer module number 430003 were equipped with PRDs at each end, giving a total of 50 PRDs installed on the module.

In accordance with the trailer and composite cylinder design, the PRDs were CG-5 type devices (combination rupture disk/fusible plug).[7] The cylinder manufacturer's drawings call for Sherwood Valve, LLC (Sherwood) model 3132SB9-95 PRDs with a set pressure of 10,000 psig. These PRDs contain a copper rupture disk that is directly exposed to the internal cylinder pressure and is situated immediately upstream of a fusible metal plug in the discharge port.[8] The design intends for the fusible metal plug to weaken from thermal exposure before the rupture disk bursts from overpressure. (See figure 2.) The CG-5 type devices require a combination of both high pressure and high temperature (212°F) to first melt the fusible metal, after which the device affords the same overpressure protection as does a type CG-1 rupture disk. The rupture disk is reinforced against rupturing by the fusible metal, and the fusible metal is reinforced against extrusion by the rupture disk. The advantage of using a CG-5 type device to protect cylinders used for flammable gases is it may provide a few minutes of extra time for personnel to evacuate a cylinder exposed to fire before its rupture disk activates, leading to greater potential for injury.

[6] Compressed Gas Association, *Pressure Relief Device Standards Part 1-Cylinders for Compressed Gases.* CGA S-1.1, 14th edition (Chantilly, Virginia: Compressed Gas Association, 2011).

[7] Pressure relief device types are described by CGA S-1.1.

[8] The fusible metal is a eutectic mixture of lead, tin, and bismuth in nearly equal proportions.

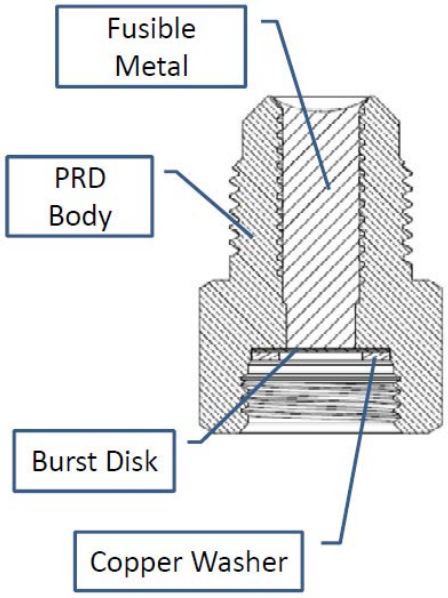

Figure 2. Sherwood valve type 3132SB PRD.

Type 3132SB PRDs are available in a range of pressures. Lower-pressure devices, such as the model 3132SBF9-55 nickel disk variant with a burst pressure of 5,833 psi, are typically used for cylinders containing compressed natural gas. The 10,000 psi PRDs are used in hydrogen carbon fiber composite cylinder service.

The incident module PRDs were contained in an assembly that consisted of a brass-threaded adaptor, brass-body PRD, stainless-steel straight fitting, and stainless-steel elbow. (See figure 3.) The 50 front and rear cylinder heads were each equipped with a PRD assembly and vent line. The rear heads were also fitted with Tescom shutoff valves to control discharge and filling, and tubing associated with the module's manifold system.

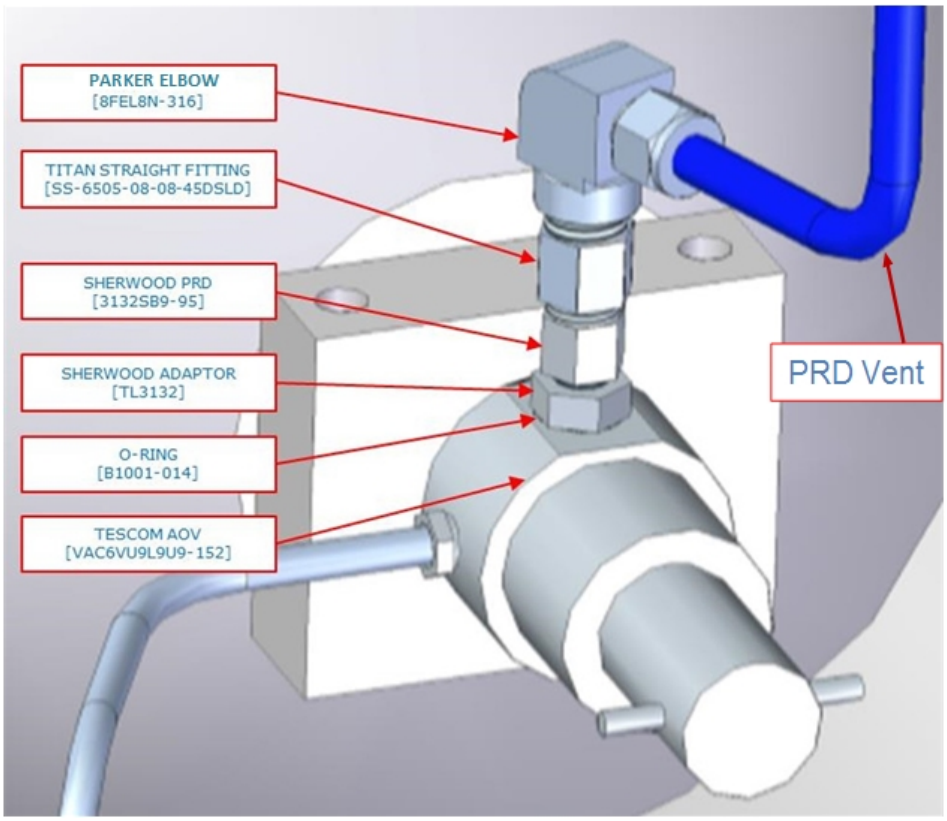

Figure 3. Cylinder fittings arrangement for rear heads. The PRD vent line compression fitting is attached to the Parker elbow.

Title 49 *CFR* 173.301(g) and CGA S-1.1 (Table 3), require the PRDs to be arranged to discharge upward and unobstructed to the open air to prevent any impingement of escaping gas upon the containers or personnel. This is accomplished on the CT-250 tube trailer modules by fixing 0.5-inch outside diameter stainless steel tubing to each of the PRD discharge ports that are designed to direct any pressure-relieved gases upward and away from the module. Under normal transportation conditions, the vent tubing is under atmospheric pressure and would only convey gas if a rupture disc were to actuate. As shown in figure 4, the vent tubing downstream of each front and rear PRD assembly had a 90° bend and extended upward to a transverse horizontal bulkhead at the highest point on the module frame.

Figure 4. Hydrogen tube trailer module PRD vent lines and tubing bulkhead.

Between January 30, 2015, and May 29, 2015, Atlas Machining and Welding, Inc. (Atlas) of Northampton, Pennsylvania, under contract with Air Products, assembled PRD vent tubing and high-pressure tubing and fittings on 12 CT-250 hydrogen tube trailer modules. Atlas completed the incident module number 430003 on February 15, 2015.

The discharge side of the Parker elbow is a compression fitting in which the nut and ferrule must be tightened sufficiently in accordance with the manufacturer's nut rotation specification to compress and engage the vent line tubing wall.[9] A properly tightened fitting will swage and bite the ferrules into the tubing, narrowing the tubing diameter at that point to secure it in place. Before the incident, Air Products provided Atlas written assembly instructions that included details for proper compression fitting securement.

[9] A *ferrule* is defined as a ring or cap usually of metal put around a slender shaft (such as a cane or a tool handle) to strengthen it or prevent splitting.

1.6 Hazardous Materials Information

1.6.1 Safety Information

The incident tube trailer module was loaded with compressed hydrogen, which is a Division 2.1 flammable gas. Tube trailers are used to transport bulk quantities of compressed hydrogen gas. Because hydrogen gas has a low energy content at atmospheric pressure, commercially useful quantities must be compressed and transported at high pressure.

Hydrogen is a colorless and odorless gas that is 14 times lighter than air. It is extremely flammable, may form explosive mixtures in air, burns with an invisible flame, and may ignite if a cylinder valve is opened to the air. Upon exposure to intense heat or flame, gas cylinders can vent rapidly or rupture violently.

1.7 Emergency Response

The primary emergency response organizations were the Los Angeles County Fire Department (LACoFD), Los Angeles County Sheriff's Department, and Air Products. The California Highway Patrol, California Office of Emergency Management, City of Diamond Bar, and the American Red Cross were also involved in the response.

Firefighters' initial actions were to take up positions within feet of the burning trailer and to douse the fire and cool cylinders with water hoses. The incident commander told NTSB investigators that his decision to launch an offensive attack on the fire was made to prevent loss of life should the cylinders catastrophically fail because he recognized there was little chance of a timely evacuation in the highly congested area. Firefighters later established monitor nozzles to cool the hydrogen cylinders from a safer distance.[10]

Soon after first responders arrived, one of the PRDs actuated. The most intense gas venting lasted for about 30 to 45 minutes. With a reduction in venting intensity, responders believed the risk of catastrophic cylinder failure had diminished.

The Air Products truck driver remained on the scene to further inform emergency responders about the contents of the tube trailer module until the company's Santa Fe Springs site manager and a vehicle response and recovery team arrived almost 1 hour after the incident began. The Air Products site manager encouraged the incident commander to continue the cylinder cooling efforts with water spray to prevent the fire from involving additional cylinders.

The LACoFD incident commander consulted the DOT *Emergency Response Guidebook* (ERG) Guide 115, which recommended a 1-mile isolation distance.[11] The incident was managed with a 150-foot exclusion zone and 400–500-foot distance to the command post. Although

[10] A *monitor nozzle* is a high-capacity water jet used for fighting fire from a distance. Monitor nozzles may be mounted on top of fire engines and can be operated manually or remotely.

[11] US Department of Transportation, *Emergency Response Guidebook*, 11th edition (Washington, DC: US Department of Transportation, 2016).

expanding the evacuation zone was a major goal of the response, the ERG-recommended protective distance was not practical given traffic congestion in the area.

After a 30-minute cycle of water spray cooling followed by thermal imaging inspection, firefighters detected a persistent heat signature in the module that kept this process continuing throughout the evening. Air Products technicians were unable to access the module until 10:00 p.m., about 9 hours after the incident began.

Between 11:00 p.m. and 3:00 a.m., the Air Products terminal manager and vehicle recovery team began a controlled venting procedure for the remaining hydrogen cylinders. To accelerate the process, the Air Products team checked pressure in the remaining cylinders and vented them simultaneously. About 3:30 a.m., the scene was secured, and Air Products towed the empty tube trailer module to its Santa Fe Springs, California, terminal for storage.

1.8 Previous NTSB Findings and Safety Recommendation

On May 1, 2001, a tractor, in combination with a tube trailer of horizontally mounted cylinders filled with compressed hydrogen, struck a pickup truck on U.S. Highway 75, 2 miles south of Ramona, Oklahoma. The tractor-semitrailer overturned and damaged some of the cylinders, valves, piping, and fittings, releasing and igniting hydrogen that burned the rear of the semitrailer. The emergency responders used the ERG as their first reference and referred to the guide for hydrogen. However, the guide did not provide complete information about the unique properties of hydrogen, specifically that hydrogen burns with an invisible or almost invisible flame. The guide also contained generic information about chemical properties, such as vapors sinking to the ground, which did not apply to hydrogen. The NTSB issued the following safety recommendation to the Research and Special Programs Administration (RSPA):[12]

H-02-25:

> Revise the information about hydrogen in the *North American Emergency Response Guidebook* so that it specifically identifies the unique chemical and flammability properties of hydrogen. (Closed—Acceptable Action)

On September 4, 2004, RSPA published the 2004 revision to the ERG which incorporated specific information about the unique chemical and flammability properties of hydrogen.[13] The information was on Guide 115, since Hydrogen, compressed (ID No. 1049) was assigned to Guide 115. The information appeared in two sections of Guide 115, as follows: 1. Under POTENTIAL HAZARDS, in the section on FIRE OR EXPLOSION, the caution statement stated: “Vapors from liquefied gas are initially heavier than air and spread along ground. CAUTION: Hydrogen (UN1049), Deuterium (UN1957) and Methane (UN1971) are lighter than air and will rise. Hydrogen and Deuterium fires are difficult to detect since they burn

[12] As part of a DOT reorganization on November 30, 2004, RSPA was disbanded, and responsibilities for the safety of the transportation of hazardous materials were transferred to the newly created Pipeline and Hazardous Materials Safety Administration (PHMSA).

[13] US Department of Transportation, *Emergency Response Guidebook*, 2004 edition (Washington, DC: US Department of Transportation, 2004).

with an invisible flame. Use an alternate method of detection (thermal camera, broom handle, etc.)" 2. Under EMERGENCY RESPONSE, in the section on FIRE, the caution statement stated: "DO NOT EXTINGUISH A LEAKING GAS FIRE UNLESS LEAK CAN BE STOPPED. CAUTION: Hydrogen (UN1049) and Deuterium (UN1957) burn with an invisible flame." Based on the information added to the 2004 ERG about the difficulty of detecting and extinguishing hydrogen-fueled fires, on April 1, 2005, the NTSB classified Safety Recommendation H-02-25 "Closed—Acceptable Action."

2. Safety Issues

2.1 Emergency Responder Awareness

The initial incident commander told NTSB investigators that firefighters did not realize they were responding to a hydrogen fire until after they arrived. He said that their first indication of hazardous materials was a placard marked United Nations (UN) number 1049, which they observed as the fire engine approached the burning tube trailer. Although the tube trailer module was correctly placarded and marked "hydrogen compressed" on all four sides, its general appearance within a square cabinet enclosure did not provide the visual clues the first responders usually expected to see for tube trailers transporting high-pressure gases, such as an exposed bundle of long gas cylinders mounted on a chassis within open framework. It was not until firefighters arrived on scene and from very close distance that they saw the placard and the burning trailer containing "individual hydrogen tanks." They had first received erroneous reports about an exploding gasoline station fire, followed by a report of a tanker truck fire, and finally a tube trailer. These reports added to initial confusion about the hazards the emergency responders faced.

On March 28, 2018, the LACoFD published a *Canyon IC* training video that summarizes lessons learned from the emergency response to this incident.[14] The video addresses several safety issues the first responders confronted, including:

- Confusing hazard communications and difficulty recognizing the presence of hazardous materials
- Lack of familiarity with hydrogen fueling infrastructure
- Difficulty estimating the likelihood for severe outcomes, injury, and damage
- Lack of familiarity with appropriate response actions for mitigating the potential of catastrophic cylinder failure

The video includes statements made by the responding firefighters, some of whom expressed similar concerns to the NTSB investigators. The firefighters pointed to the need for greater awareness and training resources for jurisdictions that are experiencing an increased use of FCEVs and bulk hydrogen fuel shipments.

First responders received erroneous reports about the type of emergency. Thus, the firefighters were unaware of the hydrogen fire until they were very close to the fire, putting firefighters at risk. In addition, they lacked familiarity with this type of hydrogen tube trailer module and the appropriate response to the hydrogen fire. Therefore, the NTSB concludes that greater first responder training and awareness about hydrogen tube trailer modules transported

[14] Los Angeles County Fire Department, *Canyon IC* (Los Angeles: Los Angeles County Fire Department, 2018). (See website at https://vimeo.com/262314786).

within their jurisdiction could have helped the first responders to initially respond to this incident more effectively, efficiently, and safely.

At the time of this incident, there were at least three resources available to the emergency response community for guidance in handling compressed hydrogen incidents.

The Pacific Northwest National Laboratory, US Department of Energy (DOE), partnered with the California Fuel Cell Partnership to produce an emergency responder training program that is available from its website https://h2tools.org.[15] In addition to providing guidance for responding to vehicle crashes involving hydrogen fuel cell vehicles, the program describes the potential hazards associated with hydrogen transport vehicles and tactics for mitigating hydrogen release incidents.

As noted above, hydrogen burns with an invisible or almost invisible flame. The program advises first responders:

- Listen for venting gas and watch for thermal waves that could signal hydrogen flames.
- When available use a thermal imaging camera if no flame is visible.
- Be aware that ignited hydrogen in an existing, carbon-based fire will most likely be visible due to the other products of combustion.
- Eliminate all potential ignition sources, and do not touch or walk through the product.
- Allow a hydrogen-fed fire to burn, if safe to do so, and protect adjacent exposures.
- Do not spray water into the pressure relief vent, as this could prevent it from working properly.

On October 9, 2018, the California Fuel Cell Partnership and Air Products provided LACoFD membership an in-person updated presentation of its responder training program. The California Fuel Cell Partnership is also considering adding content to the program such as tank testing, nonvehicle applications, vehicle extrication techniques, and information about bulk hydrogen shipping. In addition, the training program is being transitioned to the American Institute of Chemical Engineers Center for Hydrogen Safety. This is an international nonprofit corporate membership organization that promotes the safe operation, handling, and use of hydrogen and hydrogen systems across all installations and applications.

Similar to the DOE program, the International Association of Fire Chiefs Fusion Center provides a hydrogen response online training course that is focused on providing basic education about alternative fuels.[16] The course has four modules that test student's knowledge of hydrogen use, chemical and physical characteristics, and suggested emergency response tactics and

[15] Pacific Northwest National Laboratory, *National Hydrogen and Fuel Cells Emergency Response Training* (Richland, Washington: US Department of Energy, Pacific Northwest National Laboratory, 2015).

[16] See the International Association of Fire Chiefs website at https://www.iafc.org/events/event/2018/12/31/self-paced/hydrogen-response-considerations-online. (Accessed August 22, 2019.)

strategies. However, the course does not contain descriptions of tube trailer modules that double as both compressed hydrogen transport vehicles and fueling stations, nor does the course provide recommended firefighting tactics for mitigating hazards associated with fires, hydrogen releases, and vehicle accidents.

The NTSB concludes that although there is ample generic hazard information for compressed hydrogen and vehicle fuel systems, the available guidance lacks critical hazard recognition and firefighting information specific to FCEV fueling infrastructure and containers currently used for the bulk transportation of compressed hydrogen. The DOE Pacific Northwest National Laboratory Hydrogen Tools Portal contains a comprehensive collection of hydrogen safety training materials for first responders and provides a single repository of credible and reliable information intended to eliminate duplicative efforts among various training programs. Therefore, the NTSB recommends that DOE Pacific Northwest National Laboratory revise its hydrogen emergency responder training programs to include readily accessible specific information and guidance on hazard recognition and firefighting relative to tube trailers and FCEV fueling infrastructure.

The DOT ERG is intended for use by first responders during the initial phase of a transportation incident involving hazardous materials.[17] Among the recommendations for hydrogen (UN 1049) contained in Guide 115 are the following:

- Cylinders exposed to fire may vent and release flammable gas through pressure relief devices.
- Containers may explode when heated; ruptured cylinders may rocket.
- Fight fire from maximum distance or use unmanned hose holders or monitor nozzles.
- Cool containers with flooding quantities of water until well after fire is out.
- Withdraw immediately in case of rising sound from venting safety devices or discoloration of tank.
- For a fire involving a tank truck, isolate for 1 mile in all directions; also consider initial evacuation of at least 1 mile in all directions.

The LACoFD used the ERG as its primary reference material in response to this incident. However, the information provided in Guide 115 is a generic description of a variety of gases and cryogenic liquids that may not be directly pertinent to such an incident as occurred in Diamond Bar, California. As part of an ongoing effort to address shortcomings in emergency response guidance for hydrogen, the National Fire Protection Association (NFPA) 2 Task Force on Emergency Response on October 1, 2018, provided a submission to the Pipeline and

[17] US Department of Transportation, *Emergency Response Guidebook*, 11th edition (Washington, DC: US Department of Transportation, 2016).

Hazardous Materials Safety Administration (PHMSA) for proposed revisions to the 2020 ERG.[18] The NFPA task force stated that while the amounts of fuel on the vehicles described in this submission (and the fact that hydrogen is being used to propel the vehicle) do not fall under the jurisdiction of the ERG, the NFPA stated there is a need for an informational product about such vehicles to avoid potentially unnecessary actions and evacuations around a hydrogen-fueled vehicle incident. The proposed NFPA 2 task force guidance contains visual descriptions of the hydrogen fueling system components typically found in light and medium duty vehicles, buses, and trucks. The proposed guidance also contains a description of safety features, handling precautions, and advice for rescue and extraction.

Also, on October 1, 2018, to provide emergency responders with the most up-to-date guidance pertinent to hydrogen transportation, the CGA provided a submission to PHMSA with the following suggested revisions to the 2020 ERG:

- Modify Guide 115 to remove Hydrogen (UN 1049); Hydrogen, refrigerated liquid (UN 1966); and Deuterium (UN 1957) from its scope; and

- Create a new guide with the guide number to be determined, for Hydrogen (UN 1049); Hydrogen, refrigerated liquid (UN 1966); and Deuterium (UN 1957) to address their unique emergency response requirements.

One concern the CGA cited was adjusting the evacuation distances recommended for large spills and fires that are based on analysis of incidents and models dealing with blast overpressure, thermal radiation, and other effects. The CGA proposal points out that the existing ERG Guide 115 that groups hydrogen with other flammable gases recommends evacuation and isolation distances well in excess of applicable hazard distances for hydrogen and can pose an unnecessary burden on emergency responders and evacuees as well as additional hazards to those being unnecessarily evacuated. The proposed new guide recommends that small fires be allowed to burn out if the source of hydrogen cannot be stopped. The CGA points out that attempting to extinguish a fire without stopping the source of releasing gas could create a more hazardous condition. The proposed new guidance also calls attention to cylinder vent pipes as safety devices and recommends not spraying water directly on vent outlets because plugging the vent system could lead to overpressurization and container rupture. Therefore, the NTSB concludes that the generic guidance for flammable gases contained in the ERG Guide 115, does not adequately describe unique hazards associated with compressed hydrogen or best response actions for public safety personnel. Therefore, the NTSB recommends that PHMSA revise its ERG to include information about hazards and protective actions specific to hydrogen, and to provide guidance on how to manage incidents involving FCEVs and hydrogen fueling infrastructure.

[18] (a) PHMSA, nonrulemaking docket PHMSA-2018-0055-0001. (b) The NFPA 2 ER Task Force members include fire personnel and individuals from industrial gas companies, all of whom use and are familiar with the ERG.

2.2 Tube Trailer Module Damages

This section describes evidence relating to the origin of the fire and factors influencing the propagation and severity of the incident.

2.2.1 Trailer and Frame

Investigators observed thermal damage on the exterior upper-right rear of the trailer door and upper-right side of the CT-250 module structure. (See figure 5.) This damage ranged from discoloration of the paint to areas where the paint was completely burned off the exterior.

Figure 5. Air Products tube trailer module 430003, exterior right side, March 12, 2018.

The right-rear door handle hasp was bent upward, and the door panel was bowed outward. The frame of the door panel also buckled outward about 1.5 inches. The bow in the right-rear door was centered opposite the position of cylinder No. 14. The trailer frame and appurtenances were not damaged in the incident.

2.2.2 Composite Cylinders

Thermal damage was concentrated in the upper right interior of the tube stack and is summarized in the Table. Investigators observed no cylinder cuts and no abrasions. Damage was limited to the exposure of heat and flame. (See figure 6.)

Figure 6. Module number 430003 rear view with the area of greatest thermal damage circled, March 12, 2018.

Following visual examination, the tube trailer module was released to the cylinder manufacturer, SCI/Worthington for disassembly, detailed cylinder inspection, and residual strength testing of two heat-damaged cylinders. SCI/Worthington technicians classified each of the 25 cylinders based on the extent of thermal damage. This examination found that four of the cylinders were visually undamaged and exhibited no discoloration but some soot accumulation. The remaining 21 cylinders sustained heat damage sufficient to require them to be removed from service.[19] Five cylinders sustained heat discoloration, blistered cylinder paint, and melted labeling. Five cylinders sustained scorching and surface burns. Eleven cylinders exhibited severe thermal damage in which layers of carbon composite fiber burned away. (See figure 7.) Although the severely damaged cylinders had most of the paint and fiberglass protective wrap burned away, investigators observed no evidence of cylinder pressure containment failure.

[19] Under DOT special permit DOT-SP 14576 and CGA Standard C-6.4, composite cylinders with indications of extreme heat damage are considered to have Level 3 (rejectable) damage and must be condemned. The SCI/Worthington product group manager told NTSB investigators that industry practice is to classify as Level 3 damage any CFFC cylinder that exhibits heat marking or discoloration because the severity of underlying damage is often unknown without destructive examination.

Figure 7. Cylinders 21 through 25 thermal damage with protective fiberglass and epoxy coating burned away, March 14, 2018.

SCI/Worthington technicians noted that the cylinder in position 24 exhibited the most severe fire damage, with its outermost carbon fiber layers that were wrapped in the hoop orientation burned away in three locations. The underlying carbon fiber composite layers wrapped in the helical orientation were exposed. SCI/Worthington burst tested this cylinder, finding that the cylinder wall failed at 24,600 psig, whereas the minimum burst pressure permitted in a DOT-SP 14576 test for a new and undamaged cylinder is 25,500 psig.

On May 9, 2018, technicians selected a second, lesser-damaged cylinder for burst testing in position 16 to simulate a scenario where a cylinder with unrepairable damage might be improperly returned to service or might not have been properly inspected following an incident. To simulate use of the cylinder for its remaining service life, cylinder 16 was pressure cycled 3,650 times before burst testing. The cylinder did not leak during the testing. The burst pressure for the cylinder was 21,500 psig, whereas the design criteria under DOT-SP 14576 would allow a minimum burst pressure of 22,950 psig for an undamaged cylinder that experienced its full-service life. Postincident destructive testing determined that burst pressures for fire-damaged cylinders were below the minimum requirements for new and used cylinders. Therefore, the NTSB concludes that none of the incident tube trailer cylinders lost mechanical integrity, and they did not contribute to the cause or perpetuation of the incident.

2.2.3 Pressure Relief Devices and Vent Line Assemblies

The inspection found 12 rear PRDs had actuated during this incident and had fully released the contents of 12 cylinders, or a total of 120 kg of hydrogen. (See table.)

Table. Tube trailer module inspection summary.

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

Incorrect PRD = 4
PRD actuated = 12[21]
Vent line ejected = 7
Severe fire damage = 11

Severe burning damage, composite caught fire[20]
Scorching, surface burns
Heat discoloration, blistered paint, melted label
No discoloration, some soot accumulation

Four of the 50 PRD assemblies for the cylinders contained the incorrect type CGA-5 Sherwood model 3132SBF9-55 PRD, with nickel rupture disk and a set pressure of 5,833 psig. One incorrect PRD affixed to the front of cylinder 4 was known to have actuated on February 4, 2018, thus rendering cylinder No. 4 out of service at the time of the incident.[22] Two of the incorrect PRDs had been installed in cylinder No. 11, but the cylinder sustained mild fire exposure and neither PRD had actuated. The final incorrect PRD installed in the rear of cylinder

[20] The SCI/Worthington classification of heat damage severity is consistent with the NTSB investigator's visual observations. See Engineering Report No. 2996.18.

[21] There were 12 PRDs that actuated during the February 11, 2018, incident, and one PRD that actuated during the February 4, 2018, incident, which was still installed in the unused cylinder No. 4.

[22] The technician isolated cylinder 4 from the module's manifold system and scheduled the module for later inspection. Therefore, Air Products was not aware incorrect PRDs had been installed in the module prior to the Diamond Bar incident.

No. 14 was missing its burst disk and copper retaining washer, and the fusible metal plug had been ejected from the discharge port.

The rupture disk contained in the rear incorrect PRD for cylinder No. 11, which was outside of the area of greatest thermal exposure, had a concave shape with a deflection toward the discharge port. A radial crack had formed on the rupture disk surface and the concavity of the center of the disk suggests the disk was subjected to high pressure during its 6 weeks in service. The cylinder manufacturer specifications call for the cylinders to be equipped with a PRD rated at 10,000 psi. Additionally, the disk should have been fabricated from material other than nickel because the Sherwood type 3132SB technical information states that nickel PRDs and fittings must not be used in hydrogen service. Metallurgical analysis of rupture disks following other PRD failures have shown that hydrogen embrittlement of nickel disks has led to stress cracks and premature failures.[23] Figure 8 shows a magnified view of the fracture area on the surface of the cylinder No. 11 PRD rupture disk, which reveals a rough textured area primarily below the fracture that is circumferentially continuous and indicative of tensile stretching. The cylinder No. 11 rupture disk fracture mode was a ductile overstress fracture, suggesting that it likely would have actuated within a short time given additional use and pressure cycling.[24]

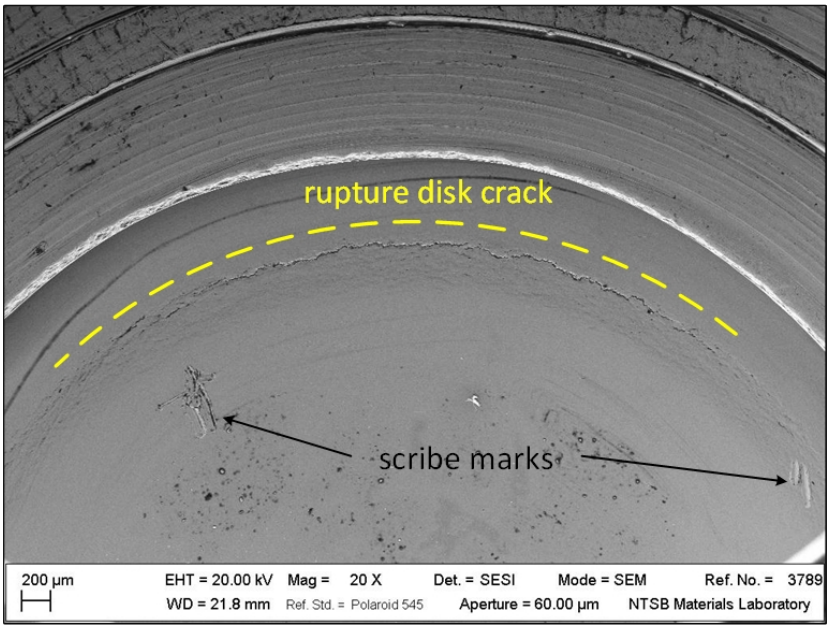

Figure 8. Magnified view of cylinder No. 11 PRD rupture disk (magnification of 20X). Scribe marks were etched into the disk during the postincident laboratory examination.

A similar overstress fracture probably occurred with the incorrect cylinder No. 14 PRD, since the disk was exposed to 22 hydrogen fill-and-discharge cycles exceeding its design

[23] National Renewable Energy Laboratory, *Pressure Relief Devices for High-Pressure Gaseous Storage Systems: Applicability to Hydrogen Technology*. Technical Report NREL/TP-5400-60175 (Golden, Colorado: US Department of Energy, National Renewable Energy Laboratory, 2013).

[24] When stress is placed on a metallic component to a level greater than the material can resist, then failure of the component occurs by overstress. If the material is ductile, then it may exhibit a large amount of deformation before rupture occurs.

pressure between the time the PRD was installed on December 29, 2017, and the time of the incident. The 5,833 psig-rated PRD did not immediately activate when the trailer was put into service due to reinforcement provided to the rupture disk portion of the PRD from the fusible metal located downstream behind the disk. Therefore, the NTSB concludes that the hydrogen release most likely initiated because a PRD with the wrong pressure rating was installed on cylinder No. 14 and actuated under normal working pressure loads.

Following the incident, Air Products technicians found the cylinder No. 14 PRD assembly laying in the bottom pan of the tube trailer module underneath the rack of cylinders.

Under the thrust force and pressure of gas flowing from the actuated PRD, the cylinder No. 14 vent line was ejected from the PRD assembly fitting and was bowed outward and partially wrapped around a handrail. (See figure 9.) The separated vent line allowed the escaping high-pressure hydrogen to be directed to the interior of the cabinet rather than upward and outside of the cabinet as intended by the design. The hydrogen could have been ignited by the shock wave from the sudden release and/or impact between the dislodged vent tubing, handhold bar, and the rear door of the trailer.

Figure 9. No. 14 vent line displacement. The vent line was bent outward from the cylinder and against the handhold rail. March 12, 2018.

The nut-and-fitting ferrules were missing from the vent line that should have swaged the tubing if the compression fitting had been sufficiently tightened. (See figure 10.) When the vent tubing is initially assembled with the fitting, it is supposed to be checked with a No-Go gap gauge to ensure that the nut has compressed the ferrules, narrowing the tubing diameter enough to lock the ferrules in place. This compression secures the fitting against gas leakage and retains the tubing in place.

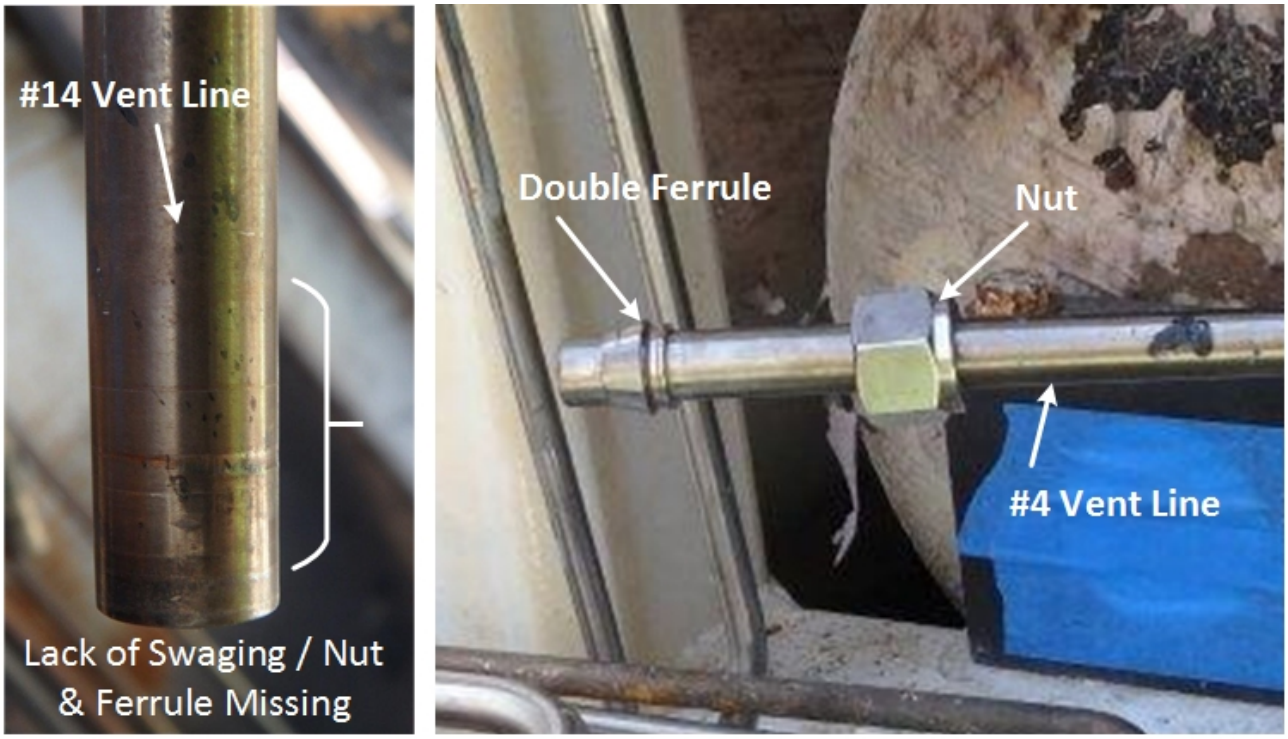

Figure 10. Comparison of No. 14 vent line (left) with No. 4 vent line (right). The nut and the ferrule for coupling to the Parker elbow is missing from the No. 14 vent line.

As the fire impinged on other cylinders, the heat actuated the 11 adjacent rear PRDs. An additional six vent lines were ejected from their elbow fittings thus directing more burning hydrogen into the interior of the module's cabinet and escalating the severity of the cylinder damages. Vent tubing affixed to only five of the affected cylinders functioned as designed.

The cylinder No. 14 adaptor fitting remained fastened to the Tescom shutoff valve; however, its downstream "male" threads were damaged, and the corresponding PRD body "female" threads were flattened from forced separation of the two pieces. (See figure 11.)

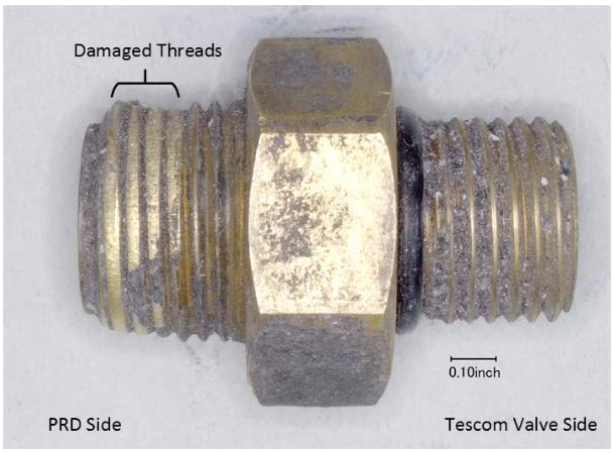

Figure 11. Cylinder No. 14 PRD adaptor fitting with damaged male threads.

The cylinder No. 14 PRD assembly fitting separation occurred after the vent line was ejected as high-pressure venting gas jetted from the open 90° elbow with downward perpendicular thrust. (See figure 12.)

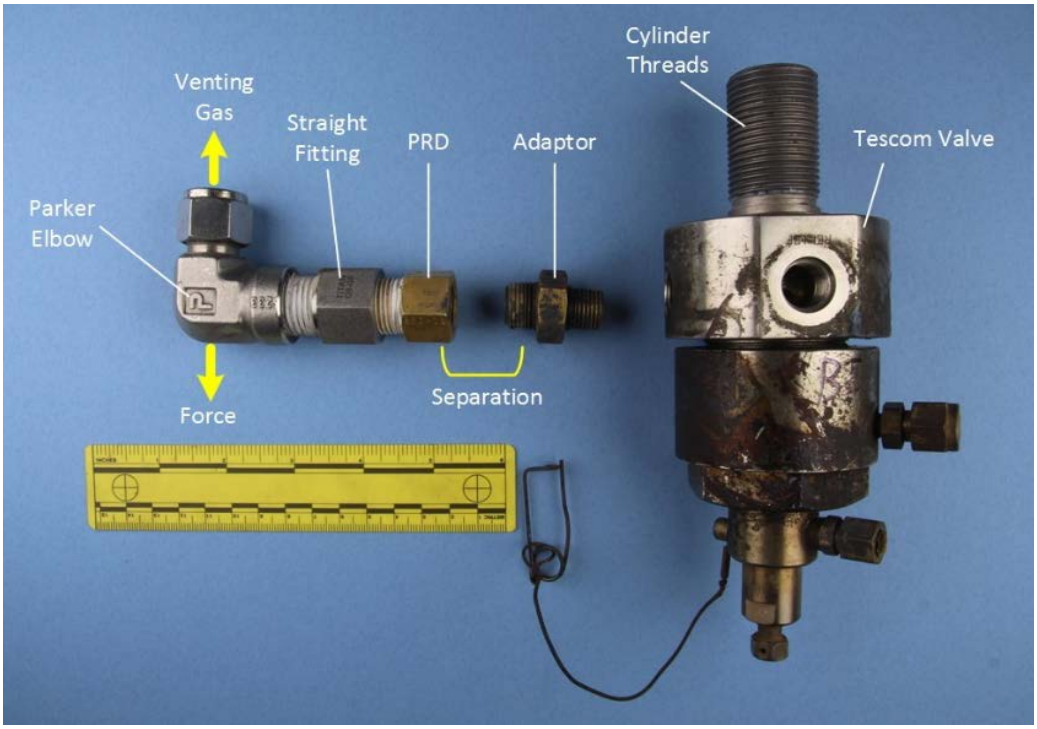

Figure 12. Cylinder No. 14 PRD assembly, adaptor, and Tescom valve. Hydrogen gas vented from the vent line compression fitting.

The venting gas imparted force against the PRD assembly adaptor attachment point, stripping its brass threads and causing the assembly to drop to the bottom pan of the trailer where it was not directly exposed to the subsequent fire. This was evident from the relatively clean state of the PRD assembly and the lack of indication that the fusible metal had melted. A short soot

trail on one corner of the PRD body hex flat suggests the hydrogen ignition may have occurred during its separation from the adaptor fitting. This evidence suggests the severe fire damage to cylinder No. 14 and the surrounding cylinders and PRDs occurred after the cylinder No. 14 PRD assembly separated from its adaptor fitting. Therefore, the NTSB concludes that the hydrogen ignited during the forced separation of the cylinder No. 14 PRD assembly from the cylinder.

The resistance of the fusible metal plug to being extruded from the PRD discharge port is dependent on heat exposure, as the material melts at a temperature of 212°F. However, the Sherwood Valve vice president and general manager told NTSB investigators that in a situation where the rupture disk has failed, the fusible metal plug alone under nonfire conditions would not resist pressure of 7,500 psi for long because the highly ductile fusible metal would soon extrude from the discharge port allowing the cylinder contents to vent.

NTSB investigators compared fusible metal residues in the discharge ports of the PRDs from cylinder Nos. 4, 14, and 19 (located directly above cylinder No. 14 in the tube trailer) with the unaffected and intact PRD from cylinder No. 7. Some fragmented fusible metal material and residue was observed adhering to the cylinder No. 14 PRD discharge port interior grooved surfaces. Optical microscope images revealed the fusible metal residue microstructure away from the thread roots in the discharge port of the cylinder No. 14 PRD appeared very different to the melted and resolidified fusible metal residues found in the cylinders Nos. 4 and 19 and the unaffected fusible metal in the cylinder No. 7 PRD. (See figure 13.)

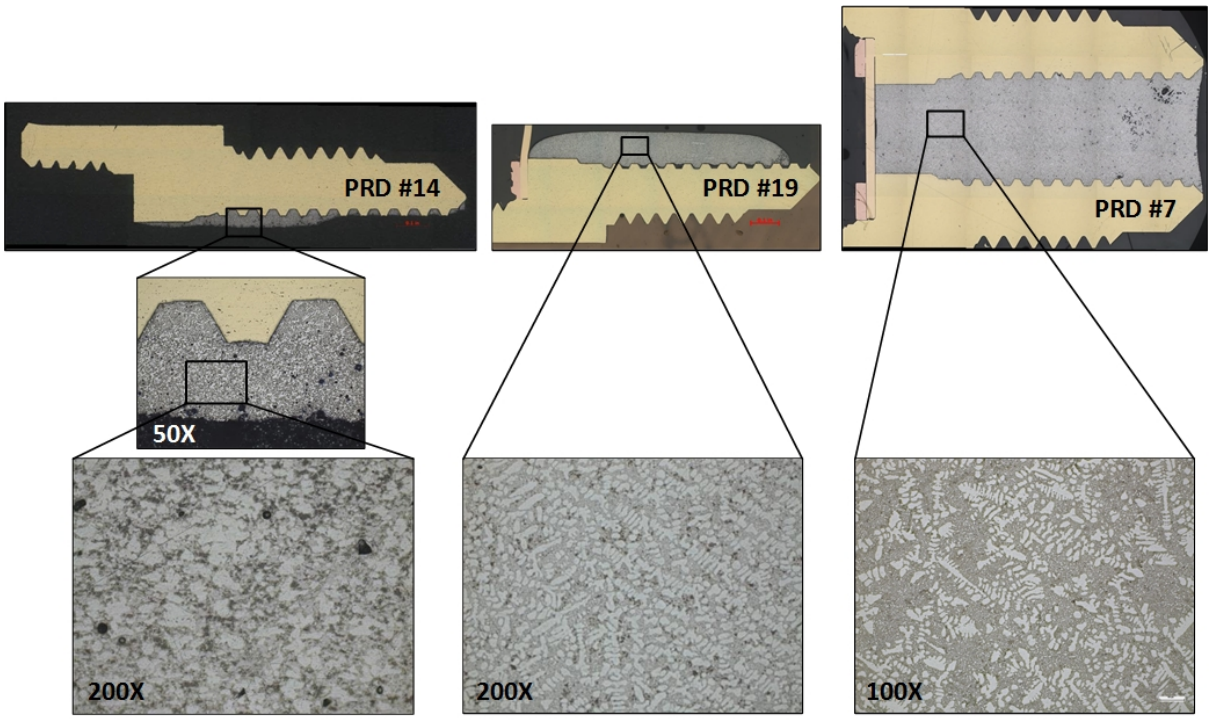

Figure 13. Comparison of fuse metal residues from PRD No. 14 (left), PRD No. 19 (center), and PRD No. 7 (right).

The teardrop and rounded shapes of melted and resolidified fusible metal residue in the cylinder No. 19 PRD that sustained heat exposure during the module fire were also different from the fusible metal residue adhering to the discharge port groves in the cylinder No. 14 PRD. The shape and microstructure differences of fusible metal residue from the cylinder No. 19 PRD suggests it was heated and flowed from the discharge port, while in cylinder No. 14, the fusible metal appears to have been mechanically expelled from the discharge port under pressure alone. Therefore, the NTSB concludes that although the other cylinder PRDs in the tube trailer module were actuated because of fire exposure, the cylinder No. 14 PRD actuated before the fire began.

2.3 Tube Trailer Requalification and Inspection

As required by the DOT special permit conditions, on December 29, 2017, the tube trailer was subjected to a 5-year requalification inspection 6 weeks before the Diamond Bar incident. Air Products contracted with FIBA to perform the requalification inspection.

The FIBA chief technical officer and the Adelanto, California, facility manager told NTSB investigators that Air Products brought tube trailer module No. 430003 to the facility about 3 weeks prior to its requalification inspection. FIBA considered CT-250 modules a "delicate" item, therefore the facility manager and one other technician were the only personnel assigned to work on the units. The technician performed all the tubing, fitting, and valve disassembly and reassembly work, while the facility manager checked his work and conducted the internal visual inspections. The technician removed all fittings and valves from the cylinders to facilitate the internal inspections.

The technician began the inspection process by purging the cylinders with nitrogen. Next, the technician disconnected the 0.5-inch vent line nut couplings to the PRD assemblies and swiveled the tubing out of the way. The facility manager said that he had instructed the technician to notify him if any of the compression fitting ferrules were not properly swaged into the tubing. The facility manager said he was not aware of any loose couplings and none of the ferrules slid from the tubing. Loose couplings or ferrules would have indicated they had not been swaged onto the tubing walls. The facility manager added that if he had been informed of any loose fittings, he would have checked the ferrules and replaced the fittings and tubing as necessary.

The FIBA shop had a Swagelok No-Go gap gauge that fits between the nut and the fitting shoulder if the fitting has not been sufficiently tightened. The facility manager referenced an instructional video for assembling the fittings on the Swagelok website and understood that the gauge is compatible with Parker fittings that were used on the module. These instructions state that the nut should be finger tightened, further tool tightened 1 1/4 turn, and then the fitting gauged to confirm tightness. According to the facility manager, reassembling a properly assembled compression fitting does not require tightening and gauging beyond a snug fit. Once a compression fitting is properly tightened to correct specifications and checked with a gap gauge, the ferrules would have been permanently swaged onto the tubing. Thus, the technicians determined there was no need to check with the gap gauge when reassembling the fittings on the incident module.

However, because the tubing on the ejected vent lines had not been swaged, it should have been obvious to the FIBA technician during disassembly that these fittings were loosely attached. If the compression fitting had been properly installed during initial assembly, the ferrules would have been permanently swaged onto the tubing and the fitting should not have disassembled during venting. Verifying vent tube securement was not specifically listed among the items the facility manager initialed on the FIBA Trailer Shipping Final Inspection Report. The fittings must be disassembled to perform the internal visual cylinder inspections and would not have required much effort to verify each fitting had been completely secured. A properly assembled vent line would have vented the gas relieved through the PRD harmlessly upward and away from other cylinders, even if it had ignited. Therefore, the NTSB concludes that had the requalification personnel inspected each vent line compression fitting for tightness, the propagation of the fire to the adjacent hydrogen cylinders may have been avoided.

The NTSB investigators also requested that Atlas provide its quality assurance and inspection records for the February 2015 assembly of the tube trailer module. The records did not reflect details of any compression fitting inspection or disassembly to confirm proper tubing securement and that all of the ferrules had been installed on each vent line.

On February 22, 2018, Air Products visited the Atlas facility in Northampton, Pennsylvania, to audit the module construction process and to discuss the Diamond Bar incident. The audit found that on three modules under assembly, about 50 percent of the PRD vent fittings were not sufficiently tightened. Air Products representatives found that while Atlas did possess a No-Go gap gauge, it had not been used for the assembly of the modules under construction.

The vent line tubing attached to the PRDs of seven cylinders had been ejected from their respective fittings and the tubing had not been swaged to lock ferrules onto the tubing. Therefore, the NTSB concludes that the vent line compression fittings that disassembled during venting were not properly installed at the time the tube trailer module was fabricated and should have been noticed and repaired during the requalification inspection.

As part of the December 2017 requalification inspection, the FIBA technician removed the PRD assemblies from the Tescom valves, which control the flow of gas into and out of the cylinders. The technician changed the Tescom valve O-rings and checked the valve seats for wear and evidence of gas pass-by, finding no exceptions.

Next, internal visual inspections for each cylinder were undertaken from each end of the open cylinders. The technician shined a flashlight in one end of the cylinder while the facility manager visually inspected the cylinder from the opposite opening. Had any suspicious features been noted, FIBA personnel could have inserted a borescope into the cylinders for a more detailed visual inspection, but the borescope inspection for module number 430003 was deemed unnecessary. The visual inspections checked for buckling, bulges, cracks, or splits in the aluminum liner. The technician and facility manager noted no exceptions.

Prior to the Diamond Bar incident, Air Products had directed FIBA to replace all PRDs during normal requalification inspections. Air Products decided that it would add the PRD change-out to the requalification work because (1) the PRDs experience numerous pressure cycles over a 5-year requalification cycle and (2) the PRD assembly must be removed from the

cylinders to facilitate internal cylinder visual inspections, and since there is a compression washer between the parts, installing a new part would improve leak-tightness. FIBA obtained its inventory of new PRDs for the hydrogen tube trailer modules directly from Air Products.[25] When FIBA received delivery of the PRDs, the facility manager stored them in his office until needed. The only equipment FIBA has worked on requiring the 3132SB9-95 PRDs are the Air Products CT-250 hydrogen tube trailer modules. FIBA had not performed any requalification work on other cylinders that would have required the use of Sherwood Valve model 3132SBF9-55 PRDs with a rated actuation pressure of 5,833 psi. Therefore, FIBA did not intentionally maintain any inventory of that model PRD.

During the tube trailer module number 430003 requalification inspection, the technician replaced the front and rear PRD assemblies with new Sherwood Valve PRDs that were supposed to be part number 3132SB9-95 rupture disk/fusible metal plug combination, rated at 10,000 psi and 212°F.

Following reassembly, the pressure proof test involved filling each cylinder with nitrogen to a pressure of 9,375 psig (1.25 times the working pressure) for 10 minutes. The cylinder passes the test if the pressure does not drop more than 5 percent of the original test pressure. The technician and facility manager noted no pressure test exceptions. At the time of this requalification inspection, FIBA's procedure was to conduct pressure proof tests with the new PRDs installed, and thus they were exposed to a pressure cycle of 1.25 times the working pressure.

The facility manager initialed each of the line-items in the Trailer Shipping Final Inspection Report to indicate he had checked the work. Although the facility manager initialed line number 58(a) on the inspection report, "verify PRV [*sic.*] psig matches schematic," he told NTSB investigators that he did not check the PRD markings to verify their pressure ratings. The facility manager explained that he assumed that Air Products shipped the correct parts to FIBA.

Once the module was reassembled with new PRDs, the FIBA technician affixed qualification stickers to the cylinders and test plate to the module. The trailer was returned to Air Products pressured with about 20 psig of nitrogen. Air Products retrieved the trailer shortly after the FIBA requalification tests were complete.

The FIBA trailer inspection report incorrectly stated that the facility manager verified the PRD pressure matched the manufacturer's requirement. PHMSA's special permit and regulatory controls include requirements for a cylinder's pressure retaining components but not the condition of safety devices and appurtenances such as the PRD and vent. Thus, PHMSA lacks the authority to intervene in cases such as this where a testing facility falsely reports conducting a safety inspection. The PRD and vent tubing may never be used during the normal course of a module's service life, therefore it is essential that they function at the intended pressure and that the gas is vented in a harmless direction to prevent an incident from escalating or causing injury and property damage. Therefore, the NTSB concludes that the lack of a PHMSA special permit and regulatory requirements for verifying that PRDs used on cylinders actuate at the correct

[25] Air Products ordered the PRDs from Sherwood Valve and then forwarded the shipment to FIBA.

pressure and that venting equipment has been properly assembled and secured increases the risk of uncontrolled fires on flammable gas tube trailers.

Among the requirements of DOT-SP 14576 is the requirement that cylinders be manifolded to the requirements of 49 *CFR* 173.301(g). This regulation requires PRDs for manifolded horizontal cylinders transporting flammable gases to be arranged to discharge upward to prevent escaping gas from contacting personnel or any adjacent cylinders. Additionally, the special permit requires that all cylinders must be operated and maintained in accordance with the *Structural Composites Industries Cylinder Component Operations Manual*, and those who perform inspection and testing of cylinders subject to this special permit must comply with 49 *CFR* 180.205(b) and with all the terms and conditions of the special permit. However, none of the terms of the special permit, the federal regulations, and the industry specifications require periodic inspections to ensure that PRD venting equipment is secured and functional.

The tube trailer module had unintended PRD actuations twice: February 4, 2018, and February 11, 2018. In the first instance, the relieved gas vented upward and away from the cylinders during the night while the module was parked at a hydrogen fueling facility and was not immediately noticed. The responding technician discovered that cylinder No. 4 had vented and found no evidence of either fire or vent tube separation. If the vent line had not separated during the February 11 incident, the venting hydrogen from one cylinder (No. 14) would have been harmlessly vented above and away from the trailer even if the hydrogen gas had ignited.

Air Products conducted a full tube trailer module and fleet inspection following the incident and found that half of their PRD vent line compression fittings were not assembled with sufficient tightness. During these inspections, Air Products reassembled the compression fittings and verified tightness with No-Go gap gauging. Air Products has implemented procedures to inspect the assembly of the fittings and the PRDs of new tube trailer modules prior to putting them into service. However, the PRD compatibility checks, and the vent line securement may be overlooked by other fleet owners because of the lack of inspection requirements in the DOT special permits and the Hazardous Materials Regulations.

In 2013, the National Renewable Energy Laboratory (NREL) published a report examining mechanisms of high-pressure hydrogen storage system PRD failure incidents and the applicable codes and standards that have been developed to minimize the risk of such failures.[26] Among the documented incidents involving hydrogen tube trailers was an event in 2009 in which a PRD rupture disk failed prematurely at 5,200 psig while filling a tube trailer with hydrogen to 6,000 psig. The vent line attached to the PRD was not sufficiently anchored, and it bent outward violently from the thrust of the release, causing significant damage to nearby system components. There were no personnel in the immediate area when the disk failed. Although the PRD was rated at 10,000 psig, metallurgical analysis showed the rupture disk was composed of nickel, and hydrogen embrittlement in the disk led to stress cracks and eventual failure. The Diamond Bar, California, incident and the events cited in the NREL report, can be prevented by

[26] National Renewable Energy Laboratory, *Pressure Relief Devices for High-Pressure Gaseous Storage Systems: Applicability to Hydrogen Technology*, Task number HT12.72.10 (Golden, Colorado: US Department of Energy, National Renewable Energy Laboratory, 2013).

ensuring that the correct PRD has been installed in equipment and that the vent assembly has been adequately secured. Therefore, the NTSB recommends that PHMSA revise all hazardous materials special permits for transporting gases in manifolded horizontal cylinders to require that requalification inspections include verifying that PRDs of the correct pressure rating are used and that PRD venting equipment is inspected and tested to ensure that it can withstand forces generated by PRD actuation. Furthermore, because special permits are issued for nonspecification cylinders and there are other DOT-specification horizontally mounted cylinders with similar PRDs and venting equipment, the NTSB also recommends that PHMSA revise 49 *CFR* Part 180, subpart C, "Requirements for Requalification of Specification Cylinders," to ensure that inspectors requalifying cylinders verify that PRDs of the correct pressure rating are used and that PRD venting equipment is inspected and tested to ensure that it can withstand forces generated by PRD actuation.

2.4 Hydrogen Tube Trailer Component Design Criteria

2.4.1 PRD Vent Systems

CGA standard G-5.5, which is for hydrogen vent systems used in gaseous and liquid hydrogen systems and excludes applicability to PRDs for cylinders and tube trailers regulated by the US DOT, recommends that the discharges of gaseous hydrogen through PRD activation be directed through an engineered vent system.[27] According to the standard, the force of the venting gas shall be taken into consideration on the design and anchoring of the vent system components. Consideration for the system's design pressure should include such factors as the flow capacity of the vent system, the effect of deflagrating or detonating hydrogen-air mixtures within the vent, and supersonic flow effects. The standard also recommends against the use of low melting point materials for vent systems, such as aluminum, copper, brass, and bronze, which can weaken and fail when exposed to external fires. In contrast, DOT-SP 14576 and 49 *CFR* 173.301(g) provide no design criteria to ensure that PRD venting hardware used in horizontally mounted cylinders and tube trailers are properly designed, constructed, and maintained such that they will function as intended when PRDs activate. Instead, the federal regulations only specify the desired outcome in that escaping gas must be arranged to discharge upward to prevent it from contacting personnel or adjacent cylinders. The NTSB concludes that although the PRD vent tubing that separated in module number 430003 likely did so because of incomplete assembly of the compression fitting, the lack of vent system design requirements that consider factors such as the force of venting gas and construction material may leave vent systems for cylinders and tube trailers vulnerable to unexpected failure during an incident. The vent installation design should consider the characteristics of the discharge piping and pipe supports. Reactive force from an actuated PRD imposed on either the valve or the outlet piping can be transmitted to the valve inlet and associated piping. This force could cause extensive damage if the discharge piping is not sufficiently supported. This issue may be applicable to other hazardous material gases transported in horizontally mounted cylinder tube trailers as well. Therefore, NTSB recommends

[27] Compressed Gas Association, *Hydrogen Vent Systems.* CGA G-5.5, 3rd edition (Chantilly, Virginia: Compressed Gas Association, 2014). This standard is not incorporated by reference in the Hazardous Materials Regulations. The publication presents guidelines for the design, installation, and maintenance of hydrogen vent systems at stationary facilities.

that PHMSA work with the CGA to develop design guidelines for tube trailer PRD vent systems. The NTSB further recommends that the CGA work with PHMSA to develop design guidelines for tube trailer PRD vent systems.

2.4.2 Pressure Relief Devices

The NTSB investigators found that the Sherwood Valve model 3132SBF9-55 (5,833 psi) PRD and the 3132SB9-95 (10,000 psi) PRD are visually identical, except for a small font laser etching that indicated the model number and intended operating pressure.

This incident was not the only occasion in which the misidentification of PRD models resulted in incorrect PRDs being installed in hydrogen tube trailer modules. In 2015, Air Products reported premature actuation of four PRDs affixed to SCI/Worthington model ALT-1015 cylinders. Multiple cylinders Air Products purchased from SCI/Worthington in 2012-2013 had incorrect 5,833 psi PRDs installed during assembly instead of the specified 10,000 psi PRD. The issue was not discovered until several cylinders vented at service pressure. The venting was determined to be caused by the incorrect 5,833 psi PRDs. Worthington's internal investigation report concluded that the 5,833 psi PRDs were incorrectly installed at its manufacturing facility and that the pressure rating was not verified on installation. Worthington also found that multiple PRDs with nearly identical appearance and marked with no part number were stored adjacent to one another, which allowed for possible commingling at the valving workstation. As a corrective measure in August 2015, SCI/Worthington instituted a just-in-time production system to ensure no excess components remain from one shift to the next. SCI/Worthington further revised its work instructions and retrained operators to verify the PRD pressure rating prior to its installation.

In addition to the four incorrect PRDs that investigators found installed on the incident tube trailer module number 430003, the FIBA facility manager told investigators that after the February 11 incident he discovered three more 5,833 psi PRDs at the facility in Adelanto, California. Two of these PRDs were found commingled in a bag of new 10,000 psi PRDs shipped from Air Products. One 5,833 psi PRD had already been installed in a tube trailer. This mistake was found during the inspection process (it had not yet been pressurized). Also, after the incident and during the Air Products inspection of another tube trailer module, one 10,000 psi PRD was found without any external pressure etching on its housing, however markings on the rupture disk surface found that it had been manufactured with the proper 10,000 psi-rated disk. Because Air Products had never purchased any 5,833 psi PRDs, they likely became commingled at the Sherwood Valve facility with the Air Products order for 10,000 psi PRDs.

The identification requirements outlined in CGA standards for PRDs list the safeguards and the guidelines to avoid jeopardizing PRD performance by improper service practices.[28] While the CGA suggests that PRDs that are replaceable should also be marked with the rated burst pressure and yield temperature as applicable, the PRDs involved in this incident were laser-etched with this information in a small font on one hex flat. Although the requalification technician probably believed that he was installing the correct PRDs, the PRD's identification

[28] CGA S-1.1 (2011), Paragraph 7, Identification Requirements.

with a small font on one hex would not have been sufficient to alert him of his error. Therefore, the NTSB concludes that the lack of noticeable marking or other visual indicators, unique design features, and unique model numbering to readily identify PRDs intended for different applications, made them easy to confuse and did not avert the requalification technician from installing four wrong PRDs on the incident tube trailer module.

Since this incident, the PRDs manufactured for Air Products now have larger-font pressure ratings engraved on multiple locations such that the number is visible regardless of the PRD body orientation. Further, Air Products has requested future 10,000 psi PRDs to be fabricated from stainless steel, which is silver in color and visually different from the gold-colored brass PRD body used for a 5,833 psi PRD. Air Products successfully subjected the alternative PRD design to bonfire testing as required by the conditions of DOT-SP 14576, and is seeking PHMSA approval to switch to the stainless steel version for greater identification and robustness.[29] Figure 14 shows the new PRD design compared to the previous design, including improved markings to eliminate confusion between the PRD models and ensure that the devices are selected for the appropriate service criteria.

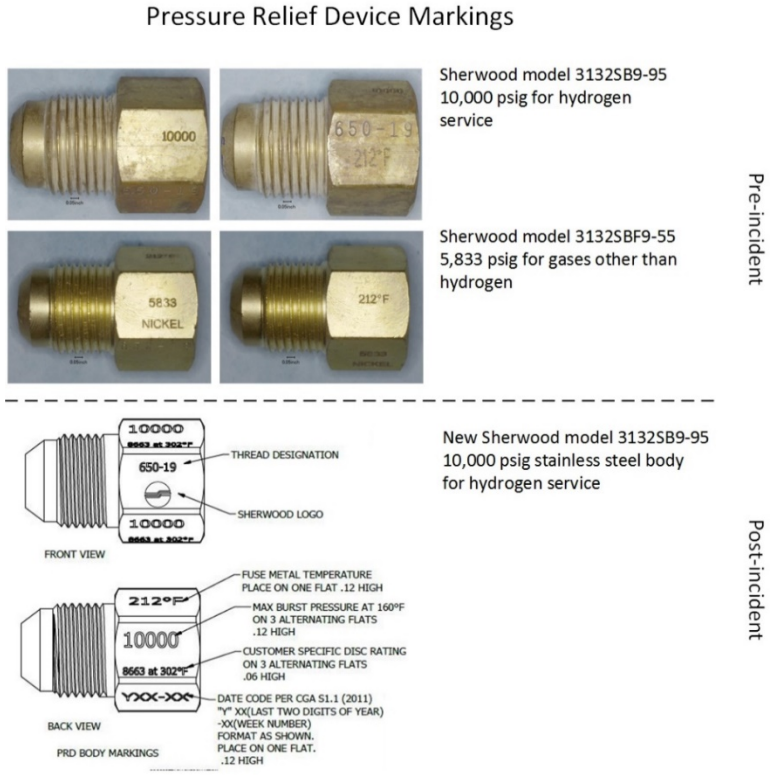

Figure 14. Comparison of old and new PRD markings.

[29] DOT-SP 14576 condition 7a references DOT-CFFC Basic Requirements, Fifth Revision (March 2007). Among these requirements is a bonfire test of two cylinders in which the cylinders are exposed to fire until fully vented. The cylinders must remain intact and gas must be vented predominantly through the PRD.

3. Postaccident Actions

3.1 FIBA Technologies Technicians

The FIBA procedure for pneumatic pressure proof testing for DOT special permit cylinders requires for the technician to have had at least 2 years of experience in conducting inspections or be supervised by a person with 2 years of experience. According to the FIBA facility manager, the technician had about 3 years of experience working at FIBA. The facility manager would periodically provide guidance and instruction to the technician as necessary.

The facility manager held his current position at FIBA since October 2017. He worked at the facility since 1989 and his knowledge and skills had been derived from on-the-job learning. He had not attended any formal training pertinent to cylinder qualification procedures. However, his personnel record documented that he received hazardous materials employee function-specific training in January 2016.

Air Products consulted with FIBA to develop the following postaccident changes to inspection and qualification procedures for its hydrogen tube trailer modules. These practices were included in a jointly written Air Products-FIBA updated cylinder inspection and qualification procedure and were reviewed with the facility manager.

- The FIBA facility manager now checks to make sure each PRD is the correct part, even though this step was already reflected on FIBA's written checklist. As an added quality assurance measure, the FIBA facility manager marks each PRD currently in storage with a marker pen to signify their pressure ratings have been verified. In addition, each PRD is visually checked as they are installed in the cylinders.

- FIBA is double checking that the ferrules are correctly swaged into the vent line tubing and that sufficient amount of tubing extends beyond the crimped ferrules into the PRD body seat.

- If the tubing does not match up with the PRD assembly easily and without placing bending stress on the fitting, FIBA will fabricate a new vent line from stock stainless steel tubing.

- All fittings are torque checked and marked with paint to avoid errors in omission.

- Cylinder pressure tests will be conducted with no PRDs installed to avoid placing overpressure on the devices (1.25 times the working pressure). The pressure-proof test is now done with the PRD removed and blanked off so that the disks are not exposed to elevated pressure that could induce premature failure during normal operation.

- Air Products has provided FIBA with stainless steel PRD adaptor fittings to replace the brass ones to avoid frequently observed thread damage.

3.2 Atlas Machining and Welding Technicians

The Air Products procedure for assembling tube trailer modules states that all personnel involved in the installation of compression fittings must be trained in the installation and inspection of the fittings, and the training shall be documented in the employee's file. The Atlas president and chief operating officer told NTSB investigators that the assembly technician has received 28 years of "on-the-job" training with Atlas for installing tube trailer piping, manifolds, and fittings. The available documentation did not indicate whether the assembly technician had been trained on the provisions of DOT special permits. As a result of this incident, Air Products revised and reviewed with Atlas in detail the assembly and retest procedures that include additional inspections and instructions. The assembly instructions include the following details for compression fittings:

- Compression fittings must be hand tightened, marked, and then further tightened 1 1/4 turns in accordance with manufacturer's recommendations. The No-Go gap gauge shall be used as a check to verify that the fitting has been properly tightened.

- At the initial make-up all fittings must be disassembled and visually inspected to ensure the proper tubing insertion and that all ferrules are installed.

- After reassembly, the applicable manufacturer's No-Go gap gauge shall be used as a check to verify that each fitting has been properly tightened.

- For high pressure (that is, greater than 150 psig) or flammable materials at any pressure, 5 percent of the fittings in a system are to be reexamined by disassembly to confirm proper tubing insertion and that all ferrules are installed. A written report of the inspection shall be maintained with quality assurance records.

- When accepting delivery of new modules, Air Products shall perform random checks by disassembly.

4. Conclusions

4.1 Findings

1. Greater first responder training and awareness about hydrogen tube trailer modules transported within their jurisdiction could have helped the first responders to initially respond to this incident more effectively, efficiently, and safely.

2. Although there is ample generic hazard information for compressed hydrogen and vehicle fuel systems, the available guidance lacks critical hazard recognition and firefighting information specific to fuel cell electric vehicle fueling infrastructure and containers currently used for the bulk transportation of compressed hydrogen.

3. The generic guidance for flammable gases contained in the *Emergency Response Guidebook*, Guide 115, does not adequately describe unique hazards associated with compressed hydrogen or best response actions for public safety personnel.

4. None of the incident tube trailer cylinders lost mechanical integrity, and they did not contribute to the cause or perpetuation of the incident.

5. The hydrogen release most likely initiated because a pressure relief device with the wrong pressure rating was installed on cylinder No. 14 and actuated under normal working pressure loads.

6. The hydrogen ignited during the forced separation of the cylinder No. 14 pressure relief device assembly from the cylinder.

7. Although the other cylinder pressure relief devices in the tube trailer module were actuated because of fire exposure, the cylinder No. 14 pressure relief device actuated before the fire began.

8. Had the requalification personnel inspected each vent line compression fitting for tightness, the propagation of the fire to the adjacent hydrogen cylinders may have been avoided.

9. The vent line compression fittings that disassembled during venting were not properly installed at the time the tube trailer module was fabricated and should have been noticed and repaired during the requalification inspection.

10. The lack of a Pipeline and Hazardous Materials Safety Administration special permit and regulatory requirements for verifying that pressure relief devices used on cylinders actuate at the correct pressure and venting equipment has been properly assembled and secured increases the risk of uncontrolled fires on flammable gas tube trailers.

11. The lack of vent system design requirements that consider factors such as the force of venting gas and construction material may leave vent systems for cylinders and tube trailers vulnerable to unexpected failure during an incident.

12. The lack of noticeable marking or other visual indicators, unique design features, and unique model numbering to readily identify pressure relief devices intended for different applications, made them easy to confuse and did not avert the requalification technician from installing four wrong pressure relief devices on the incident tube trailer module.

4.2 Probable Cause

The National Transportation Safety Board determines that the probable cause of the February 11, 2018, tube trailer module fire in Diamond Bar, California, was the requalification technician's installation of an incorrectly rated pressure relief device in cylinder No. 14, which actuated during normal transportation and released high-pressure hydrogen, and the tube trailer module assembly contractor's failure to sufficiently tighten compression fittings on the pressure relief device vent lines that disassembled under the pressure of escaping gas allowing a fire to develop inside the module and impinge on adjacent cylinders. Contributing to the incident was a lack of a requirement for requalification inspectors to verify the pressure relief device pressure rating and to inspect for vent line assembly securement.

5. Safety Recommendations

As a result of this investigation, the National Transportation Safety Board makes the following new safety recommendations:

To the Pipeline and Hazardous Materials Safety Administration:

Revise your *Emergency Response Guidebook* to include information about hazards and protective actions specific to hydrogen, and to provide guidance on how to manage incidents involving fuel cell electric vehicles and hydrogen fueling infrastructure. (H-19-18)

Revise all hazardous materials special permits for transporting gases in manifolded horizontal cylinders to require that requalification inspections include verifying that pressure relief devices of the correct pressure rating are used and that pressure relief device venting equipment is inspected and tested to ensure that it can withstand forces generated by pressure relief device actuation. (H-19-19)

Revise Title 49 *Code of Federal Regulations* Part 180, subpart C, "Requirements for Requalification of Specification Cylinders," to ensure that inspectors requalifying cylinders verify that pressure relief devices with the correct pressure rating are used and that pressure relief device venting equipment is inspected and tested to ensure that it can withstand forces generated by pressure relief device actuation. (H-19-20)

Work with the Compressed Gas Association to develop design guidelines for tube trailer pressure relief device vent systems. (H-19-21)

To the US Department of Energy, Pacific Northwest National Laboratory:

Revise your hydrogen emergency responder training programs to include readily accessible specific information and guidance on hazard recognition and firefighting relative to tube trailers and fuel cell electric vehicle fueling infrastructure. (H-19-22)

To the Compressed Gas Association:

Work with the Pipeline and Hazardous Materials Safety Administration to develop design guidelines for tube trailer pressure relief device vent systems. (H-19-23)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

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Vice Chairman

Date: October 10, 2019

Appendix. Investigation

The National Transportation Safety Board (NTSB) was notified on February 11, 2018, of the incident in which a fire occurred on a hydrogen tube trailer while in transportation within a business district of Diamond Bar, California. The NTSB was initially informed that the fire initiated from gas cylinder valve and fitting leakage. None of the gas cylinders were breached. Several days later, the carrier, Air Products and Chemicals, Inc., inspected the trailer and found that a cylinder testing contractor had installed improperly rated pressure relief devices in several cylinders during a recent requalification inspection and that improperly secured vent tubes became disassembled and directed burning hydrogen into the interior of the trailer module.

On February 22, 2018, the NTSB initiated a formal investigation into the incident and began collecting information about the tube trailer from Air Products and Chemicals, Inc. and from the Pipeline and Hazardous Materials Safety Administration. On March 12, 2018, the NTSB launched two accident investigators to collect evidence from the tube trailer wreckage that was stored at the Air Products terminal in Santa Fe Springs, California, and from the gas cylinder requalification facility in Adelanto, California. Investigators also visited the incident scene and a hydrogen fuel cell vehicle fueling facility in Diamond Bar, California, and the Air Products tube trailer module loading facility in Long Beach, California.

Following the on-scene investigation, investigators traveled to the Sherwood Valve, LLC pressure relief device manufacturing facility located in Valley View, Ohio, to review their manufacturing and shipping processes.

Parties to the investigation included Air Products and Chemicals, Inc., Sherwood Valve, LLC, and the Pipeline and Hazardous Materials Safety Administration.