HYDROGEN
Safety Panel

Report on the June 2019 Hydrogen Explosion and Fire Incident in Santa Clara, California

June 2021
PNNL-31015-1

DISCLAIMER

Executive Summary

A major uncontrolled release of high-pressure hydrogen occurred at the Air Products hydrogen trailer transfill facility in Santa Clara, California on June 1, 2019 during a gaseous hydrogen fill of a modular multi-cylinder trailer. Hydrogen was accidentally released from an open pipe as a result of an unauthorized attempt to repair a leaking valve and a subsequent miscommunication between the two drivers filling the trailer. A hydrogen-air mixture explosion occurred within seconds of the release, followed by a high-pressure gas jet fire. The fire and explosion caused pipe damage and activation of hydrogen cylinder temperature-pressure relief devices, adding additional hydrogen fuel to the incident, and eventually spreading to other materials on adjacent vehicles. Approximately 250 kg of hydrogen was released during this event. Air Products' personnel initiated a shutdown and isolation of other trailers and tanks to prevent further releases.

The Santa Clara Fire Department responded to the fire and ordered an evacuation of the surrounding area. Firefighters extinguished fires of diesel fuel and tires and initiated elevated water streams to protect other hydrogen gas trailers, a liquid hydrogen tanker, and a stationary liquid hydrogen tank exposed to the fire from the burning trailer module. Based on the assessment of the damage, emergency responses by Air Products' personnel and the Santa Clara Fire Department were appropriate and effective. Air Products noted that only two employees sustained minor injuries resulting in work restrictions. The Air Products transfill facility was minimally affected, although parked vehicles at the transfill facility suffered extensive damage. Evacuations of nearby businesses occurred per instructions of the fire department and there was no significant damage to other industrial facilities or public residences.

Air Products performed a Root Cause Analysis of the incident. The primary causes of the incident were: (1) Unauthorized maintenance was performed by personnel not following proper procedures, and (2) Miscommunication between the two drivers filling the trailer. Follow up action items included improvements to the trailer filling procedures, an enhanced driver training program, and improved labeling of control functions. Curtailment of hydrogen deliveries to vehicle refueling stations in northern California occurred while the investigation was underway; Air Products' procedures were improved, and additional personnel training was provided.

The Hydrogen Safety Panel analyzed several generic equipment and operational issues that were pertinent to the initiation and escalation of this incident. The analysis has led to recommendations for specific improvements in the National Fire Protection Association Hydrogen Technologies Code, Compressed Gas Association guidelines, and Department of Transportation regulations for modular multi-cylinder trailers. Additional risk evaluation and feasibility studies are proposed that could facilitate the implementation of some of the recommendations. The California Energy Commission, by chartering this report and promoting communication of this report to industry stakeholders, is supporting safety improvement to the hydrogen industry.

Acknowledgments

The Hydrogen Safety Panel is honored to be involved with the California Energy Commission and hydrogen supply industries to further advance the safety of the hydrogen and fuel cell industry. Numerous researchers, project test personnel, regulators, and safety experts have contributed to this Hydrogen Safety Panel report through their evaluations and writings.

The Hydrogen Safety Panel appreciates the support and responses of Air Products and their representative who supplied the primary technical data for this report and graciously answered numerous panel questions. Also acknowledged is the Santa Clara Fire Department, who provided excellent emergency response to minimize damage and personnel injury and provided supplemental details to their incident report. Both the Santa Clara Fire Department and Air Products supplied photographs from their various documents and are footnoted.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ATTACHMENTS

ACRONYMS

Air Products	Air Products and Chemicals, Inc.
CEC	California Energy Commission
CGA	Compressed Gas Association
CNG	compressed natural gas
COPV	composite overwrapped pressure vessels
DOE	Department of Energy
DOT	Department of Transportation
ES	emergency-stop/e-stop
GH2	gaseous hydrogen
HMI	human machine interface
HSP	Hydrogen Safety Panel
ISO	International Standards Organization
LH2	liquid hydrogen
LOTO	lockout, tagout
MEGC	multi-element gas container
NFPA	National Fire Protection Association
NTSB	National Transportation Safety Board
P&ID	piping and instrumentation diagram
PFD	process flow diagram
PHMSA	Pipeline and Hazardous Materials Safety Administration
PNNL	Pacific Northwest National Laboratory
PRD	pressure relief device

UNITS

bar	pressure - absolute
bar-g	pressure - gauge
cm	centimeter
°C	degrees Centigrade
°F	degrees Fahrenheit
ft.	foot
gpm	gallons per minute
in.	inch
kg	kilogram
lbs.	pounds
lpm	liters per minute
m	meter
psi	pound per square inch
psig	pound per square inch gauge
s	second
scm	standard cubic meter

A. Purpose

This report provides an evaluation by members of the Hydrogen Safety Panel (HSP) of the June 1, 2019 hydrogen release incident at the Air Products and Chemicals Inc. (Air Products) hydrogen trailer transfill (transfill) facility located in Santa Clara, California. This review was requested by the California Energy Commission (CEC) in May 2020 and examines data from Air Products, and the Santa Clara Fire Department to provide an HSP perspective on the incident cause, response, and recommended follow-up actions.

Revision 1 adds a clarification to injury information in the Summary, and additional citations to similar personnel injury information within the report, in response to a post revision 0 publication comment. Other minor editing corrections were made.

B. Background

Air Products Facility Location

The incident occurred at the Air Products transfill facility, 1700 Russell Ave, located in Santa Clara, California. The site is within an industrial park with many other industrial occupancies, and one-half mile west of a major residential area. This facility pressurizes liquid hydrogen from an on-site storage tank, warms it to ambient temperature, and transfers the gaseous hydrogen into high-pressure trailer assemblies, which then deliver hydrogen to multiple retail fueling locations. The transfill facility is part of a larger Air Products facility, at 1375 Norman Ave, Santa Clara, California, containing industrial gas production and storage systems, including an air separation plant to produce oxygen and nitrogen. Figure 1 is an aerial view of the Air Products facility, with its boundary highlighted in red.[1]

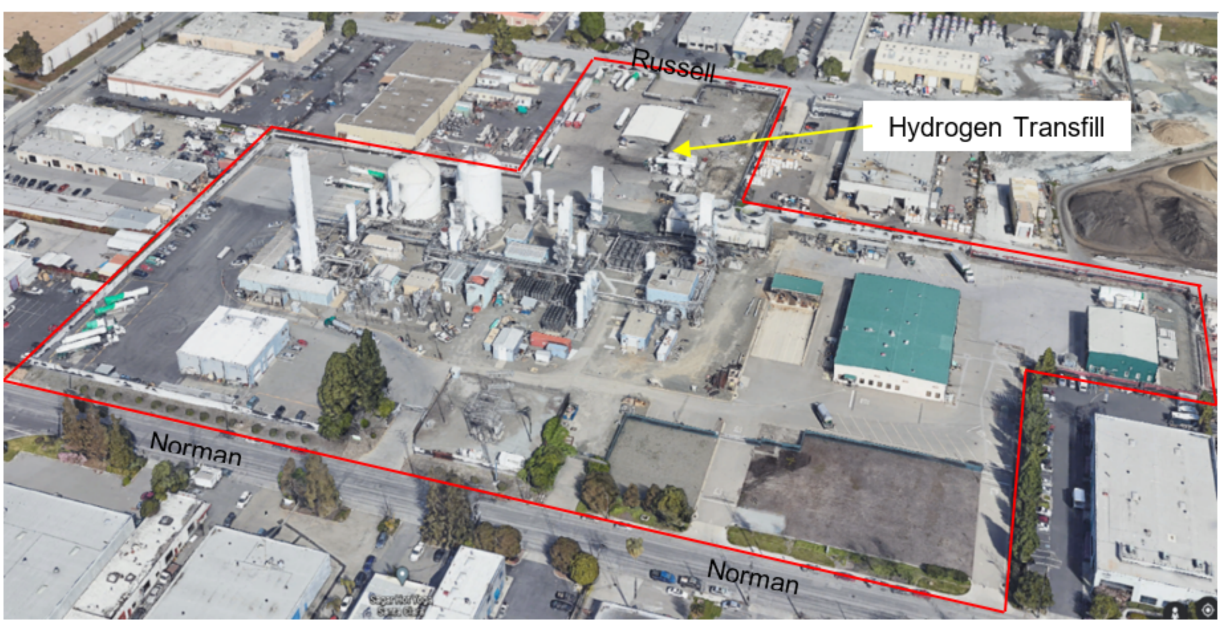

Figure 1. Air Products Facility, Santa Clara, CA (Looking NW)

[1] https:\\www.google.com/earth/ – accessed November 3, 2020 (photograph pre-dates the installation of the transfill).

Air Products Transfill System Description

Figure 2 is a more detailed diagram from the Santa Clara fire department report of the transfill area, showing the location of the hydrogen trailers at the time of the incident, and storage tank, vaporizers, hose connections, and emergency-stop/e-stop (ES) locations.[2]

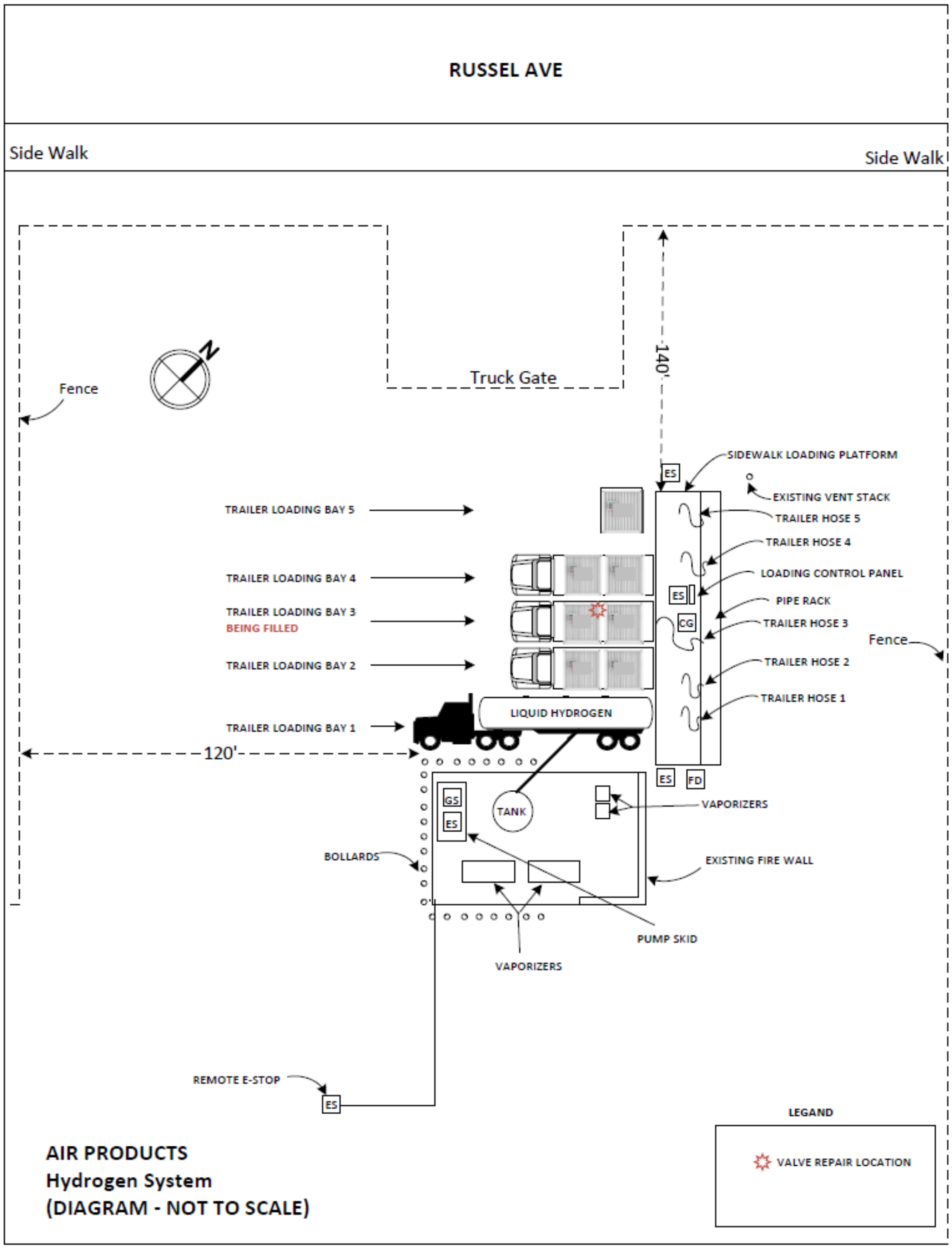

Figure 2. Air Products Hydrogen Transfill Facility Plan View (not to scale; from Fire Department report)

[2] Santa Clara Fire Department Report, Case #19-4295, August 19, 2020, page 14.

There are five trailer bays in the transfill facility. Bay #1 is used to fill the vertical 15,000-gallon liquid hydrogen (LH2) storage tank from LH2 delivery tankers. Bays #2 through #5 are used to fill the Air Products' high-pressure GH2 hydrogen tube trailers from the LH2 storage tank. The LH2 is pressurized, transferred, and warmed to ambient temperature via two cryogenic LH2 pumps and associated vaporizers. The vaporization equipment area is protected by an L-shaped concrete firewall and a series of bollards. The facility equipment locations and separation distances to property lines comply with National Fire Protection Association (NFPA) 2 and NFPA 55 requirements for both gaseous and liquid hydrogen.

Both single and dual-module trailers are filled at the Santa Clara facility. The modules are also qualified as multi-element gas containers (MEGC). A typical Model CT-250 MEGC contains 250 kg of hydrogen in 25 carbon-fiber-reinforced, aluminum lined (Type 3) composite cylinders. The cylinders are Worthington Industries Model ALT1015 and each has a capacity of 10 kg when filled to service pressure of 7,500 psig (517 bar-g). A typical single-module trailer is shown in Figure 3. Dual-module trailers are designated as "CT-450" or "CT-500," depending on whether they contain two MEGCs totaling either 450 kg (992 lbs.) or 500 kg (1102 lbs.) of hydrogen.[3] The trailer fill connection and isolation valve on each module is situated at the lowest row of cylinders, accessible when opening the module rear doors. The transfill hose connection to the module isolation valve and the tubing manifold to the individual cylinders are visible in the Figure 3 photograph.[4]

Each cylinder in a module is equipped with two Type CG-5 pressure relief devices (PRDs); one at each end of the cylinder. The PRDs consist of a rupture disk, with a burst pressure of 9,500 ± 500 psig (655 ± 34 bar-g), backed with a fusible metal alloy that melts at 212°F (100°C).[5] Sufficient heat is required to first melt the fusible metal before activation of the rupture disc. The PRD vent outlets are piped vertically to about 12 in. (30 cm) above the top row of cylinders.

Figure 3. Air Products Single-Module Hydrogen Cylinder Trailer

---

[3] Worthington Industries Type III Hydrogen Bulk Gas Transport Cylinders Brochure, April 2020, retrieved from https://worthingtonindustries.com/getmedia/08e78416-abe0-4aba-ab6f-80dc4f6e77e8/Hydrogen_Type_3_v8.pdf?ext=.pdf, accessed on November 10, 2020.

[4] Transportation Safety Board Investigator-In-Charge Factual Report, *February 11, 2018, Tube* HMD18FR001, National *Trailer Module Hydrogen Release and Fire*, July 30, 2018, https://dms.ntsb.gov/pubdms/search/document.cfm?docID=465882&docketID=61458&mkey=96772.

[5] Sherwood Pressure Relief Devices Technical Information Sheet, SWD0215, 2015, retrieved from https://www.sherwoodvalve.com/sites/default/files/pressure-relief-devices-technical-information.pdf, accessed on November 10, 2020.

Normal Trailer Gaseous Fill Operation

LH2 is withdrawn from the storage tank at approximately -400°F (-240°C) and pumped to the vaporizers. GH2 exits the vaporizers within 10–20°F of the ambient air temperature. The hydrogen gas is then piped to the trailers filling them to a temperature-compensated pressure of 7500 psig (517 bar-g).

The trailer fill procedure begins with the drivers connecting the trailer fill connection to one of the facility fill stanchions. Each stanchion consists of a fill hose, vent valve, and check valve, and is connected to the facility fill equipment and control system, as shown in the simplified process flow diagram (PFD) in Figure 4.

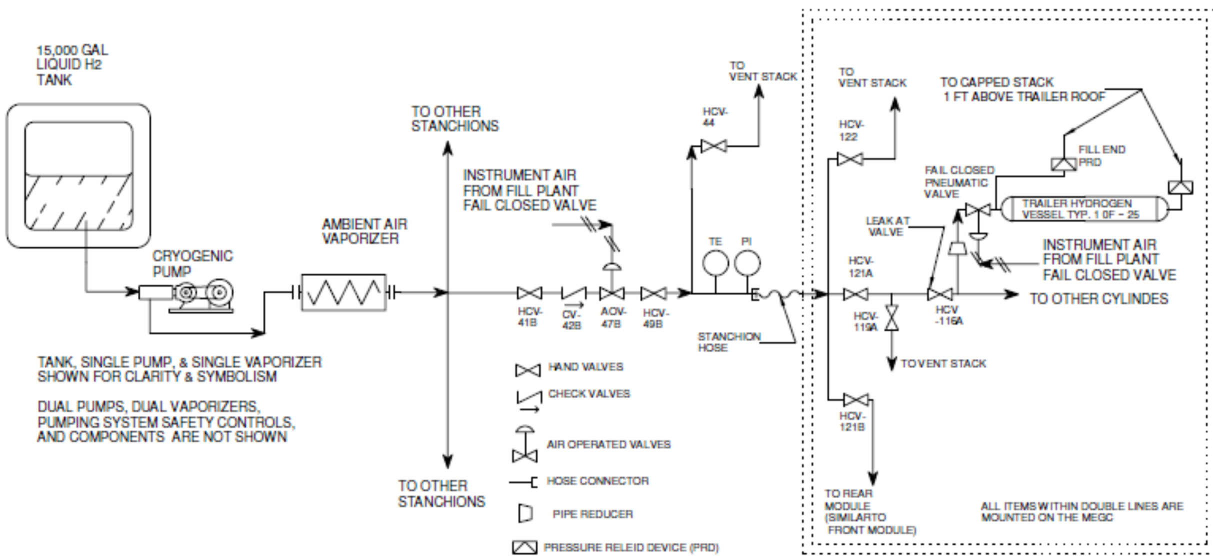

Figure 4. Air Products Fill System PFD

A module piping purge and pressure check procedure is required prior to filling the cylinder modules that involves the following steps.

- Opening the module automatic shutoff valves (including cylinder valves) by providing facility instrument air pressure.
- Opening the manual valve in the trailer fill cabinet, allowing residual pressurized hydrogen to flow backward through the hose to the stanchion.
- Pressure checking the hose connections to confirm integrity.
- Opening the stanchion vent valve (HCV-44 in Figure 4), and venting hydrogen to the vent stack until the hose and associated piping are purged.

The module cylinders are then filled by carrying out the following steps.

- Starting the pump fill system. The process begins by first cooling the cryogenic pump to its operating temperature and then starting the pump. After the pump is started by the driver, the filling process is designed to be automatic until completion.

- Shutting down the pump fill system. The system controls will stop the pump after the desired cylinder service pressure of 7,500 psig (517 bar-g) is achieved. The system can also be stopped at any time by the driver.

After the fill is completed, the manual and automatic valves are closed and instrument air and hoses are disconnected. The pump control system will shut the system down on any of several alarm conditions, including high pressure, low temperature (if vaporizers are overtaxed), and high stanchion temperature. Hydrogen sensors and flame detectors within the fill area can also trigger a system shutdown by shutting off both the pump and instrument air to the normally closed automatic valves. Manual actuation of one of the ES controls shown in Figure 2 will also initiate shutdown.

C. Event Description[6]

Hydrogen Release, Explosion, and Subsequent Fire

On Saturday, June 1, 2019, at around 4:20 p.m., a sudden, major uncontrolled release of hydrogen gas occurred, followed almost immediately by an explosion and fire. This incident occurred while a dual-module CT-500 trailer was being filled. At the time of the incident, module piping had been disassembled in an attempt to repair a leak in the hydrogen supply line of the forward-mounted CT-250 MEGC modules. Details of the sequence of activities are provided below. Refer to Figures 2, 3, and 4 for equipment and system configuration details.

Just before the GH2 release, two Air Products' drivers were working together at the centrally located trailer loading Bay #3 to complete the CT-500 trailer fill. One driver was acting as a trainer and the other was a trainee. At the time of the incident, the five loading bays in the transfill facility were occupied with hydrogen transport equipment. Two other drivers were delivering liquid hydrogen from a cryogenic LH2 tanker parked in Bay #1. Bays #2, #4, and #5 were occupied by additional trailer-mounted, previously filled, GH2 MEGC modules.

At about 4:20 p.m., when the modules of the CT-500 were about 95% full (7,200 psi/496 bar), the trainee noticed that GH2 was leaking near the front module fill line manual isolation valve (HCV-116A) and informed the trainer. The trainer then instructed the trainee to stop filling the front module. However, the trainee stopped the filling process for both modules. He did not disconnect the trailer from the filling system piping and controls. The drivers were neither trained nor authorized to perform repair work on that equipment. As a result, a safety lockout, tagout (LOTO) procedure was not performed and the trailer remained connected to the fill stanchion.

The trainer then closed the front module manual valve to isolate the front module from the GH2 stanchion supply, depressurized the front module fill manifold, and removed a piping section while he attempted to repair the leak.[7] The trainer realized that he did not have the required parts to complete the repair (particularly an O-ring) and then instructed the trainee to shut off the hydrogen supply.

---

[6] Unless noted, event data was obtained from information provided by Air Products and from the Center for Hydrogen Safety Incident Record Sheet (used by permission), and Air Products' Incident Report. All Santa Clara Fire Department documents used as redacted.

[7] Santa Clara Fire Department Report, Case # 19-4295, August 19, 2020, page 2.

The trainee misunderstood the instructions and inadvertently restarted the GH2 fill process at approximately 4:30 p.m. by pressing the "Purge/Enable Trailer" control button. This opened all pneumatic valves on the trailer. GH2 from the MEGC module then escaped through the open disassembled piping at a high flowrate for about three seconds, producing a hydrogen-air mixture in and around the module. This mixture ignited and resulted in a hydrogen-air deflagration explosion followed by a jet fire. Neither the Air Products' nor Santa Clara Fire Department's investigations determined the particular ignition source,[8] as is often the case with hydrogen incidents.

The air-operated GH2 valves on the MEGC modules closed when the trainer pressed the emergency stop and as the fire melted the plastic air supply lines. The deflagration overpressure and subsequent short-duration primary jet fire from the open piping caused additional hydrogen piping leaks/releases, primarily from PRD and cylinder seals, and resulted in a continuation of the fire. This led to normal PRD activation, additional PRD seal leakage, and abnormal failure/separation of four PRD bodies, which contributed to the escalation of the event. The entire contents of the forward-mounted module, about 250 kg (551 lbs.) of GH2, were lost during the incident. Secondary fires involving tractor-trailer diesel fuel and tires also complicated the event and required firefighter intervention.

According to the Fire Department Investigation report,[9] the Bay #3 drivers escaped to a designated evacuation area on Russell Avenue soon after the initial explosion, joined by the Bay #1 LH2 driver who had shut down the LH2 transfer. An additional Air Products' employee ran to a parked Santa Clara police vehicle on Norman Avenue and also notified Air Products Logistics.

Emergency Response

The first report of explosions was received by the Santa Clara Fire Department at 4:33 p.m. The first two fire department units arrived on the scene at 4:38 p.m.[10] The Santa Clara Fire Department found three hydrogen vehicles engulfed in flames, a large fireball centered on the middle vehicle, dark smoke from the diesel tank and tire fires, and a separate diesel pool fire in the yard. First responders met with Air Products' facility personnel, verified all Air Products' personnel were accounted for and reported that there were no injuries.[11]

An evacuation zone of 500 yards (457 meters) in all directions was ordered, with shelter-in-place ordered outside that perimeter. Second and third alarms were called; multiple aerial and hand water lines were used to extinguish the residual hydrogen fire and cool hydrogen tankers and storage. Foam was then used by fire personnel to extinguish a remaining truck diesel tank fire.

In coordination with fire department personnel, Air Products' personnel secured the hydrogen equipment by closing supply valves and using combustible gas monitors to establish that the affected area showed very low hydrogen concentrations despite some leaking sounds. Air

[8] Information provided by Air Products suggested the ignition was likely due to either static in the dust cloud or movement of the steel doors due to the high velocity jet. Another possibility Air Products identified is delayed spontaneous ignition due to shock wave formation near the release site.
[9] Santa Clara Fire Department Report, Case # 19-4295, August 19, 2020, page 2.
[10] Santa Clara Fire Department Incident Report, 2019-1904295-000, page 1.
[11] Santa Clara Fire Department Report, Case # 19-4295, August 19, 2020, page 1.

Products' personnel then reduced pressure in both the LH2 tanker truck and the LH2 storage tank by venting hydrogen through an elevated vent stack. Most fire department equipment was cleared by 10:00 p.m. Santa Clara Fire Department maintained a fire watch through 11:49 a.m. on June 4th, as Air Products conducted equipment decommissioning operations.

Personnel Injuries

While the initial fire department report described no injuries from its initial first responder evaluation, Air Products note that two of the four Air Products' employees on-site were reported to have minor recordable injuries: one GH2 driver suffered a shoulder injury when he tripped while evacuating, and a second LH2 driver suffered tinnitus from the explosion overpressure.[12] Overpressure injuries typically occurs at or above a threshold of about 5 psig (0.3 bar-g).[13]

Damage

The forward-mounted MEGC on the incident trailer sustained extensive damage. The rear-mounted MEGC on the same transport trailer, two adjacent GH2 MEGC transport trailers (in Bays #2 and #4), and the LH2 tanker (in Bay #1) each sustained less damage. Details are noted below.

Air Products' Trailer Damage

As illustrated in Figures 5[14] and 6,[15] the front module in the incident trailer suffered extensive and irreparable burn and overpressure damage, as did the three tractor cabs parked in front of the trailers. The other fuel modules had much less damage. The LH2 tanker truck only had paint damage and surface charring. The large stationary LH2 storage tank for the facility was not damaged.

[12] Air Products Incident Report presentation, October 14, 2019, provided May 14, 2020.
[13] Crowl, D.A, "Understanding Explosions," Wiley-AIChE, 2003, page 100.
[14] Courtesy Air Products.
[15] Courtesy ABC News Report, June 1, 2019, https://abc7news.com/5326601/

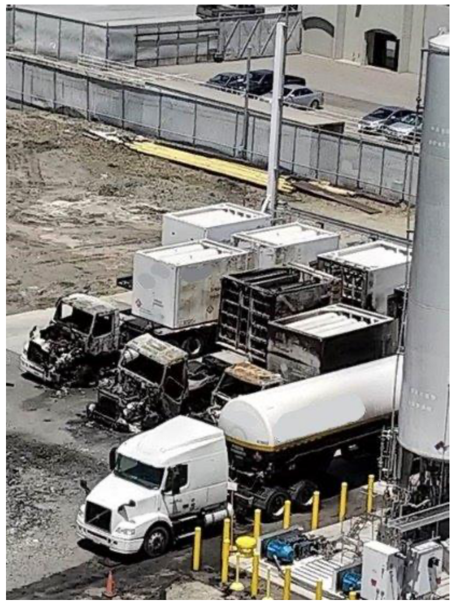

Figure 5. Fueling Tractor-Trailer Damage Overview

Figure 6. Ground Level View of Equipment Damage

Figure 7. Incident Trailer Cab and Front Module

Figure 7[16] shows the extent of damage to the incident trailer cab (including ruptured fuel tank) and front module, which had its forward wall panel blown off.

The access doors on the rear module were heavily damaged but remained closed as seen in Figure 8.[17] The intact doors prevented any significant damage to the cylinders in the rear module, as indicated in Figure 9.[18]

Figure 8. Doors on Rear Module Incident Trailer

[16] Santa Clara Fire Department Report, Case # 19-4295, August 19, 2020, page 6.
[17] Air Products Incident Report presentation, October 14, 2019, provided May 14, 2020.
[18] Air Products Incident Report presentation, October 14, 2019, provided May 14, 2020.

Figure 9. Rear Incident Trailer with Open Doors

The trailer rear module from Bay #2 is shown in Figure 10[19] with an end panel removed. The side panels were significantly scorched but protected the vessels within the enclosure.

Figure 10. Front and Side Panels on Adjacent Module in Bay #2

[19] Air Products Incident Report presentation, October 14, 2019, provided May 14, 2020.

Air Products' Cylinder/PRD Damage

None of the Type 3 cylinders exhibited the level of damage that might have resulted in catastrophic pressure vessel rupture during the event. The damage to the Type 3 composite overwrapped pressure vessels (COPVs) varied depending on placement and exposure to the event. Damage to the COPVs included the movement of the COPVs in the framework, burning of the external white paint (Figure 5), burning or melting of the epoxy resin on the outer carbon fiber plies, loss of the outer fiberglass plies, and some fraying and displacement of the graphite fibers. All of the vessels in the incident module were scrapped following the incident. There was significant structural damage to the PRDs and their connections

The conditions of the 24 vessel PRDs on the incident trailer front module and release mechanism during the incident are shown in Table 1. Ten of the cylinders vented from PRDs that actuated either fully or partially. Depressurization from the other 14 cylinders occurred due to PRD cracking or connector/tubing/seal leakage.

Table 1. PRD Actuations and Damage

PRD Condition after Incident	Number (%)
Actuated PRD	5 (21%)
Partially Actuated PRD	5 (21%)
No Actuation; Leaking connection	10 (42%)
Failed/cracked PRD	4 (17%)

Results of Blast Wave

The front module explosion produced minor blast wave damage to at least one nearby structure. A window broke in a small control building about 125 ft. (38 m) away from the module. The broken glass was found outside the building, indicating that the suction pressure of the blast wave was responsible.[20]

Supply Interruption

After the incident, Air Products curtailed hydrogen module cylinder trailer deliveries to allow for inspection of the trailers and a review of the implications of the Santa Clara incident. The suspension of hydrogen deliveries caused interruption or shutdown of nine of the eleven hydrogen vehicle refueling stations in the San Francisco Bay area.[21] These stations were impacted for approximately four months.[22] There were also shortages of hydrogen supplies for several months at other California refueling stations.[23] Air Products did not resume operation until authorized by the Santa Clara Fire Department.

[20] Air Products Incident Report presentation, October 14, 2019, provided May 14, 2020.
[21] https://www.greencarreports.com/news/1123449_hydrogen-supply-pinch-affects-san-francisco-fuel-cell-drivers.
[22] https://longtailpipe.com/2019/09/20/hydrogen-stations-in-sf-bay-area-still-offline-4-months-after-explosion/.
[23] California Air Resources Board, "2020 Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development," September 2020.

D. Analysis

Approach

The analysis was initiated 11 months after the incident. Because of the substantial time lag and travel restrictions associated with COVID-19 it was infeasible/impractical to conduct scene inspection or face-to-face interviews. The review focused on examining available incident documentation and photographs, and conducting a series of discussions and communications with a key Air Products incident investigator and with the Santa Clara Fire Department.

Air Products Causal Analysis

Air Products conducted a Root Cause Analysis as part of its incident investigation and reported the following results at a Center for Hydrogen Safety meeting and an HSP meeting in October 2019.

- **Initial Leak –** The initial hydrogen leak was caused by either a cracked O-ring or leaking cone and thread fitting on the front module hydrogen isolation valve.
- **Unauthorized Maintenance –** The trailer driver attempted an unauthorized repair of the leaking valve without properly isolating the hydrogen supply piping using standard Lockout/Tagout procedures. The system controls, hydrogen fill hose, and instrument airlines (for valve actuation) were still configured for an automated system fill.
- **Miscommunication –** There was a misunderstanding of the senior driver's instructions to the trainee. The senior driver told the trainee to stop the trailer fill, but the fill control process had been stopped ten minutes previously. When the trainee attempted to stop the fill a second time, the trainee accidentally actuated the "Purge/Enable Trailer" control button which opened the pneumatic valves and allowed hydrogen flow into the disconnected manifold pipe.
- **Hydrogen Explosion –** The hydrogen explosion was caused by the accumulation and subsequent ignition of hydrogen released into the front module. Confinement by the module walls and vessels prevented free dispersal of the released hydrogen. The open module roof did not provide adequate venting to prevent damaging overpressures from developing upon ignition of the accumulated flammable mixture within the module.
- **Hydrogen Jet Fires –** Hydrogen jet fires originating from the disconnected piping burned for a few seconds until the pneumatic lines controlling hydrogen flow either melted or were shut by ES actuation. Other hydrogen fires continued from multiple leaking PRD seals and damaged O-rings. This ultimately led to multiple PRD actuations, several broken cylinder PRDs, and fire impingement on the trailer cab and the adjacent trailers. These hydrogen fires caused subsequent diesel fuel fires and tire fires.
- **Subsequent Fires –** Subsequent tractor fuel fires, tire fires, and cab fires were extinguished by aerial streams from responding firefighters.

Based on their root cause analysis, Air Products implemented the following measures.

- **Improved Training and Retraining of Drivers**
- **Improved Trailer Filling Procedures**
- **Equipment Evaluations and Modifications**

One limitation of the Air Products' initial causal analysis as presented to the HSP is that there was no discussion of how or why the relief devices on the incident trailer were damaged, although the analysis acknowledged that it occurred and showed where it occurred per a diagram. The HSP later received a more complete analysis from Air Products and had discussion with Air Products about how the PRDs and breached piping influenced the subsequent damage. However, the more complete analysis and follow-up discussion did not address the absence of installed facility fire protection and the effect of close trailer spacing. These gaps are addressed in the HSP analysis below, with issues related to PRDs, trailer module design and construction, and hydrogen piping and fittings.

Pertinent Generic Issues

Repairing Hydrogen Piping Systems

The hydrogen release in this incident occurred because of an individual attempting an unauthorized repair of a leaking valve on the module trailer without following proper procedures. This is a common issue for the GH2 industry; other similar accidental hydrogen releases have occurred during faulty ad hoc hydrogen valve maintenance and repair attempts. One example is a hydrogen fire due to an incorrect and mishandled valve opening attempt on the hydrogen supply to the main generator at a power plant.[24]

The need for following proper written procedures for operating and repairing any hydrogen system is vital. Recommendations for safely isolating hydrogen piping during repairs is described in Attachment A, "Guidelines and Practices for Repairing Leaks in Hydrogen Systems."

Confusing Operator Controls

The specific event causing the hydrogen release in this incident was the driver/trainee actuating the "Purge/Enable Trailer" control in response to the driver/trainer instruction to shut down the trailer fill process. Purge/Enable is a confusing control label, especially for someone first learning the supply piping controls. Air Products revised control panel labels after the incident, but the generic issue warrants discussion. It is conceptually similar to operator error explanations in many other major industrial accidents. For example, in the Formosa Plastics chemical plant incident, the absence of clearly labeled valve controls was linked to the erroneous opening of a bottom valve on a fully loaded vinyl chloride polymerization reactor when the operator was attempting to clean a different empty reactor.[25]

---

[24] https://h2tools.org/lessons/hydrogen-leak-due-inappropriate-operator-action-results-fire.

[25] Chemical Safety Board Report, "Formosa Plastics Vinyl Chloride Explosion," 2007.

Several guidelines and standards describe best practices in the design and implementation of an improved human machine interface in process and pipeline controls to enhance operational safety. These include publications by the Abnormal Situation Management Consortium,[26] the International Standards Organization,[27] and the American Petroleum Institute.[28] It would be helpful for the Compressed Gas Association (CGA) or related hydrogen safety associations to produce similar guidance for hydrogen refueling systems and to emphasize the advantages of a graphical controls interface (e.g., Lee 2020) in such guidance.[29]

Gaseous Hydrogen Trailers

The Air Products' trailer modules are regulated by the Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) under Special Permit DOT-SP-14576 for the transport of fully wrapped carbon-fiber reinforced aluminum lined (Type 3) cylinders of hydrogen and other compressed gases.[30] The pertinent regulation requires that the module should provide a permanent structural framework for mounting the cylinders during transport. The structural framework design must be supported by a finite element analysis to demonstrate the framework's ability to protect the cylinders from rupture due to designated static equivalent impact loads and rollover. There are no requirements regarding enclosing the sides and roof of the module or installing bulkheads unless the sides/bulkheads are needed to meet structural framework integrity requirements.

Potential non-catastrophic release of hydrogen or other compressed gas during roadway accidents such as rollover were addressed in CGA-TB-25 and are now addressed in CGA C-29.[31] These require installation of protective devices or housings for cylinder valves and PRDs. Although there are no fire resistance requirements, it would be beneficial to require that the framework and support materials be constructed of materials that maintain the necessary mechanical integrity under fire conditions. For example, while not pertinent to this incident, aluminum frames would not meet this requirement.

The Air Products' CT 500 module involved in the Santa Clara incident had no roof, but it did have open steel structural supports, side walls, and doors. The trailer module's overall dimensions are approximately 12 ft. long, 8.5 ft. wide, and about 9 ft. high, (3.6 m x 2.6 m x 2.7 m) corresponding to a volume of about 920 ft^3 (26 m^3).[32] The release rate from the removed pipe section could fill this volume in roughly one second.[33] Thus a gas mixture well within the flammable range rapidly formed within the module and the surrounding area at the time of ignition. The confinement of the walls/bulkheads probably contributed to the explosion pressure that developed as the flame propagated through the flammable mixture, as did the

---

[26] ASM Consortium, "Effective Console Operator HMI Design," Abnormal Situation Management Consortium, 2nd edition, 2015.

[27] ISO Standard 11064-5:2008, Ergonomic Design of Control Centers – Part 5: Displays and controls, International Organization for Standardization, 2008.

[28] API RP 1165, "Recommended Practice for Pipeline SCADA Displays," American Petroleum Institute, 1st edition, 2007.

[29] Lee, D., "Safe Operations Using Advanced Operator Graphics," Article: *Process Safety Progress*, Volume 39, Issue 3, 2020.

[30] DOT-SP-14576 (Ninth Revision), Grantee: Structural Composites Industries (SCI), January 19, 2017, See also Eleventh Revision, January 9, 2020, United States Department of Transportation.

[31] CGA-TB-25-2008, "Design Considerations for Tube Trailers," replaced by CGA-C29, November 2019, CGA.

[32] Trailer module overall dimensions from NTSB report HMD18FR001, 2018, page 10.

[33] Using HYRAM software, the hydrogen release rate from a 9/16 in. pipe orifice at 7500 psi is about 4.3 kg/s (52 scm/s).

array of cylinders and piping in the module. The module's front wall panels were ejected from the module in the explosion; fortunately, they did not strike anyone or damage any piping or valves.

Module walls/bulkheads have a bi-directional beneficial effect for hydrogen jet fire scenarios. The walls can prevent an internal jet flame from extending beyond the module and possibly impinge on adjacent vehicles and personnel. Similarly, the walls protect the cylinders from external fire exposure. None of the cylinders within adjacent trailers in the Santa Clara incident suffered direct jet flame exposure since they were shielded by the steel walls of the module. The steel walls and steel floor pan also protected the cylinders from direct exposure to the diesel fuel and tire fires that followed the hydrogen fires. A significant advantage of front and rear cylinder bulkheads is to separate the leak areas or mechanical joints from the cylinders and confined areas, similar to many industrial tube pressure trailer designs.

Since DOT/PHMSA regulations and CGA design guidelines do not specify a particular type, size, and extent of module enclosure, composite cylinder module carriers have been designed by different companies with different degrees of enclosure. Because there is a tradeoff between the increased explosion hazard and the reduced jet flame hazard created by the module bulkheads, the issue lends itself to a risk assessment. The CGA or PHMSA could sponsor such a risk assessment (which might include testing or computer modeling) followed by stakeholder discussion and revision of trailer construction permits/guidelines. An inherently safer design that could be explored during this assessment would be one that would prevent the possibility of hydrogen accumulation and explosion damage within the module while still providing fire resistance or a fire barrier, with the consideration of some type of module wall deflagration vent panel.

Cylinder Pressure Relief Devices and Vent Lines

In this incident, PRD actuations, partial actuations, and leaks/failures were responsible for a large quantity of released and burning hydrogen. An obvious advantage of a cylinder PRD is the depressurization during fire exposure to help prevent cylinder rupture. However, when exposed to fire, cylinder PRDs and related components (e.g., vent lines) could fail in multiple ways. The bodies of four PRDs failed and separated while heated during the fire incident. Therefore, safety improvement considerations might include enhancing PRD material and functional integrity to withstand heat, investigating PRD vent lines when exposed to fire, and exploring additional safety features of cylinders without PRDs at high temperature.

The incident investigation results show that the PRDs' brass material of construction failed to withstand extreme heat, supporting the need to evaluate materials with superior heat resistance property. The PRDs were exposed to high-temperature conditions from leaks/fire caused by the initial release and deflagration, which continued to burn after the initial valve isolation. The cause of this failure could be a reduction of the tensile strength from high temperature, liquid metal embrittlement, damage from the initial deflagration, or a combination. It is worth noting that the brass materials used in the 7,500 psig (517 bar-g) PRDs are comparable to the PRDs used on standard industrial tube trailers, generally below 3,000 psig (207 bar-g). The use of brass in these lower-pressure systems for PRDs, valves, and connection components has been a common design approach for the last 80 years. These lower pressure PRDs have no recorded incidents in the HSP database, but limited anecdotes have indicated similar issues with brass components, at a relatively low frequency. The high combustion temperature of GH2 and the increased stresses at higher pressures may have played contributing roles in challenging the component fire endurance. For the reasons above, Air Products has since replaced all brass body PRDs with stainless steel PRDs on trailer module cylinders/piping with pressures greater than 3,000 psig (207 bar-g).[34]

Conducting fire tests on cylinder PRDs provides a means to assess PRDs' functional integrity while being exposed to heat, and has become a permit requirement by certain government agencies or standards organizations. For example, hydrogen vehicle fuel containers are required by ANSI HGV 2 to have PRDs to protect the container from rupture during fire exposure.[35] DOT Special Permit SP 14576 requires the cylinders to have PRDs capable of passing a bonfire test in which the cylinder exposed to fire is fully vented through a PRD.[36]

Furthermore, failures associated with vent lines might also offer opportunities for PRD safety improvement. In the Diamond Bar incident, a PRD with an underrated set point was responsible for the initiation of the fire, and an exacerbating factor was the deformation and displacement of the vent lines due to inadequate restraint of the thrust developed during venting.[37] Although this was not a contributing factor in the Santa Clara incident, because PRDs tend to have similar issues it might still be beneficial to improve PRD vent lines consensus standards and guidelines (e.g., CGA-S1.1, "Pressure Relief Standards") to mitigate the related potential safety risk.

As with cylinders with PRDs, high temperatures might create unique safety challenges for cylinders without PRDs. A number of fire or fire exposure tests have been conducted on cylinders without PRDs to assess their functional integrity. The results suggest considerable variability in these cylinders' capacity to withstand fire. A fire exposure test on a Type 3 cylinder pressurized to 5000 psi (345 bar) with hydrogen without a PRD or fire barriers resulted in cylinder catastrophic failure about 12 minutes after fire initiation.[38] A similar fire exposure test on a hydrogen pressurized Type 4 cylinder resulted in catastrophic cylinder failure in about six and a half minutes.[39] Other hydrogen cylinder fire exposure tests without PRDs, described in Ruban S. et al. (2012), showed the cylinder time-to-failure was approximately the same for localized fires as it was for full cylinder fire exposures.[40] Cylinders without PRDs may also depressurize through failure of peripheral connections.

Air Products performed a bonfire test on a comparable module with five of the Model ALT 1015 SCI vessels filled with 7,500 psig (517 bar-g) hydrogen. Fire exposure time before venting caused by failed instrument tubing was almost 29 minutes. All five cylinders vented down below 100 psig (6.9 bar-g) without rupture after more than 46 minutes of fire exposure.

---

[34] Information provided by Air Products, December 4, 2020.
[35] ANSI HGV 2-2014, Compressed hydrogen gas vehicle fuel containers, CSA Group.
[36] DOT-CFFC Basic Requirements For Fully Wrapped Carbon-Fiber Reinforced Aluminum Lined Cylinders, CFFC 10H, Fifth Revision, March 2007.
[37] https://h2tools.org/lessons/high-pressure-burst-disk-failure.
[38] Zalosh, R. "Blast Waves and Fireballs Generated by Hydrogen Fuel Tank Rupture During Fire Exposure," 5th Intl Seminar on Fire and Explosion Hazards, 2007; also Zalosh, R and Weyandt, N. SWRI report for Motor Vehicle Fire Research Institute, December 2006.
[39] Zalosh, R. and Weyandt, N., "Hydrogen Fuel Tank Fire Exposure Burst Test," SAE Paper No. 2005-01-1886, 2005
[40] Ruban, S. et al., "Fire risk on high-pressure full composite cylinders for automotive applications," International Journal of Hydrogen Energy, Volume 37, Issue 22, 2012, pages 17630-17638.

The module and cylinders successfully performed without failure.[41]

In summary, while PRDs might off some protective functions when a cylinder is exposed to high temperatures, there is a host of disadvantages that could undermine hydrogen safety and need to be addressed. Specifically, a major disadvantage of PRDs is inadvertent actuation due to the use of an incorrect PRD set pressure (as in the Diamond Bar incident) or fatigue, from moisture entry and subsequent ice formation (as occurred in some compressed natural gas (CNG) cylinder incidents), inappropriate component material (Transit Emeryville incident[42]), and faulty PRD installation. Another important disadvantage is the jet fire hazard associated with PRD actuation or damage, particularly if the vent line is deformed or broken. In that case, or if the module is on its side from a rollover accident, the jet flame can impinge on other equipment and modules, as happened in both the Santa Clara and Diamond Bar incidents. PRDs are also often oversized. Ruban, S. et al. (2012) maintained that the PRD jet fire hazard can be significantly reduced, without compromising cylinder integrity during fire exposure, by using a smaller orifice PRD. Another disadvantage of cylinder PRDs is that they are not necessarily effective when the cylinder is exposed to an impingement fire that is not close enough to the PRD for it to actuate.[43]

Because of potential failure modes of PRD type systems, the best means of protecting the vessels from fire exposure should be further investigated. A critical question currently being explored by industrial gas suppliers is the extent to which hydrogen cylinder rupture can be prevented during fire exposure without the installation of a cylinder PRD. One approach to this issue has been to provide thermal insulation on and around the cylinder to prevent direct fire exposure. A supplemental approach is to rely on the limited fire resistance of tubing fittings and valves so that the cylinder tubing will allow cylinder depressurization before cylinder failure. A fire exposure test on a standard 3AAX steel tube trailer in 2008 demonstrated how cylinder depressurization, through tube valve seat leakage, allowed three cylinders without PRDs to depressurize at about the same time as two cylinders equipped with PRDs.[44] It should be noted that some DOT Special Permits allow a configuration with no PRDs on hydrogen vessels. European regulations also do not require PRDs for trailer cylinders that carry hydrogen. As a matter of policy, whether or not to allow hydrogen trailer cylinders without PRDs needs to be examined in-depth with all potentially affected parties (including general public representatives) participating in the review and discussion of pertinent research, testing, and incident compilations.

Open Piping Flow Rate Curtailment/Reduction

The unrestrained flow of about 7,200 psi (496 bar) hydrogen through the disassembled piping occurred for about three seconds until the driver actuated the ES and/or the hydrogen fire melted the plastic pneumatic line serving the normally closed air-actuated valves. The short-duration uncontrolled hydrogen release allowed the formation of a flammable mixture in and around the trailer front module, and the ignition of that mixture caused the explosion within the front module. A device able to shut down or minimize gas flow in the event of an

[41] Information provided by Air Products, January 20, 2021.
[42] Harris, A. et al, "Investigation of the Hydrogen Release Incident at the AC Transit Emeryville Facility," SAND2012-5170, June 2012, Sandia National Laboratories, Albuquerque, NM.
[43] Zalosh, R., "CNG and Hydrogen Vehicle Fuel Tank Failure Incidents, Testing, and Preventive Measures," Paper: AIChE Loss Prevention Symposium, April 2008.
[44] DOT/PHH22 (MT), "Test Report Hydrogen Tube Trailer Engulfing Fire Test," July 2010.

open/broken pipe would be ideal. Two possible flow-limiting devices are excess flow valves and mechanical orifices.

Use of excess flow valves would require identifying a valve with the required specifications for high-pressure hydrogen applications and locating and orienting the valves to allow cylinder filling and prevent uncontrolled flow from each of the pressurized cylinders. The use of a mechanical orifice to limit flow rates from accidentally open piping would have to be reviewed from the perspective of possible constraints on filling flow rate restrictions during normal fills and deliveries. An engineering review of the feasibility and advantages and disadvantages of these and other possible flow reduction devices would help establish their potential applicability for scenarios similar to this incident.

Trailer Separation Distances and Fire Barriers

Both the spacing of the parked trailers and the dual-module arrangement on the CT-500 allowed flame impingement on adjacent modules. This would not have occurred if there had been much greater separation distance or a fire-resistant barrier between the loading stations as in some other facilities. The design intent of the modules was for the steel sides of the trailer modules to protect the cylinders and piping within the adjacent modules to prevent serious risk or damage.

NFPA 2 does not address separation distances between cylinder storage arrays contained within the same operating system. This includes trailer refilling and fill stanchion separation distances. Since DOT trailer regulations do not address non-transportation hazards, it is incumbent upon either NFPA 2 or CGA to provide appropriate guidance on this topic.

Water Spray Cooling of Hydrogen Storage Equipment

Water spray cooling of fire-exposed hydrogen gas and liquid storage equipment was an important factor in this incident to prevent the rupture of any cylinders and tanks. The water spray was provided by the Santa Clara Fire Department in the form of aerial master streams generated by fire department trucks located outside the facility fence. One of the trucks produced a measured water flow rate of 500 gpm (1,893 lpm).[45] Figure 17[46] shows the water stream application, which also helped to extinguish the secondary fires on the middle trailer.

[45] Santa Clara Fire Department Incident Report 2019-1904295-000, page 10.
[46] Retrieved from Twitter.com posting June 2019.

Figure 11. Elevated Aerial Water Streams

Although the Fire Department aerial stream application was effective, there was an understandable delay due to the time required for briefing fire department officers and making the hose connections and pump startup. If there had been provision for automatic water spray application triggered by heat detectors on and around the LH2 tank and tanker truck unloading station, the tank and cylinder module cooling could have been initiated sooner. NFPA 15 provides guidance on the design and installation of such systems.[47]

Another possible installed water spray delivery method is maneuverable monitors or cannons. These devices have been used in at least one other hydrogen dispensing facility. The technology of automatic water cannons for fire protection in large open spaces has been described by Xin et al (2014).[48]

One additional benefit of a fixed water spray or water cannon system for LH2 tank and tanker cooling is that the water spray could be designed or controlled to avoid spray impingement on the tank and tanker vent. This would eliminate the potential hazard of water entering the vent and freezing, with subsequent obstruction. There is no easy way to avoid this potential hazard with aerial water stream application from a remote location.

E. Conclusions

The uncontrolled release of high-pressure hydrogen at the Air Products Santa Clara transfill facility resulted from a miscommunication between the senior driver/trainer, who had disassembled the hydrogen supply piping to the trailer cylinders (in an attempt to make an unauthorized repair of a leaking valve) and the driver/trainee, who actuated the flow to the open pipe section when he inadvertently opened the trailer valves that had an ambiguous control label. A flammable hydrogen-air mixture rapidly formed in and around the trailer front module and an explosion occurred when the mixture was ignited. The open top of the module did not provide adequate venting to prevent the generation of deflagration pressures that subsequently damaged the module (including ejected front wall panels) and pressured

[47] NFPA 15-2017, “Standard for Water Spray Fixed Systems for Fire Protection,” National Fire Protection Association.
[48] Xin, Y. et al, “An Experimental Study of Automatic Water Cannon Systems for Fire Protection of Large Open Spaces,” Fire Technology, Volume 50, 2014, pages 233-248.

components such as PRDs and high-pressure seals.

The closing of the air-actuated valves (probably by an ES actuation) stopped the uncontrolled release of hydrogen after about three seconds, but additional hydrogen releases and jet fires had been initiated from thermal and mechanical damage caused by the initial explosion. These additional hydrogen jet fires caused actuation of PRDs and further thermal damage to PRDs and O-rings on trailer cylinders. Damaged PRDs allowed still other jet fires to impinge on the trailer cab and the adjacent trailers, causing subsequent diesel fuel fires and tire fires.

The Santa Clara Fire Department responded and ordered an evacuation radius of 500 yards (457 m), but relatively few people were affected because there were not many people working in the surrounding industrial premises at the time of the incident. The Fire Department successfully used aerial water spray application to cool the liquid hydrogen tank and surrounding equipment exposed to the residual fires.

Fortunately, there were only two minor injuries to Air Products' employees. The trailer module in which the deflagration occurred was damaged beyond repair, but the damage to the surrounding trailers and equipment was reparable. Following the incident and during the Santa Clara Fire Department investigation, Air Products curtailed delivery of hydrogen in the San Francisco Bay area for approximately four months as Air Products restored and modified its equipment and operations. During that time, Air Products implemented improved training of drivers.

The Pertinent Generic Issues in Section D of this report and the following Recommendations section identify possible improvements to relevant Air Products' equipment design and operation, and, by inference, other similar industrial applications.

The HSP review and analysis of the Air Products' and Santa Clara Fire Department's activities during and following the incident produced the following specific conclusions.

- Air Products and Santa Clara Fire Department personnel effectively dealt with a difficult situation and successfully gained control of the incident without incurring serious personnel injuries. The Santa Clara Fire Department responded quickly and effectively. One possible improvement might be a faster water deluge application, but that would probably entail Air Products installing a water spray system for either the Fire Department or automatic application as discussed in Recommendation 7 below.
- Air Products devoted time, resources, and personnel to conduct a thorough investigation and apply learnings via modifications to equipment and operations. Air Products is continuing discussions with industry partners and standards committee members on possible revisions to standards and regulations.
- Although Air Products' design and operations complied with pertinent portions of NFPA 2, CGA TB-25, and DOT-SP-14576, there is a need for further study and discussions with the NFPA and the DOT to address the recommendations and conclusions in this report concerning applicable standards and regulations. Specifically, for the NFPA, distance requirements between hydrogen storage containers should be considered. In this case, significantly increased separation distances between hydrogen storage modules might have prevented the involvement of the adjacent hydrogen vehicles in

the fire. For the DOT, trailer design issues such as materials of construction, the requirement for PRDs, and module construction requirements (e.g., use of additional bulkhead walls) could have reduced the severity of the incident.

- The HSP reviewers agree with the Air Products' causal analysis. The HSP agrees with some, but not necessarily all of their recommendations for improvement. The HSP was not provided with details of improvements to equipment and operations and would like to see further studies of some recommended changes to regulations (e.g., removing PRDs) and standards. Several additional HSP recommendations are described below.
- The HSP concludes the potential need to improve the design of MEGC cylinder modules based on this Santa Clara incident and the significant hydrogen incident involving an MEGC trailer in February 2018, at Diamond Bar, CA.[49] It is not in the scope of this report to evaluate the Diamond Bar incident or the related NTSB recommendations; however, the occurrence of two major incidents involving hydrogen MEGC trailers demonstrates the potential need for improved design requirements for MEGC cylinder modules to enhance safety.

F. Recommendations

The HSP review of this incident has identified the following hydrogen equipment and operational recommendations to improve the safety of the hydrogen industry.

Code and General Industry Improvements

1. NFPA should consider providing additional guidance on GH2 system repairs in NFPA 2-2020 section 7.1.10 as described within Attachment A of this report. Considerations should also include requirements for training all personnel with responsibilities on mobile and stationary hydrogen systems.
2. CGA and other standards organizations (e.g., CSA Group) should explore improvements in their standards for PRDs intended to actuate and relieve cylinder pressures during fire exposure. Improvements are needed to specify direct fire exposure requirements and vent line thrust restraint requirements.
3. DOT and CGA should conduct an in-depth examination on fire protection of high-pressure hydrogen cylinders and the requirements for PRDs. Transportation regulations allow cylinders without PRDs under certain conditions and should be part of the evaluation. All potentially affected parties, including the fire service/protection community, should participate in the review and discussion of pertinent research, testing, and incident compilations. This discussion would be facilitated by a comprehensive quantitative risk assessment comparing risks of cylinder use with and without PRDs as well as consideration of other fire protection measures.
4. NFPA should consider including recommendations (or requirements) for hydrogen process and transfer controls to implement best practices (such as those described in guidelines and standards cited in this report) in NFPA 2 for clarity and operator understanding. A proposal to this effect is under review for inclusion in the next edition of NFPA 2.

[49] National Transportation Safety Board Incident Report, NTSB/HZM-19/02, October 10, 2019.

5. The fire resistance and the exacerbated explosion hazard associated with walls on hydrogen trailers should be explained in a revision to CGA-C-29, supported by a CGA or DOT/PHMSA sponsored risk assessment. The risk assessment would evaluate the tradeoff of additional walls or bulkheads and the potential increased explosion hazard. Walls can trap hydrogen but walls can also exclude hydrogen accumulating from different sources.
6. The use of flow-limiting devices for inadvertently opened piping during hydrogen transfers and refueling should be encouraged in NFPA 2 and CGA C-29. Toward this end, it would be helpful for DOE, PHMSA, or hydrogen safety organizations such as the Center for Hydrogen Safety to conduct feasibility studies for the application of specific types of devices, e.g. orifices and excess flow valves.
7. Guidance on improved fire protection for trailer/tanker transfill stations should be provided in NFPA 2. This guidance could include explicit transfill station separation requirements between gaseous cylinder module trailers, liquid hydrogen trailers, and gaseous hydrogen trailers, and/or recommendations on installed water spray cooling provisions via deluge nozzles or water cannons/monitors to prevent fire spread and cylinder/tanker flame exposure heating. The implications of these improvements should be discussed with local fire departments so that pre-fire planning and training can be revised accordingly.

Other Improvements

8. The preceding recommendations on improved guidance for trailer piping repairs, hydrogen transfer control systems, flow-limiting devices, trailer fire resistance, explosion hazard mitigation, and transfer station installed fire protection should be incorporated into h2tools.org Best Practices recommendations. These recommendations should cite both this report and the previous HSP report on mobile applications.[50]
9. The CEC could encourage continuous safety improvements by promoting communication of hydrogen incident reports/data and evaluations to pertinent state regulators, emergency responders, hydrogen industry partners, and other stakeholders.

G. References

1. Air Products Incident Report, "Review of Santa Clara Incident," PowerPoint® presentation to Center for Hydrogen Safety - October 14, 2019, updated and provided May 14, 2020.
2. API RP 1165, "Recommended Practice for Pipeline SCADA Displays," American Petroleum Institute, 1st edition, 2007, Washington DC.
3. ASM Consortium, "Effective Console Operator HMI Design," Abnormal Situation Management Consortium, 2nd edition; June 2015.

[50] https://h2tools.org/sites/default/files/Safety_of_Mobile_Hydrogen_and_Fuel_Cell_Technology_Applications-Oct_2019.pdf.

4. California Air Resources Board, “2020 Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development,” September 2020.
5. Center for Hydrogen Safety Incident Record Sheet, “H2 Tube Truck Deflagration and Fire,” May 5, 2020, AIChE Center for Hydrogen Safety, New York, NY.
6. Chemical Safety Board Report, “Formosa Plastics Vinyl Chloride Explosion,” 2007, United States Chemical Safety Board, Washington DC.
7. Crowl, D.A., “Understanding Explosions,” 2003, Wiley-AIChE, New York, NY.
8. DOT/PHH22 (MT), “Test Report Hydrogen Tube Trailer Engulfing Fire Test,” July 28, 2010, United States Department of Transportation, Washington DC.
9. Harris, A. et al, “Investigation of the Hydrogen Release Incident at the AC Transit Emeryville Facility,” SAND2012-5170, June 2012, Sandia National Laboratories, Albuquerque, NM.
10. Lee, D., “Safe Operations Using Advanced Operator Graphics,” Article: *Process Safety Progress*, Volume 39, Issue 3, February 2020.
11. National Transportation Safety Board Incident Report, NTSB/HZM-19/02, October 10, 2019, United States National Transportation Safety Board, Washington DC.
12. NFPA 15-2017, “Standard for Water Spray Fixed Systems for Fire Protection,” 2017, National Fire Protection Association.
13. Ruban, S. et al., “Fire risk on high-pressure full composite cylinders for automotive applications,” Article: *International Journal of Hydrogen Energy*, Volume 37, Issue 22, November 2012.
14. Santa Clara Fire Department Incident Report, 2019-1904295-000, printed on 2/11/2020, Santa Clara Fire Department, Santa Clara, CA (redacted version).
15. Santa Clara Fire Department Report, Case # 19-4295, August 19, 2020, Santa Clara Fire Department, Santa Clara, CA (redacted version).
16. Xin, Y. et al., “An Experimental Study of Automatic Water Cannon Systems for Fire Protection of Large Open Spaces,” Article: *Fire Technology*, Volume 50, March 2014.
17. Zalosh, R., “Blast Waves and Fireballs Generated by Hydrogen Fuel Tank Rupture During Fire Exposure,” 5th Intl Seminar on Fire and Explosion Hazards, 2007.
18. Zalosh, R. and Weyandt, N. “Blast Waves and Fireballs Generated by Hydrogen Fuel Tank Rupture During Fire Exposure,” SWRI report for Motor Vehicle Fire Research Institute, December 2006.
19. Zalosh, R., “CNG and Hydrogen Vehicle Fuel Tank Failure Incidents, Testing, and Preventive Measures,” Paper: *AIChE Loss Prevention Symposium*, April 2008.

Attachment A

Guidelines and Practices for Repairing Leaks in Hydrogen Systems

All hydrogen-related operations, including emergency response and maintenance should be conducted using written procedures that include essential safety steps. Personnel responsible for system operations should be trained at least in the minimal actions necessary to maintain the integrity of the hydrogen system should a leak occur, even though they may not be qualified to repair the leak. These procedures include initial preparation of the system such as shutting down and locking out of the system, troubleshooting the system, system repair, and system restart.

Initial System Preparation

The first step that should be taken is to immediately isolate the leak point from the source by shutting off the hydrogen (double-isolation is preferred) and then venting the hydrogen through a normal vent path. People should be moved to a safety zone away from the hydrogen system until the hydrogen has been fully vented. During this step, ignition sources must not be introduced into the operation and one should never intentionally ignite a hydrogen leak since the temperature effects on the system could increase the size of the leak resulting in an even greater hazard. When the system has been fully vented and isolated from the source, then the system should be purged with an inert gas, typically either helium or nitrogen. Once the system has been purged then steps can be taken to troubleshoot and repair the system.

Troubleshooting the System

In many cases, identifying the source of the leak may be obvious; however, there are cases where the leak or leak rate may be dependent on system dynamics or operational parameters and require troubleshooting. Leak checks should always be conducted using an inert gas after purging the lines. Nitrogen works very well for gross leaks, but helium or other inert gases may be required for small leaks or leaks in cryogenic systems. Purging includes venting any residual hydrogen prior to filling with inert gas. Leak checks should be accomplished according to a written procedure and should start at low pressure and then increase the pressure stepwise until the leak has been adequately identified. Use of leak detection aids, such as soap solutions or inert gas detectors, may be used if allowed by the system owner.

System Repair

Repair of the system should be accomplished according to a written procedure. If the portion of the system to be repaired cannot be double isolated from the source, then the source should be fully vented and purged with an inert gas before initiating the repair. During the repair of the system, all valves should be in their fail-safe position and remotely operated valves are isolated from their power source (pneumatic or electrical). Following the repair, a leak check of the repaired portion of the system should be conducted with an inert gas.

System Restart

Restarting the system should be accomplished according to a written procedure. If the above steps have been followed the system should contain inert gas. If not, then it is important to purge any air out of the system prior to the introduction of hydrogen. If hydrogen purity is a concern, then series of pressurization and vent cycles can be accomplished.

The **Hydrogen Safety Panel** (https://h2tools.org) was formed in 2003 by the U.S. Department of Energy to help develop and implement practices and procedures that would ensure safety in the operation, handling, and use of hydrogen and hydrogen systems. The primary objective is to enable the safe and timely transition to hydrogen and fuel cell technologies. This is accomplished by:

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

The 17-member panel has over 500 years of combined experience and is comprised of a cross-section of expertise from the commercial, industrial, government, and academic sectors. Panel members participate in a variety of standards development organizations including the ASME, CSA, ISO, NFPA, SAE, and UL. Panel members also contribute to peer-reviewed literature and trade magazines on hydrogen safety and present at national and international forums. The Panel has reviewed over 389 projects covering vehicle fueling stations, auxiliary power, backup power, combined heat and power, industrial truck fueling, portable power, mobile applications, and R&D activities.

If you have an interest in utilizing the expertise of the Panel, contact the program manager by email at **hsp@h2tools.org**.

HYDROGEN
Safety Panel