HYDROGEN
Safety Panel

Hydrogen Incident Examples

Select Summaries of Hydrogen Incidents from the H2tools.org Lessons Learned Database

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Document Purpose and Navigation

The Hydrogen Safety Panel was established by the U.S. Department of Energy (DOE) to provide independent safety reviews and guidance to contractors in the DOE Hydrogen and Fuel Cells Program. In September 2017, the panel set up a task group to compile select hydrogen incidents from the H2Tools.org Lessons Learned database (https://h2tools.org/lessons) in a publication form for written reference, that are most pertinent to various types of DOE contractor projects. This report is the result of the task group's work.

This document does not amplify nor include the complete information in the web database, though text may be edited; H2Tools.org remains the most current listing. This publication is another tool for DOE contractors and others to use as an aid in developing safety plans that include identification of potential hydrogen incident scenarios and appropriate prevention and mitigation measures.

The listing is intended to enable readers to find incidents in a document form that are most pertinent to their materials, equipment, and activities. Accessing the document as an electronic version enables the full usage of the embedded document links and direct linked access to the source information in the H2Tools.org database. Table 1 can be used to find incident descriptions in the following hyperlinked categories. Some incidents appear in multiple categories.

Table 1. Incident Category Links

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Readers can use Table 2 to look up incidents by involved equipment, and causes/issues. Incidents are labeled in Table 2 by the dates of occurrence, which are hyperlinked to the actual incident abbreviated descriptions. Incident labels highlighted in yellow denote an explosion incident, while red highlighted labels denote a fire incident. The absence of any color shading indicates that the incident did not result in an ignition. Such incidents include unignited releases and near-misses.

Table 2. Hydrogen Incident Summaries by Equipment and Primary Cause/Issue

Equipment / Cause	Equipment Design or Selection	Component Failure	Operational Error	Installation or Maintenance	Inadequate Gas or Flame Detection	Emergency Shutdown or Response	Other or Unknown
Hydrogen Gas Metal Cylinder or Regulator		3/13/2012 4/30/1995 2/6/2013	4/26/2010	12/31/1969			3/17/1999 11/1/2001 12/23/2003
Piping/Valves	4/4/2002 2/6/2008 5/11/1999	4/20/1987 11/4/1997 12/31/1969 8/19/1986 7/27/1991 12/19/2004 2/6/2008 10/3/2008 4/5/2006 5/1/2007 9/19/2007 10/31/1980	2/7/2009	1/24/1999 2/24/2006 6/8/1998 12/31/1969 2/7/2009	9/1/1992 10/31/1980	10/3/2008	
Tubing/Fittings/Hose		9/23/1999 8/2/2004 8/6/2008 9/19/2007	1/1/1982	9/30/2004 10/7/2005		10/7/2005	
Compressor		10/5/2009 6/10/2007 8/21/2008 1/15/2019			10-5-2009	8/21/2008	
Liquid Hydrogen Tank or Delivery Truck	4/27/1989	12/19/2004 1/19/2009	8/6/2004	12/31/1969		1/1/1974	12/17/2004
Pressure Relief Device	7/25/2013 5/4/2012	1/15/2002 1/08/2007	12/31/1969				

Table 2. Hydrogen Incident Summaries by Equipment and Primary Cause/Issue

Equipment / Cause	Equipment Design or Selection	Component Failure	Operational Error	Installation or Maintenance	Inadequate Gas or Flame Detection	Emergency Shutdown or Response	Other or Unknown
Instrument	1/15/2019	3/17/1999 12/31/1969 2/6/2013					
Hydrogen Generation Equipment	7/27/1999			10/23/2001			
Vehicle or Lift Truck		7/21/2011					2/8/2011 12/9/2010
Fuel Dispenser		8/2/2004 5/1/2007 6/11/2007 9/19/2007		2/24/2006 1/22/2009			
Fuel Cell Stack							5/3/2004 12/9/2010 2/8/2011
Hydrogen Cooled Generator				12/31/1969 2/7/2009			
Other (floor drain, lab anaerobic chamber, heated glassware, test chamber, gaseous hydrogen composite cylinder, delivery truck)		11/14/1994 7/21/2011	7/27/1999 6/28/2010 8/21/2008	12/31/1969 3/22/2018			6/10/2019

Color Key
xx/xx/xxxx = no ignition
xx/xx/xxxx = explosion
xx/xx/xxxx = fire

A. Pressure Relief Device Incidents

A-1. Jul 25, 2013: Burst Disk Actuation

The temporary manual valve selected for testing of an automated gas environment system had an integral burst disk rated at 1900 psi +/- 100 psi. This is an unusual valve configuration, typically used for cryogenic service. The valve was an on-hand spare, but the documentation of the burst disk feature was not available. It was not recognized that the burst disk was an integral part of the valve at the time of the failure. The pressure in the small, ultra-high-purity hydrogen bottle was approximately 2015 psi. The regulator downstream of the gas bottle is rated for 3000 psi input, so it could accommodate the bottle's supply pressure. The direct cause of this event was the improper selection of the manual valve with integral burst disk rated below the bottle supply pressure for this temporary testing configuration. The manual valve was needed to successfully test the system; however, the fact that this particular valve could not accommodate the full cylinder pressure was overlooked.

No ignition, no injuries. The valve was in a ventilated, hazardous storage-type, gas cabinet.

https://h2tools.org/lessons/unexpected-burst-disk-rupture-during-testing-activity

A-2. Jan 15, 2002: Burst Disc Actuation

Six hydrogen tubes, each about 23 feet in length and having a diameter of 24 inches, were installed at the northwest corner of the turbine house. The uncontrolled release of hydrogen occurred as a result of the rupture of the No. 6 hydrogen storage tube's burst disc. This disc failed in response to being overloaded by mechanical stresses that developed as water expanded and formed ice while in direct contact with the burst disc. It was the degraded condition of the vent cap (defective equipment) that enabled water to access the burst disc. The hydrogen supplier had previously found ice in a vent pipe, and was aware that the vent caps were cracked (the vent cap cracks were painted over).

The burst disc fitted to the No. 6 hydrogen storage tube had ruptured, allowing 14,500 ft^3 of hydrogen stored in the two reserve tubes to release into the atmosphere. This burst disc was rated at 3300 to 3700 psi. However, the tank pressure at the time of the failure was only 2100 psi. A pressure relief valve, set at 2450 psi, was available to respond to any over-pressure condition. The only known mechanism by which the burst disc could have been loaded in this manner is by the expansion of water as it freezes to ice while in direct contact with the burst disc. Temperature profiles are consistent with the formation of ice. Tank temperatures were recorded to be 0 °C (32 °F) for 48 hours preceding the incident, and ambient temperatures recorded at a nearby weather station dropped to -6 °C (21 °F) on the evening preceding the incident.

The released hydrogen was ignited, causing an explosion that damaged a wall near the tube storage area.

https://h2tools.org/lessons/hydrogen-explosion-due-inadequate-maintenance

A-3. Jan 8, 2007: Rupture Disk Failure during Hydrogen Delivery

An explosion at a coal-fired power plant killed one person and injured 10 others. The blast killed the delivery truck driver who was unloading compressed hydrogen gas. Evidence pointed to the premature failure of a pressure relief device rupture disk, which had earlier been repaired by the vendor 6 months prior to the explosion.

https://h2tools.org/lessons/hydrogen-explosion-coal-fired-power-plant

A-4. Dec 31, 1969: Incorrect Relief Valve Set Point Leads to Explosion

During a standard testing procedure, a 3000-psig relief valve actuated at normal line pressure, releasing gaseous hydrogen. The gaseous hydrogen combined with air, resulting in an explosion which damaged the test facility.

The relief valve was improperly set to open at line pressure, and the inspection was inadequate in that it didn't identify this error. A contributing cause was poor design of the venting system, which was installed in a horizontal position, causing inadequate venting and buildup of static electricity.

https://h2tools.org/lessons/incorrect-relief-valve-set-point-leads-explosion

B. Hydrogen Cylinder Incidents

B-1. Mar 13, 2012: Leaking Hydrogen Cylinder

An alarm sounded at a recently inaugurated hydrogen fueling station in a major metropolitan area. Of the 120 high-pressure hydrogen cylinders located on the roof of the fueling station, one failed in service. Gaseous hydrogen was leaking from a screw fitting of the cylinder, but the hydrogen was not ignited. Three hydrogen gas sensors detected the leakage and triggered an alarm that resulted in an immediate emergency shutdown, isolating the leaking high-pressure cylinder bank from the other three banks and notifying the local fire department. The maximum content of the leaking cylinder bank was determined to be ~ 70 kg of hydrogen at 800 bar. The leak rate at the high-pressure storage bank was ~5 kg/hr.

After 2.5 hours, the hydrogen supplier's technician manually opened a bypass line to let the hydrogen escape through a vent line. This action was taken from the ground-floor control room, distant from the general hazard. About 4 hours later, the leaking high-pressure bank was essentially empty, with a pressure of around 1 bar. The cylinder with the failed Teflon-sealed screw fitting was sealed with a plug with the intention of never using it again.

There was no ignition.

https://h2tools.org/lessons/hydrogen-cylinder-leak-fueling-station

B-2. Mar 17, 1999: Over Pressurized Cylinder at Test Vault

A 2000-psia-rated gas cylinder (nominal size 10 inches x 1½ inches) was being filled with hydrogen to a target pressure of 1500 psia. The cylinder suffered a failure at an indicated pressure of 1500 psia during filling. Investigation of the failure subsequently revealed that a faulty digital readout had allowed the cylinder to be over-pressurized. There were no safety consequences due to the failure and no damage to the facility or equipment. The cylinder was being filled in a test vault that was specially designed for the high-pressure burst testing of pressure vessels and components. Investigations revealed that the pressure transducer was faulty and the actual pressure could have been more than five times the indicated pressure. Although the high-pressure manifold has rupture-disk protection, the rupture disk was not adequately sized to provide protection for this type of cylinder.

There was no ignition.

https://h2tools.org/lessons/concerns-related-hydrogen-bottle-rupture

B-3. Nov 1, 2001: Incorrect Flammable Gas Cylinder

A laboratory research technician entered a laboratory to begin preparing samples that were to ultimately be purged in an anaerobic chamber (glove box) located in that room. As the technician walked into the lab, she looked at the chamber to see if it was adequately inflated. This chamber is equipped with a gas concentration meter, capable of simultaneously displaying the oxygen and hydrogen concentrations of the chamber atmosphere. Under normal operating conditions, the anaerobic atmosphere inside the chamber is comprised of 0% oxygen, approximately 2-3% hydrogen, and the remaining 97-98%, nitrogen. Under normal operating conditions, the hydrogen concentration inside the chamber is less than the lower explosive limit of hydrogen to prevent an explosion in case air or oxygen were ever inadvertently introduced into the chamber. When the technician observed the meter's digital readouts, the oxygen concentration in the chamber was still 0% but the hydrogen concentration was at 43%. (The explosive range of hydrogen in air is 4-75%.) An alarm light was also flashing on the meter, but an audible alarm was not heard. At first, the technician turned the meter off and back on again, believing something was wrong with the meter.

She then checked the placarding of the compressed gas cylinders that were hooked up to the chamber manifold system and discovered that one of the cylinders was a mixture of 95% hydrogen and 5% nitrogen, instead of the 5% hydrogen and 95% nitrogen cylinder that was supposed to be there, and immediately summoned assistance. The face of the manifold onto which the erroneous cylinder was connected is labeled as "5% H2/95% N2". The cylinder was last changed out 30 days prior to the incident, by the facility's maintenance personnel. An equipment user log indicates that the chamber had been used a couple of times since the cylinder change-out. In addition to the manifold labeling, there are also job aid instructions posted in the work area pertaining to the operation of the chamber by the laboratory researchers.

Evidence showed that the research staff actually requested a mixture 5% hydrogen and 95% nitrogen through the onsite acquisition system, but the vendor failed to supply the customer with the requested mixture; instead, a mixture of 95% hydrogen and 5% nitrogen was supplied. The investigation team determined that this mixture would have never been in the facility (for maintenance staff and end users to select from) had the vendor error not occurred.

https://h2tools.org/lessons/incorrect-flammable-gas-cylinder-attached-anaerobic-chamber

B-4. Apr 30, 1995: Ruptured CO_2 Cylinder Causes Hydrogen Fire

A 5-pound carbon dioxide cylinder being stored in a compressed gas storage cage at a power plant failed catastrophically and became a missile. The cylinder destroyed the storage cage, then struck one of six stationary hydrogen storage cylinders used as emergency make-up for the hydrogen supply system. One of the hydrogen cylinders was broken away from its mounts and moved 10 feet from its original location. The loss of this cylinder severed the manifold tubing, creating a leak path to the atmosphere for the remaining five hydrogen cylinders. The leaking hydrogen gas apparently self-ignited, engulfing the immediate area. The site fire brigade responded and used hose lines from a distance to provide cooling until the hydrogen supply was consumed. The fire was out within 7 minutes, and no off-site fire assistance was needed. All normal supplies of hydrogen were isolated and a reflash watch was established until all damaged hydrogen cylinders were removed to an isolated "safe zone." Damage was restricted to the carbon dioxide cylinder, the six hydrogen cylinders, associated piping (which showed flame impingement), and the compressed gas storage cage.

Preliminary results indicated that the carbon dioxide cylinder rupture was caused by tensile strength overload from over-pressurization. The safety disc assembly was dissembled and it was found to contain three safety discs where there should have only been one. Installation of multiple safety discs probably resulted in failure to relieve the overpressure condition prior to cylinder rupture.

https://h2tools.org/lessons/ruptured-co2-cylinder-causes-hydrogen-fire

B-5. Apr 26, 2010: Release from Cylinder when Removing Cap

The cap on a full cylinder of hydrogen was difficult to remove. A wrench was applied to turn the cap. When the cap was turned, a part of the wrench contacted the valve and opened it. Since the cap was still on the cylinder, the valve could not be closed. The area was evacuated until the cylinder had emptied.

https://h2tools.org/lessons/release-cylinder-when-removing-cap

B-6. Dec 23, 2003: Hydrogen Cylinder Transport Accident Results in Explosion

A hydrogen leak and subsequent explosion occurred when tie-downs on a hydrogen transport trailer securing hydrogen cylinder packages failed. The tie-down failure caused the hydrogen cylinder packages to fall off the trailer and eject some cylinders onto the roadway. The cause of the accident is unknown, but it appears to be unrelated to hydrogen (i.e., likely tie-down strap weakness or error in properly securing tie-downs). The cylinders contained compressed hydrogen gas at 200 bar (2900 psi). The accident caused some hydrogen cylinders to leak and the associated cylinder package plumbing systems were breached. A spark or other local heat source (e.g., from a nearby vehicle motor) ignited the leaking hydrogen and caused a deflagration/explosion that damaged a car following the trailer and broke windows in a nearby house. Emergency crews arrived at the accident scene and cooled the hydrogen cylinders with a water stream to reduce their temperature.

No injuries resulted from this accident.

https://h2tools.org/lessons/hydrogen-cylinder-transport-accident-results-explosion

B-7. Feb 6, 2013: Hydrogen Gas Regulator Failure

A single-stage regulator "failed" while flowing hydrogen gas from a standard 200 ft^3 gas bottle. The regulator had functioned properly prior to the event through several on-off cycles. During the event, a solenoid valve was opened to allow hydrogen to flow, when a rather loud noise was noted, and gas began flowing out of the pressure relief valve on the side of the regulator. It was noted that the low-pressure gauge on the regulator was "pegged" at the high side (200 psi). The valve on the bottle was shut off, and hydrogen flow was immediately stopped. Hydrogen flowing out of the relief valve did not ignite. With the bottle shut off, the regulator was removed and replaced with another regulator of the same type, and activities continued.

The failed regulator was later taken apart to try to determine the cause of failure. All the internal parts appeared to be intact except for a small elastomeric ring that seals the internal nozzle to the seat assembly. This elastomeric ring was deformed and had become lodged in the nozzle orifice, preventing the seat assembly from properly seating and allowing high-pressure hydrogen to continuously flow into the low-pressure side of the regulator. The regulator has a pressure relief valve as protection and it operated properly, relieving the pressure in the system. Fortunately, nothing downstream of the regulator was damaged. It is not known what led to the failure of the elastomer ring.

The manufacturer was contacted, and the event was described and observations discussed. Damage to the elastomeric ring on that valve stem, thus limiting its ability to seal, is a rare event. The ring material was specifically selected for hydrogen/methane service and subjected to tens of thousands of open-close cycles. The manufacturer doesn't require a periodic maintenance program for these regulators but occasional replacement of the elastomer seal and O-ring on the outer part of the regulator body is recommended.

Pressure relief device discharges need to be routed to a safe location. In the event of a pressure relieving event, it is important for the flow to be directed away from personnel, preferably such that the shut-off valve can be accessed safely.

https://h2tools.org/lessons/hydrogen-gas-regulator-failure

C. Piping Incidents

C-1. Sep 30, 2004: Laboratory Compression Fitting Installation

While research staff were working in a laboratory, a staff member opened the primary valve to a 0.2-inch (1500 psi) hydrogen gas line connected to an instrument supply manifold. When the valve was opened, the hydrogen gas line failed at a fitting on the switching manifold, releasing a small amount of hydrogen gas. The staff member closed the valve immediately, then inspected the gas line and found the front ferrule (of the compression-style fitting) to be missing. There were no injuries or damage to equipment.

Start-up testing was considered less than adequate because it would have normally caught this type of leakage before introduction of hydrogen. The person installing the compressed gas line into a compression style fitting tee failed to include the front ferrule. Later, when the line was pressurized at 1500 psi, the fitting and line separated. It was learned from the research staff that approximately 1 month earlier, a similar condition (front ferrule missing from a fitting) was found while performing a modification to a similar manifold.

https://h2tools.org/lessons/concern-identified-regarding-installation-and-commissioning-compressed-gas-systems

C-2. Apr 30, 1995: Severed Hydrogen Tubing at Power Plant

A 5-pound carbon dioxide cylinder being stored in a compressed gas storage cage at a power plant failed catastrophically and became a missile. The cylinder destroyed the storage cage, then struck one of six stationary hydrogen storage cylinders used as emergency make-up for the hydrogen supply system. One of the hydrogen cylinders was broken away from its mounts and moved 10 feet from its original location. The loss of this cylinder severed the manifold tubing, creating a leak path to the atmosphere for the remaining five hydrogen cylinders. The leaking hydrogen gas apparently self-ignited, engulfing the immediate area. The site fire brigade responded and used hose lines from a distance to provide cooling until the hydrogen supply was consumed. The fire was out within 7 minutes, and no off-site fire assistance was needed.

https://h2tools.org/lessons/ruptured-co2-cylinder-causes-hydrogen-fire

C-3. Nov 4, 1997: Check Valve Shaft Blow-Out

Several workers sustained minor injuries and millions of dollars’ worth of equipment was damaged by an explosion after a shaft blew out of a check valve. The valve failure rapidly released a large vapor cloud of hydrogen and hydrocarbon gases, which subsequently ignited. The valve had a shaft or stem piece which penetrated the pressure boundary and ended inside the pressurized portion of the valve. When this penetration happened, an unbalanced axial thrust on the shaft occurred, which would tend to force it, if unconstrained, out of the valve. In this case, the shaft was retained by a dowel pin, which also transmitted torque from the shaft to the disk. The dowel pin was made from hardened steel and may have been subjected to hydrogen embrittlement. The valve repeatedly slammed shut with great force during compressor trips and shutdowns. Such repeated loads may have caused propagation of cracks in the dowel pin. System pressure at the failure point was approximately 300 psig.

Most modern valve designs incorporate features that reduce or eliminate the possibility of shaft blow-out. However, certain types of check and butterfly valves can undergo shaft-disk separation and fail catastrophically or "blow-out," causing toxic and/or flammable gas releases, fires, and vapor cloud explosions. Such failures can occur even when the valves are operated within their design limits of pressure and temperature.

Several design and operational factors may have contributed to this failure. The valve contains potential internal failure points, such as shaft dowel-pins, keys, or bolts such that shaft-disk separation can occur inside the valve. The dimensions and manufacturing tolerances of critical internal parts (e.g., keys, keyways, pins, and pin holes) as designed or as fabricated cause these parts to carry high loads. Two-piece valve stems ("stub shafts") that penetrate the pressure boundary (resulting in a differential pressure and unbalanced axial thrust as described above), single-diameter valve shafts (i.e., shafts with internal diameters smaller than the diameters of their packing glands), or shafts without thrust-retaining devices (such as split-ring annular thrust retainers) are susceptible to blow-out. These valves are subject to high cyclic loads. Valves used in hydrogen-rich or hydrogen sulfide-containing environments may be more susceptible to blow-out due to hydrogen embrittlement of critical internal components, particularly if these are made from hardened steel (as was the dowel pin in this incident).

https://h2tools.org/lessons/check-valve-shaft-blow-out-due-hydrogen-embrittlement

C-4. Dec 31, 1969: Hole Rubbed in Hydrogen Piping

During inspection of a hydrogen make-up compressor, it was discovered that a 1/4-inch stainless steel screw and nut that mounted a temperature gauge to a stainless-steel pipe was resting against the side of a schedule 160 high-pressure hydrogen pipe. Constant vibration of the process equipment had caused the bolt to rub a hole in the high-pressure suction piping, resulting in the release of make-up hydrogen. The pipe was out of sight, and the problem was identified by an employee who heard the whistling sound of escaping hydrogen. The compressor was taken offline and depressurized.

https://h2tools.org/lessons/hydrogen-make-compressor-piping-hole

C-5. Apr 20, 1987: Hydrogen Leak in Auxiliary Building

A portable survey instrument was used to detect hydrogen in the auxiliary building at 20% to 30% of the lower flammability limit (LFL) for hydrogen. A level of about 30% of LFL corresponds to about 1.2% hydrogen by volume.

When hydrogen was discovered in the auxiliary building, the operator isolated the cryogenic hydrogen skid outside the turbine building and soon located the source of the leak from the packing on a globe valve, in a small line to the volume-control tank. The operator opened doors that quickly caused the hydrogen to dissipate. The globe valve was of a conventional design and had no special packing. The globe valve was in a vertical pipe chase where little ventilation was present because of ongoing heating, ventilation, and air conditioning (HVAC) testing.

The following five lessons may be concluded here: (1) proper in-plant communications during events, (2) proper valve application for use with hydrogen, (3) excess flow check valve set point, (4) HVAC maintenance and flow testing, and (5) hydrogen line routing. The operator is examining ways to improve communications in the plant during events and the training of personnel in reading portable instruments.

https://h2tools.org/lessons/hydrogen-leak-auxiliary-building

C-6. Aug 19, 1986: Failure of Stainless-Steel Valves due to Hydrogen Embrittlement

Difficulties were experienced with two solenoid-operated globe valves in a charging system. When shut, the valves could not be reopened without securing all charging pumps. During a refueling outage, the two valves were disassembled and examined to determine the cause of the malfunction. It was found that the springs of the disc guide assembly in both valves had undergone complete catastrophic failure. The springs, which initially had 25 coils, were found in sections of only 1-2 coils. Metallurgical analysis of the failed springs attributed the probable cause of failure to hydrogen embrittlement. The springs are made of 17-7 PH stainless steel.

Discussion with the valve manufacturer revealed that similar failures occurred on three previous occasions. These spring failures were also attributed to hydrogen embrittlement.

https://h2tools.org/lessons/failure-stainless-steel-valves-due-hydrogen-embrittlement

C-7. Jan 24, 1999: Fire at a Hydrogen Storage Facility

A fire occurred in a hydrogen storage facility. The fire was reported by an employee who saw the fire start after he had aligned valves at the hydrogen storage facility in preparation for putting the hydrogen injection system into service. The employee escaped injury because he was wearing fire-retardant protective clothing and was able to quickly scale a 7-foot-high fence enclosing the hydrogen area. The local fire brigade was dispatched, and offsite firefighting assistance was requested. Upon reaching the scene, the local fire department reported seeing a large hydrogen-fueled fire near the hydrogen tube trailer unit. The heat of the fire potentially endangered the nearby hydrogen storage tanks. The onsite fire department, with offsite firefighting support, fought the fire until the hydrogen supply was exhausted, and the fire was declared out approximately 6 hours later.

The company identified the lack of effective maintenance as a root cause of the hydrogen fire event at the facility. Three valves failed, starting the fire. According to the root cause evaluation, all the failures were due to an inadequate preventive maintenance program by the hydrogen system vendor and inadequate system monitoring and management oversight by the facility.

https://h2tools.org/lessons/hydrogen-fire-hydrogen-storage-facility

C-8. Jul 27, 1991: Hydrogen Excess Flow Valve Fails to Close Completely

While refilling the hydrogen system after an outage caused by a power failure, the excess flow valve located at the hydrogen tank tripped but did not fully shut.

The large valve is equipped with a small bypass valve so that the valve can be pressurized on both sides as is required before the valve can be reset. The O-ring which makes this small valve gas tight was deformed and improperly seated, thus allowing gas to flow to each side of the large valve. This permitted the valve to trip normally, but not to seat properly.

The valve was returned to the manufacturer, rebuilt, tested, and re-installed in the system. Testing on re-installation indicates that the valve is working properly.

https://h2tools.org/lessons/hydrogen-excess-flow-valve-fails-close-completely

C-9. Feb 6, 2008: Ball Valve Fails to Open Due to Valve Stem Failure

A safety research laboratory experienced two similar air-actuated ball valve failures in a 6-month period while performing hydrogen release experiments. The hydrogen release system contains several air-actuated ball valves which are sequenced by a programmable logic controller (PLC). During an experimental release sequence, a PLC valve command failed to open the valve even though the PLC signal indicated the valve had opened. On further investigation, the researchers discovered that the valve actuator and valve stem were found to be moving correctly, but the valve was not opening. The system was depressurized and purged with nitrogen, and the valve was removed for inspection. Inspection required dismantling the valve, and in both incidents a sheared valve stem was found. The valve stem failures occurred after 8 to 14 months of continuous hydrogen operation at pressures of 800 to 850 bar (11,603 to 12,328 psi). The two failed hydrogen valves were identical and rated by the valve manufacturer for hydrogen service.

The cause of this incident has not been determined, but valve stem material incompatibility with hydrogen (causing a material weakening) is suspected, although it could also have been a design flaw. Review of the valve manufacturer's drawings showed the valve stem material to be 17-4 precipitation hardening stainless steel that has been reported in the literature as having a 90% reduction in fracture toughness in a hydrogen environment. No metallurgical analysis was done on the failed valve stems to confirm the mode of failure. The valves were repaired with new valve stems made from 316 stainless steel, placed back in service, and have operated satisfactorily for 18 months without failure.

https://h2tools.org/lessons/automated-hydrogen-ball-valve-fails-open-due-valve-stem-failure

C-10. Oct 3, 2008:Response to Pin Hole Fire

During normal operations, a 2-inch flame was discovered emanating from a pinhole leak in a hydrogen line at an aircraft parts manufacturing facility. Hydrogen was not in use by any process in the facility at the time. The flame was discovered by a contractor who was about to start welding on scaffolding about 3-5 feet away. Before starting, the welder searched the immediate area for any signs of fire per his training. When he spotted the flame, he called his supervisor.

An operator tried to put out the fire with a fire extinguisher, which resulted in the flame enlarging by 1 inch. All employees and contractors were instructed to leave the area, and the Environment, Health and Safety (EHS) team leader called 911 and informed the fire department that there was a hydrogen fire at the facility. She then put an evacuation call out over the public address system. The administrative assistant hit the fire alarm on her way out of the office and went to the evacuation area. Then the operators began the process of shutting down the five furnaces.

The EHS team leader met the fire department and advised them of the fire. They began blocking the street and preparing to enter the building. The decision was made to close the hydrogen valves. Plant personnel and two firefighters proceeded to the hydrogen tank to close the valves. The firefighters asked about the routing of the hydrogen line, the status of hydrogen tank valves, and the likelihood that the fire could spread to the nearby gas feed shelter containing the hazardous chemicals and other flammable gas lines. It was determined to be highly unlikely that the fire would reach the gas feed shelter, so the firefighters decided to allow the fire to burn out. There was approximately 100 feet of line from the tank to the location of the fire. After 30 minutes, the fire was still burning.

The EHS team leader contacted the hydrogen supplier to ensure that the hydrogen tank was shut down properly. The hydrogen supplier's technical phone support also advised that it might require an extended length of time for the pressure in the line to drop enough for the fire to go out. This information was communicated to the firefighters. The hydrogen supplier also dispatched a technician to the site. When the technician arrived, he and the maintenance team leader walked through the emergency shut-down procedure for the hydrogen tank.

An operator and a firefighter, both wearing personal protective equipment, including breathing gear, went back into the area of the fire to check if all equipment was properly turned off. They verified via the plant control system that everything was shut down. The firefighter checked the fire and verified that it had burned out. Plant personnel were then allowed to re-enter the facility.

The following corrective actions were taken: (1) Replace the existing copper and carbon steel hydrogen pipeline with 3/4-inch schedule 40 stainless steel. (2) Reroute the new hydrogen line in the preferred location. (3) Locate new hydrogen shut-off valves in a more convenient location. (4) Remove all abandoned underground hydrogen lines.

https://h2tools.org/lessons/hydrogen-fire-aircraft-parts-manufacturing-facility

C-11. Oct 31, 1980: Hydrogen Leak from Underground Pipe and Explosion

Only 25 minutes after the normal work shift ended, an explosion occurred at a hydrogen storage and use facility that had been in a non-operational mode for several months while undergoing modifications for future tests. No one was in the facility at the time of the explosion. The event was witnessed about 30 seconds after the explosion by two engineers in a blockhouse 1000 feet away. Authorities were notified and calls were placed to other personnel about 30 minutes after the explosion. The facility's other supply systems and utilities had been severed or ruptured. Shrapnel and debris were ejected up to 540 feet away. Teams of firefighters and emergency medical personnel were sent to the area to verify that no one was injured and to extinguish small residual fires.

Damage was significant, including destruction of two support buildings. Costs incurred from the explosion were estimated to be approximately $5.9 million. Detectable levels of gaseous hydrogen were recorded at several locations adjacent to the concrete pad for a 5-day period following the event.

Findings of the investigation board were as follows.

1. The explosion was the result of a massive hydrogen leak.
2. A gaseous hydrogen leak occurred in an underground NPS 3 ASTM A106 Grade B, XXS WT carbon steel pipe. The pipe was coated with coal tar primer and coal tar enamel, wrapped with asbestos felt impregnated with coal tar, coated with a second coat of coal tar enamel, and wrapped in Kraft paper, in accordance with American Water Works Association Standard G203. The source of the leak was an oval hole about 0.15 x 0.20 inches at the inner surface of the pipe and about 2 inches in diameter at the outer surface of the pipe. Upon excavation of the pipe, it was noted that the coating was not present at the leak point. This resulted in galvanic corrosion over a 15-year period and the eventual rupture when high-pressure gas was applied to the thin pipe membrane. The pipe was 8 feet 9 inches below the concrete pad.
3. Prior to the pipe rupture, a pneumatically operated gaseous hydrogen isolation gate valve, designed for 6000 psi service and located about 280 feet from the facility, failed in the open position. Pneumatic pressure had been removed earlier in the day and failure analysis indicated that the valve had been damaged during recent field servicing.
4. Gaseous hydrogen was trapped in large quantities in sand and gravel under the apron surface (a 1-foot-thick concrete pad about 160 x 140 feet). The hydrogen then entered the basement of the electrical control and instrumentation terminal building, located immediately adjacent to the facility, through penetrations in the basement wall, including cable ducts, cable pulls, and two 24-inch-diameter air conditioning ducts. Gaseous hydrogen was transported through the air conditioning ducts to a support building about 90 feet from the terminal building.
5. An explosion originated in the basement of the terminal building. A shock wave traveled through the air conditioning ducts and caused a second explosion of lesser magnitude in the support building. The actual ignition source in the terminal building is unknown; however, an electrical arc from a sump pump was the most likely source.
6. The TNT equivalent of the blast was calculated to be between 100 and 475 pounds, depending on the location.

The following lessons were identified.

1. Active gaseous hydrogen sensors should be installed and continuously monitored.
2. Any below-grade piping installation should be in open trenches covered by grating.
3. Facilities should be protected from gaseous hydrogen, at a safe distance, by manual isolation valves.

4. Valves should be subjected to functional and leak checks, including actuator and valve seals at simulated operating conditions.
5. All lines scheduled to be inactive for periods greater than 6 months should be physically isolated by blind flanges from active systems.
6. Corrosion protection systems for underground lines should be reviewed and tested to confirm the adequacy.
7. Emergency instructions for isolating hydrogen and utilities for hazardous locations should be permanently posted with names and telephone numbers of key individuals to be contacted.

https://h2tools.org/lessons/gaseous-hydrogen-leak-and-explosion

D. Liquid Hydrogen Incidents

D-1. Jan 1, 1974: Plugged LH_2 Tank

A rupture disc blew on a 20,000-gallon liquid hydrogen tank, causing the vent stack to exhaust cold gaseous hydrogen, which was ignited. Emergency responders were called to the scene. To stabilize the tank, the remaining hydrogen was removed from the tank except for a small volume in the heel of the tank that could not be removed manually.

Firefighters sprayed the tank with water and directed a stream onto the fire exiting the vent stack. The water was channeled directly into the open vent stack, and the exiting residual hydrogen gas, between -423 °F (-253 °C) and -402 °F (-241 °C) caused the water in the vent stack to freeze. The water freezing caused the vent stack to be sealed off, disabling the only exit for the cold hydrogen gas. Later, the residual hydrogen gas in the tank warmed up, causing the tank to over-pressurize and rupture with an explosion.

https://h2tools.org/lessons/liquid-hydrogen-tank-boiling-liquid-expanding-vapor-explosion-bleve-due-water-plugged-vent

D-2. Apr 4, 2002: Hydrogen Vent Line Weld Failure

Hydrogen was found to be leaking from a vent line during cryogenic loading operations. The leak was attributed to a cracked weld on a hydrogen vent line that consisted of double wall aluminum piping and slotted spacers between the inner and outer line to provide a hydrogen gas blanket for insulation. The weld that failed was repaired using a "clamshell" over the area of the failed weld to support continued operations. A portion of the failed weld was removed for analysis prior to the repair. After operations, the clamshell repair was excised from the non-vacuum-jacketed double wall piping to allow further analysis of the failed weld. It was later replaced with a new half shell piping section.

Fault in the original weld with the use of an incorrect filler material was the primary source of the failure. A contributing cause was an unexpected temperature difference of approximately 200 °F (93 °C) between the top and bottom of the piping that was found to occur during operations around the failed weld.

https://h2tools.org/lessons/hydrogen-vent-line-weld-failure

D-3. Dec 31, 1969: Hydrogen Delivery Truck/Facility Connection Leak

During transfer of liquid hydrogen from a commercial tank trailer to a receiving vessel, a leak developed in a bayonet fitting at the trailer/facility connection. The leak produced a liquid hydrogen spray which enveloped the rear of the truck, where the hand-operated shutoff valve was located. Emergency trained personnel, wearing protective clothing except for proper shoes, entered the area and shut off the flow control valve. Reentry personnel suffered frost bite of their feet when shoes became frozen to the water-wetted rear deck of the truck.

A loose hose flange connection allowed leakage of cold fluid through the lubricated bayonet seal. This allowed cold fluid to contact and shrink the O-ring seal (made of Buna-N rubber), thus permitting liquid hydrogen leakage to the atmosphere.

https://h2tools.org/lessons/hydrogen-delivery-truck-facility-connection-mishap

D-4. Jan 19, 2009: Liquid Hydrogen Leak

Hydrogen leaked from a 9000-gallon horizontal liquid hydrogen tank in the rear of a high-intensity lamp manufacturing facility. The facility manager noticed the leak during his normal morning rounds and initiated the plant's emergency response policy, which included calling the local fire department. A large vapor plume (actually condensed moisture in the air) was visible 200 feet above the tank. The technician for the hydrogen supplier arrived on site, thawed out the ice buildup around the gland nut from which the leak originated using warm water, and tightened the nut, thus ending the problem. The technician verified that the leak originated from packing material around the valve that had come loose because of the recent extreme cold weather.

The fire department requested that the facility not shut down, but rather continue operations to draw normal levels of hydrogen from the tank. A checkpoint was established near the tank side of the building, where hydrogen level readings were taken and reported every 5 minutes. Employees of the plant were notified to exit the front of the building in the event of an evacuation signal. As hoses were turned on by the fire department, a drop in water pressure tripped the internal alarm, causing an evacuation of the plant. All employees were accounted for and were asked to return to work, as this was a false alarm condition. Two local streets were closed; radios, cell phones, and other electronic devices were shut down within a 500-foot safety zone to eliminate any static electricity that could ignite the hydrogen gas; and airplanes were diverted from their normal flight path to the local airport. Firefighters set up combustible gas monitors inside the building, but no gas was detected. The incident lasted approximately 2 hours.

Excessive venting of hydrogen from the tank due to lower facility consumption, in combination with extreme temperature conditions, shrank the nonmetallic packing, causing a leak.

https://h2tools.org/lessons/first-responders-control-liquid-hydrogen-leak-lamp-manufacturing-plant

D-5. Dec 17, 2004: Delivery Truck Fire

A fire erupted from a tanker truck delivering liquid hydrogen to a factory. The truck was off-loading hydrogen into a tank behind the plant when the incident occurred.The ignition of leaking vapors created a plume of flames that rose dozens of feet into the air. The flames receded within seconds, leaving the truck with little damage and its driver unharmed.

On-site personnel reported that hydrogen vapors released through a vent in the tank somehow ignited. The driver sealed off the vent within seconds and stopped the blaze. Fire officials and the two companies are evaluating the cause of the spark. The safety equipment in place prevented the fire from spreading into the tanks. Neither the truck nor the storage tanks were in jeopardy of exploding.

https://h2tools.org/lessons/liquid-hydrogen-delivery-truck-fire

D-6. Aug 6, 2004: Delivery Truck Offloading Valve Failure

A plume of hydrogen gas escaped from the offloading valve of a liquid hydrogen delivery truck while transporting hydrogen to a commercial facility. The plume ignited, resulting in a flash and concussion loud enough to be heard inside the nearby building and to set off the building’s seismic event detectors. A small amount of hydrogen gas continued to escape from the trailer tank and burn until a company specialist arrived to manually shut off a critical valve almost 8 hours later. In the meantime, emergency response crews called to the scene sprayed water across the hydrogen tank as a precautionary cooling measure.

The actual cause of this incident appears to have been driver error. Several steps required as part of the standard safety procedure were either incorrectly applied or omitted altogether. There was no crash or any compromise of the integrity of the fuel tank aboard the truck trailer.

https://h2tools.org/lessons/liquid-hydrogen-delivery-truck-offloading-valve-failure

E. Hydrogen Instrument Incidents

E-1. Feb 6, 2013: Parking Lot of Commercial Facility

A single-stage regulator "failed" while flowing hydrogen gas from a standard 200 ft^3 gas bottle. The regulator had functioned properly prior to the event through several on-off cycles. During the event, a solenoid valve was opened to allow hydrogen to flow, when a rather loud noise was noted and gas began flowing out of the pressure relief valve on the side of the regulator. It was noted that the low-pressure gauge on the regulator was "pegged" at the high side (200 psi). The valve on the bottle was shut off, and hydrogen flow was immediately stopped. Hydrogen flowing out of the relief valve did not ignite.

The failed regulator was later taken apart to try to determine the cause of failure. All the internal parts appeared to be intact with the exception of a small elastomeric ring that seals the internal nozzle to the seat assembly. This elastomeric ring was deformed and had become lodged in the nozzle orifice, preventing the seat assembly from properly seating and allowing high-pressure hydrogen to continuously flow into the low-pressure side of the regulator. The regulator has a pressure relief valve as protection and it operated properly, relieving the pressure in the system. Fortunately, nothing downstream of the regulator was damaged. It is not known what led to the failure of the elastomer ring. The manufacturer was contacted, and the event/observations were described and discussed. Damage to the elastomeric ring on that valve stem, thus limiting its ability to seal, is a rare event. The ring material was specifically selected for hydrogen/methane service and subjected to tens of thousands of open-close cycles. The manufacturer doesn't require a periodic maintenance program for these regulators but occasional replacement of the elastomer seal and O-ring on the outer part of the regulator body is recommended.

https://h2tools.org/lessons/hydrogen-gas-regulator-failure

E-2. Jan 15, 2019: Pressure Sensor Diaphragm Ruptures

The sensing diaphragm of a pressure transducer (PT), as supplied on an outdoor hydrogen compressor, unexpectedly ruptured and released approximately 0.1 kilograms of hydrogen into the atmosphere from the compressor discharge line. At the time of incident, personnel nearby were alerted by a loud “pop” and dust disturbance. Simultaneously, the facility monitoring system detected loss of the PT signal and initiated equipment shutdown. Facility personnel then closed isolation hand valves to stop the leak, locked and tagged out the equipment, and restricted the area. The failed component, a cigar type PT rated to 20,000 psi, originally supplied and installed by the manufacturer as part of the compressor package, was removed and inspected. Inspection revealed severed wires, a separated wire housing, missing electronics, and damaged electrical potting. The PT was on a line protected by a pressure safety valve set to 15,400 psi.

Facility investigators later discovered that the failed discharge PT was manufactured with a 17-4PH stainless steel diaphragm. This type of stainless steel, while an industry standard for high-pressure resistance with other fluids, is known in the industry to be incompatible with hydrogen. The compressor manufacturer's supplied documentation generally claimed the materials used were resistant to effects of hydrogen embrittlement at expected operating conditions but did not identify the specific materials of internal components such as PT diaphragms. The facility operator's commissioning procedures included functional test of PTs but did not include review of individual compressor component specifications. Subsequent communications between facility investigators and compressor representatives revealed that the compressor manufacturer did not intend to supply 17-4PH material in its compressor components; the diaphragm material was overlooked by the compressor manufacturer when sourcing the PT.

https://h2tools.org/lessons/pressure-sensor-diaphragm-rupture-h2-compressor-0

E-3. Dec 31, 1969: Pressure Gage Rupture

A bourdon tube ruptured in a pressure gage after 528 hours of operation in a liquid hydrogen system. The alarm sounded, the system was isolated and then vented. The tube was martensitic stainless steel, which is subject to hydrogen embrittlement. It was requested that all gauges that have bourdon tubes be replaced with austenitic stainless steel.

https://h2tools.org/lessons/stainless-steel-403-failure-liquid-hydrogen-line

F. Industrial Truck Incidents

F-1. Jul 21, 2011: Government Warehouse

A significant hydrogen leak occurred during refueling of the onboard hydrogen storage tank of a fuel cell-powered lift truck while it was completely depowered. The in-tank shutoff solenoid valve had recently been replaced, and this was the initial refueling event after the replacement. The fuel zone access panel was removed to allow constant visual leak checking with Snoop leak-detection fluid. The event occurred during the final pressure testing of the repaired system when an O-ring failed at approximately 4500 psi, releasing the entire contents of the hydrogen tank in about 10 minutes. The dispenser hose/nozzle was immediately disconnected, and the leak location was quickly isolated to the tank/valve interface. A 30-foot boundary around the lift truck was cleared of personnel and equipment. The combustible gas detector mounted on the wall above the hydrogen dispenser did not alarm because a large overhead facility fan was providing ventilation throughout the event. The leaking hydrogen did not ignite, no one was injured, and there was no property damage as a result of this event.

The fuel cell systems for the lift trucks were originally built by Company A and placed into service in 2009. Company B assumed the service and support responsibilities in 2011, and then subcontracted the service labor to Company C. The only instructions given to Company C regarding the tank valve and the O-ring were to follow the tank valve manufacturer's torque specification for ensuring a seal.

Shortly after this event occurred, an investigation was undertaken by Company B. Company C reported that the O-ring was clean, lubricated, and tight when installed. However, after removing the failed tank and valve from the lift truck for investigation, it was noted that there was insufficient insertion depth of the in-tank solenoid valve, and the O-ring was not able to provide a sufficient seal due to inadequate compression at the tank/valve interface. This situation was caused by the internal thread of the tank that did not allow full engagement at the specified tank manufacturer's torque requirement, and this geometric discrepancy was confirmed by comparison with a new tank that had been purchased as a spare. The investigation revealed that the tank threads were modified on other tanks of this same model, but not on the specific tank involved in this event. Thus, the tank would have required substantially more torque than provided to fully compress the O-ring as intended (i.e., much more than the manufacturer's recommended torque specification).

https://h2tools.org/lessons/hydrogen-leak-onboard-storage-system-fuel-cell-powered-lift-truck

F-2. Feb 8, 2011: Ball of Fire from Hydrogen Fuel Cell Forklift

A fuel cell forklift operator stated that he observed a "ball of fire" coming from the left side of the forklift that seemed to flash and extinguish. Investigators found no external signs of a fire, but the forklift would not start. The fuel cell power pack access panel was removed to enable investigators to search for any internal signs of a fire. Some areas inside the fuel cell stack appeared to have experienced an electrical arc or some type of overheating. All connections were verified to be tight and secure. The internal fuel cell stack circuit board cover was then removed, and the circuit card on top of the stack also showed signs of overheating. After the fuel cell stack circuit board was removed, a broken drill bit was discovered on top of the fuel cell stack plates. Evidently, the drill bit was jostled around when the forklift was operated, causing a spark and fire inside the fuel cell stack that burned the circuit card. It is unclear how the drill bit got where it was on top of the fuel cell stack plates. Records indicated that there had not been any maintenance performed on this fuel cell pack that would require drilling. In addition, an inventory check of technician tools used for fuel cell stack assembly accounted for all drill bits.

https://h2tools.org/lessons/ball-fire-hydrogen-fuel-cell-forklift-flashes-and-quickly-extinguishes

F-3. Dec 9, 2010: Fuel Cell Evaporator Pad Fire

The evaporator pad in a fuel cell power unit installed in a hydrogen-powered forklift caught fire during operation. The evaporator pad is used for wicking the product water created by the fuel cell. The operator dismounted the forklift, observed flames coming from the fuel cell unit, and called for help. The facility fire brigade used a fire extinguisher to put out the fire. The upper left corner of the fuel cell evaporator pad was burned entirely; the plastic bracket that holds the evaporator pad in place was distorted; there was some discoloration of the radiator. No injuries were sustained by the operator and no damage was sustained by the forklift.

The fuel cell unit continued to run during the incident, as did the onboard data acquisition device. Hydrogen concentrations from an array of six hydrogen sensors around the unit during low and high duty cycles measured at less than 0.2%.

The root cause of the fire that burned the evaporator pad and distorted the plastic evaporator pad bracket remains unknown.

https://h2tools.org/lessons/fuel-cell-evaporator-pad-fire

G. Hydrogen Compressor Incidents

G-1. Apr 5, 2006: Compressor Piping Incident

The malfunctioning of the non-return valve of the hydrogen compressor caused the pressure between the hydrogen bottle and the compressor to rise up to the maximum allowed pressure of 275 bar. The rupture disk of the safety valve broke and the hydrogen content of the gas bottle and the pipe section involved was released on top of the building. The flame was seen for a very short period by a guard.

The non-return valve was dismantled, cleaned, and tested. Following positive testing, the system was restarted and pressurized without any further malfunctioning.

https://h2tools.org/lessons/near-accident-h2-compressor-room

G-2. Jun 10, 2007: Hydrogen Boosting Compressor Fails

A single-stage diaphragm compressor failed during boosting of high-pressure hydrogen ground storage banks. The compressor sources hydrogen from a 44-MPa storage bank as suction and discharges it at a stop set point of 85 MPa. The compressor capacity is 0.71 m^3/min (25 scfm). The original notice of failure was through an inter-diaphragm pressure indication and alarm. There should not be any pressure build-up between the layers of the diaphragm. When the diaphragm was opened, hydraulic oil was found, leading to the conclusion that the hydraulic-side diaphragm was leaking. Although spare diaphragms and seals were available for on-site repair, difficulty was encountered in attempting to remove the compressor nut above the diaphragms. Similar difficulties were encountered when the unit was returned to the manufacturer.

A new compressor nut of a different material was manufactured, plated, assembled to the head, and returned for re-installation and operation. However, upon commissioning, it was discovered that the unit was not developing hydraulic pressure. The root cause was determined to be a fractured plunger, likely damaged during earlier repair efforts. The plunger was re-manufactured.

https://h2tools.org/lessons/hydrogen-boosting-compressor-fails

H. System Design, Operator, and Maintenance Incidents

H-1. Jul 27, 1999: Hydrogen Release from Drain Line

A process area alarm at a nuclear waste processing facility activated. The alarm was caused by an instrument located above a reaction vessel off-gas system final high efficiency particulate air (HEPA) filter canister, which activates at 25% of the lower explosive limit for hydrogen. Since the only source of hydrogen is from the reaction vessel during the reaction of sodium with concentrated sodium hydroxide, the immediate actions were to shut down the reaction process and place the facility in a safe condition.

The root cause was inadequate or defective design. Had the pre-filter drains been vented outside the building, no hydrogen would haveaccumulated in the process area. The corrective action for this design flaw is to install a sample/drain collection system with loop seals to prevent any release of hydrogen from entering the process area. The direct cause was the pre-filter canister drain valve being left open after the fluid stopped draining through which the hydrogen was released. A contributing cause may have been that the operator was not properly instructed to shut the valve immediately when the fluid stopped draining. The corresponding corrective action is to issue improved instructions for sampling/draining the off-gas system and training the operators on these improved procedures. A task was also initiated to provide interlocks and administrative controls to ensure the process area roof exhaust fans are running prior to beginning reaction vessel sodium injection and stop sodium injection should either fan stop running.

https://h2tools.org/lessons/hydrogen-alarm-activates-processing-facility

H-2. Oct 23, 2001: Hydrogen Plant Explosion and Fire

A fire occurred at a hydrogen generation plant, causing significant damage due to a concussive combustion event that started in a high-pressure hydrogen feed pipe. Some high-pressure pipe work had ruptured or parted, and pipe was visibly swollen at some locations, indicating a significant internal overpressure condition had occurred. The initial explosions was caused by the spontaneous ignition of an explosive mix of hydrogen and oxygen inside the high-pressure feed pipes. The ingress of the oxygen to the system was likely from the hydrogen cells. The primary cause of the contamination was blockages in the water makeup lines to some cells, allowing high levels of oxygen to mix with the hydrogen as electrolyte levels fell. The low-purity hydrogen was not detected by the analyzer due to the failed isolation transformer. There are several other potential air ingress points on the low-pressure system that could have allowed contamination. These points are, however, considered unlikely to have been the cause of the contamination resulting in the explosion.

https://h2tools.org/lessons/hydrogen-plant-explosion-and-fire

H-3. Apr 27, 1989: Hydrogen Storage Siting [Near Miss] Incident

During an inspection, three potential safety problems were identified concerning the location of a hydrogen storage facility. The hydrogen storage facility is located on a building's roof, which is made of 30-inch-thick reinforced concrete. The following potential safety problems were identified during the inspection:

1. Leakage of hydrogen gas from the storage facility in proximity to the air intakes of the building's ventilation system may introduce a flammable or explosive gas mixture into the enclosure. Because the hydrogen storage facility, containing four 8000-scf hydrogen tanks at up to 2450 psig, is Seismic Category II, a seismic event may result in a hydrogen leak. Furthermore, the pressure relief valves in the hydrogen facility exhaust downward to within 6 inches of the roof in the vicinity of the ventilation system air intakes. It was also noted that

six 8000-scf nitrogen tanks were located in the vicinity of the building's air intakes. Nitrogen leakage and dispersion into the air intakes may lead to incapacitation of the occupants.

2. A detonation of a hydrogen storage tank may structurally damage and affect performance of safety-related equipment on the building's roof, such as the ventilation system intake and exhaust structure, the emergency pressurization system, and equipment in the building itself.
3. An explosion of the hydrogen delivery truck that provides hydrogen to the facility through a fill line located at ground level on the wall of the auxiliary building may structurally damage safety-related component cooling water pumps located inside the auxiliary building and near the hydrogen fill line.

https://h2tools.org/lessons/hydrogen-storage-siting-incident

H-4. Dec 31, 1969: Improper Purging Procedure Results in Hydrogen Fire

A large, hydrogen-cooled generator is driven by steam turbines at a power station. During maintenance shutdowns, the hydrogen cooling loop in the generator is purged with carbon dioxide. After carbon dioxide concentrations are measured with a densitometer to verify the complete removal of hydrogen, the generator is purged with air and the maintenance is performed.

This purging procedure was used prior to the explosion. The carbon dioxide reading was reported to be 100% at the top of the generator. The cooling system was then purged with air and a 1/2-inch pipe in the cooling loop was cut to install some new instrumentation. When the pipe was cut, pressurized gas was emitted at the opening. Workers assumed the gas was either carbon dioxide or air and proceeded with the new instrument installation. Unfortunately, there was still at least some hydrogen in the pipe and the rest of the cooling loop. When the welder struck an arc, a flame developed at the pipe opening and flashed back into the generator. This caused a low-level explosion within the generator shroud. The explosion damaged ventilation baffle plates and auxiliary equipment in the generator, which caused the plant to be out of service for 26 days.

https://h2tools.org/lessons/improper-purging-procedure-results-hydrogen-fire

H-5. May 11, 1999: Failure of a Check Valve

A facility replaced the copper tubing used for hydrogen distribution with stainless steel tubing. This was done to address a fire protection concern related to the solder on the copper tubing being susceptible to heat, melting, and releasing a flammable gas. The facility maintenance personnel completed the replacement, noted the pressure on the hydrogen bottle, and left the building. When the maintenance personnel returned on the following day, they noticed the pressure on the hydrogen bottle had dropped 500 psi overnight, indicating a leak in the system. The appropriate facility personnel were notified and they began to determine why the hydrogen had dropped 500 psi overnight. The hydrogen line originates at a manifold, which is part of a glove box atmosphere purification system that also includes an argon line. Personnel experimented with the valves associated with the hydrogen and argon lines and determined that the check valve associated with the argon line was defective. As a result, the hydrogen was back flowing through the argon check valve into the argon supply line.

The direct cause of this occurrence was attributed to a failed argon check valve that allowed hydrogen to escape from the hydrogen supply manifold and enter the argon system. The contributing and root cause was identified as a design problem. The check valve installed to prevent the back flow of hydrogen into the argon system, was designed to open with an upstream pressure of 1/3 psig. The product catalog states that valves with nominal cracking pressure of 8 psig or lower may require back pressure to provide a bubble-tight reseal. The back pressure in the system was not sufficient to reseal a 1/3-psig valve. Product data suggests that a valve having a cracking pressure of 10 psig and requiring no back pressure to reseal should have been chosen for this application. Also, double check valves (i.e., two check valves in series) should have been installed to provide double isolation between the two gas systems. However, it is doubtful in this case if two valves would have been adequate to prevent the backflow of hydrogen since the wrong sized valve (i.e., 1/3 psig) was initially chosen.

The hydrogen was sufficiently diluted with argon in the system and did not pose a safety, fire, or explosion hazard.

https://h2tools.org/lessons/failure-argon-check-valve

H-6. Jun 8, 1998: Flanged Joint Hydrogen Gas Leak and Fire

During operation of a succinic acid plant, hydrogen leaked from a flanged joint on a safety valve at the upper part of a reactor, which generated a hydrogen flame. Prior to the incident, the safety valve was removed and reattached during an inspection at a turnaround shutdown. An incorrectly sized, smaller gasket was installed in the joint, and the tightening force on the bolts was inadequate. Therefore, a gap was generated as time went by and un-reacted hydrogen leaked.

https://h2tools.org/lessons/mounting-joint-safety-valve-developed-hydrogen-gas-leak-and-fire

H-7. Dec 31, 1969: Hydrogen Tube Trailer Explosion

A faulty modification to a multiple-gas piping manifold allowed mixing of hydrogen and oxygen that resulted in a storage tube explosion. Several employees suffered severe burns and other injuries from the incident.

An employee, without authorization, fabricated and installed an adapter to connect a hydrogen tube trailer manifold to an oxygen tube trailer manifold at a facility for filling compressed-gas cylinders for a variety of gases, including hydrogen, oxygen, nitrogen, and helium. A subsequent improper purging procedure allowed oxygen gas to flow into a partially filled hydrogen tube on a hydrogen tube trailer. An ignition occurred in the manifold piping system and a combustion front traveled into the hydrogen tube where, after traveling about a meter, the deflagration apparently transitioned to a detonation that ruptured the tube.

https://h2tools.org/lessons/hydrogen-tube-trailer-explosion

H-8. May 1, 2007: Leakage from Packing of Flow Control Valve

The hydrogen sensor at a hydrogen fueling station detected a slight leakage from the ground packing of the flow control valve during refueling. The refueling operation was stopped immediately. The leak was stopped by tightening the ground packing sealing screw, but it started leaking again in about a week.

The flow control valve was disassembled and inspected. Dust was found at the ground seal and the packing was distorted. Leakage was believed to be due to the dust invasion and repeated tightening of the sealing screw. The packing had been used for 4 years and 2 months without replacement.

The packing in the flow control valve should be replaced periodically.

https://h2tools.org/lessons/hydrogen-leakage-ground-packing-flow-control-valve

H-9. Feb 7, 2009: Over Torqued Valve

Plant power was stable at 90% following a plant startup. The operator performed a pre-job briefing with shift management before adding hydrogen to the main generator. While performing the addition, the operator attempted to verify whether a half-inch hydrogen addition valve was open.

The operator was unable to move the valve by hand and mistakenly assumed the valve was stuck on its closed seat. The valve position is normally opened, and the procedure step was to verify this condition. The operator obtained a pipe wrench to assist in freeing the valve off its "closed" seat. Using the pipe wrench, the valve handwheel was turned in the open direction. The operator attempted to open the valve by hand again. Unable to move the valve by hand, the operator used the pipe wrench to further open the valve approximately six turns (two turns of the handwheel for this valve results in full stem travel). The bonnet, handwheel, stem and valve internals were eventually ejected from the body of the valve by hydrogen system pressure. The operator promptly evacuated the area due to the hydrogen release and the hydrogen ignited within seconds. The operator informed the control room, via radio, of the leak and fire at the hydrogen station. The operator and other staff proceeded immediately to the hydrogen bulk storage facility to isolate the hydrogen supply to the turbine building.

The control room supervisor directed a manual reactor trip. The plant fire plan and abnormal operating procedure were activated, and the fire brigade was dispatched. The hydrogen fire was extinguished following isolation of the hydrogen supply. However, there continued to be re-flash, arcing, and a small fire in the cable tray located in the overhead above the hydrogen add station. Fire extinguishers and eventually water was used to extinguish the fire in the cables.

The damage in the cable tray required the replacement of 29 cables (480 volt). This and other damage to local components required the unit to be shut down for approximately five days to complete repairs.

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

H-10. March 22, 2018: Unauthorized Field Modification Cause Control Cabinet Explosion, Injury

A sealed, unclassified electrical control enclosure, part of a listed and certified force-ventilated commercial hydrogen processing unit enclosure, exploded when the manufacturer’s technician pressed the machine stop switch to complete the commissioning procedure. The technician was forcefully hit by a flying metal panel and sustained serious injuries requiring lengthy hospitalization and rehabilitation. Damage to the indoor facility also occurred.

An independent investigation found that drain lines from the external hydrogen vent stack drain trap and the electrical control enclosure cooler/condenser drain were interconnected into a single external sealed floor drain, in a manner not prescribed by the manufacturer’s installation instructions. Further, a hole was drilled through the hydrogen processing enclosure to interconnect an internal hydrogen gas dryer drain trap to the external drain, contrary to product certified configuration and installation instructions. These interconnections inadvertently provided a path for low pressure hydrogen gas and water to enter the unclassified electrical enclosure during process cycles. Activation of the machine stop switch in the electrical enclosure provided the ignition source. Corrective actions taken include enhanced installation instructions warning against drain line interconnection, prohibiting field modifications without prior factory approval, and strengthened installation commissioning inspection. Key lessons learned from this incident are to separate hydrogen drain trap lines from other drain lines, to follow manufacturer’s installation instructions, to thoroughly inspect field installations, and to consult the manufacturer and listing agency before any field modifications are undertaken.

https://h2tools.org/lessons/unauthorized-field-modified-equipment-drain-lines-cause-control-cabinet-explosion

I. Laboratory Incidents

I-1. Dec 31, 1969: Hydrogen Explosion in Microbiological Anaerobic Chamber

An explosion occurred in a microbiological anaerobic chamber of approximately 2 m^3 capacity that contained an explosive mixture of hydrogen and air. A fire followed the explosion but was rapidly extinguished by staff using fire extinguishers prior to the arrival of fire service personnel. The pressure wave from the explosion blew windows out of the laboratory, with glass hitting a passerby on a path outside and glass shards landing up to 30 m away. Ceiling panels were dislodged in the laboratory and adjacent rooms, and a worker using the chamber apparatus at the time was taken to the hospital by ambulance for burn treatment. The worker subsequently fully recovered. Another worker in the laboratory at the time of the explosion required medical observation but was otherwise unharmed.

Mixtures of inert gases and hydrogen are routinely used in the type of anaerobic chamber involved in the incident. The mixtures used in the chamber involved were produced locally in the laboratory using nitrogen, carbon dioxide, and hydrogen. The hydrogen in the mixture reacts with any oxygen present in the chamber, on a heated catalyst, to eliminate oxygen and keep the chamber anaerobic. The operating procedures used in the laboratory allowed high concentrations of hydrogen to be introduced into the chamber. A worker inadvertently admitted air to the chamber while doing maintenance, allowing the hydrogen-enriched atmosphere in the chamber to mix with air and subsequently ignite, most likely on contact with the oxidation catalyst in the chamber, resulting in the explosion and fire.

Hydrogen gas has a very wide range of flammability when mixed with air (4-75%). Oxidation catalysts can ignite explosive gas mixes without heating, spark, or flame. Operating procedures and practices varied from manufacturers' guiddance. An unknown concentration of hydrogen was present in the chamber, resulting in a significant fire and explosion risk.

https://h2tools.org/lessons/hydrogen-explosion-microbiological-anaerobic-chamber

I-2. Oct 7, 2005: Hydrogen Laboratory Fire

A person working in a hydrogen laboratory unknowingly closed the wrong hydrogen valve and proceeded to loosen a fitting in one of the hydrogen gas lines. The pressure in the 1/4"-diameter hydrogen line was approximately 110 psig. Hydrogen escaped from the loosened fitting and the pressure release resulted in the tubing completely detaching and falling to the floor. The person noted seeing a white stream around the hydrogen jet leak. The person noted a color change and noise change as the leak ignited (this happened in a matter of seconds and he did not have a chance to react). The person left the laboratory and pushed the emergency stop button. Someone else pulled the fire alarm. Both of these actions were designed to close the main hydrogen solenoid (shutoff) valve. The local emergency response personnel realized that the hydrogen supply had not been turned off by the building safety systems and manually closed the main hydrogen valve next to the hydrogen tank farm.

The gas laboratory's safety system has a main control panel. The hydrogen sensors, flame detectors, emergency push buttons, fire alarm, and sprinkler system are all inputs into the control panel. In the event of an emergency, if any of these systems are engaged, the control panel should de-energize the main solenoid valve and stop the gas flow. However, this did not happen.

Onsite personnel were puzzled by the fact that apparently all the safety systems had failed to close the main solenoid valve on that day. The onsite personnel questioned some key individuals on the testing of the emergency systems and found out that they confirmed solenoid valve closure, after activation of safety devices, by listening for evidence of valve movement (click).

The main solenoid valve was removed from the gas line manifold for inspection. As the vavle was taken out, it was evident that the problem could have been due to an installation error. The valve was installed in a horizontal pipe run and 90° from upright. However, the solenoid valve had a marking on one side, which read: "Mount vertical and upright (see instructions)". This marking could not be seen when the valve was in the installed (i.e., horizontal) position. An arrow on the valve body showed what was the correct mounting position. The valve was tested in the upright position and it worked perfectly. However, when the valve was tested as installed (rotated 90° from upright), evidence of the valve stroking could be heard but it did not seal properly.

A new valve was ordered (identical to the old one), and it also did not fully close when tested (even when mounted as per the installation instructions). The new defective valve had to be returned to the manufacturer. To remedy the problem, the laboratory changed their piping configuration to have two valves in series in the system. They also changed their laboratory safety system testing procedures. Instead of listening for the valve movement to confirm valve closure, they measured the downstream pressure from the main valve as the safety devices were being activated.

Laboratory personnel could not determine with certainty the ignition source, but they suspected it could have been either static discharge or a power bar.

https://h2tools.org/lessons/hydrogen-lab-fire

I-3. Nov 14, 1994: Hydrogen Fire within a Chemical Process Hood

A small hydrogen fire occurred in a chemical process hood. A chemist was performing an experiment reacting manganese dioxide with hydrogen to produce manganese oxide and water. The chemist had left the process, which would take approximately one hour to complete, and was working in a nearby lab. While the chemist was gone, a second worker heard a pop, saw the hydrogen fire in the hood, and requested the activation of a fire alarm. A third employee in the area activated a manual fire alarm. The chemist, upon hearing the fire alarm, returned to the room, shut off the hydrogen fuel supply, and evacuated the facility. The hydrogen fire lasted for approximately one minute. The remaining small fire was extinguished about 10 minutes later with a Halon portable fire extinguisher by a radiological control technician assigned to the area when he entered to survey the room. The glass front on the hood was cracked, and except for the damage done to the glass column and equipment used in the process, there was no other damage.

The direct cause of this occurrence was a defective or failed part. The glassware column used in the chemical reduction process failed. A hole developed in the side of the glassware column that allowed hydrogen to escape and be ignited by the heat tape wrapped around the glass tube. Due to the glass fire involvement, it could not be determined if the glassware column failed or if the heat tape failed and created a hot spot which eventually caused a hole to develop in the glassware column. However, the glassware column that failed was used previously to perform the same process.

https://h2tools.org/lessons/small-hydrogen-fire-within-chemical-process-hood

I-4. Sep 23, 1999: Uncoupling of Compressed Gas Quick-Disconnect Fitting

While filling a sample cylinder with compressed hydrogen gas, a quick-disconnect coupler fitting came loose within a stainless-steel laboratory hood, allowing a small purge of the hydrogen gas to escape directly into the hood through ~1/4-inch plastic tubing. The stainless steel quick-disconnect fitting struck the stainless-steel bottom of the laboratory hood and the hydrogen gas caught fire. It is not known what caused the hydrogen gas to catch fire. The most likely sources of a spark were from metal-to-metal contact of the quick-disconnect fitting with the laboratory hood floor, or the discharge of static electrical charge generated by flow of hydrogen gas through plastic tubing. The resultant narrow jet of fire, directed toward the left side of the laboratory hood, extinguished itself within a few seconds when the operator closed an upstream valve that was supplying the compressed hydrogen gas to the sample cylinder.

The operator was not injured, and the only apparent damage was minor melting of a short length of plastic tubing. In addition to several plastic tubing that were 8 to 24 inches in length and a plastic beaker, there was a 500 milliliter (ml) glass bottle containing approximately 300 ml of hydrazine-hydrate stored in the laboratory hood. This flammable chemical is periodically used as an additive for maintaining water chemistry. No additional fire extinguishing action was necessary inside the hood, but as a precautionary measure, the operator used a low-pressure demineralized water tap within the hood to rinse/cool surfaces within the hood. Since there was no apparent remaining fire extinguishing action required, fire department assistance was not requested.

The operator immediately performed a walk down of the laboratory hood exhaust ventilation system to ensure no fire had occurred in the ventilation duct work, downstream of the laboratory hood. Some smoke was evident downstream of the laboratory high efficiency particulate air filter on the third-floor mezzanine room where the laboratory hood exhaust fan is located; otherwise, all systems visible to the operator were found to be normal.

The root cause of this incident was inadequate design. The quick-disconnect fitting on the chemical addition system became unintentionally disconnected. The release of hydrogen gas into the hood enclosure, combined with a spark generated from either the metal fitting striking the metal floor of the hood enclosure or discharge of static electricity from flow of the gas through non-metallic Tygon tubing created a fire hazard. To eliminate the hazard completely, two sets of quick-disconnect fittings (of the type that became unintentionally disconnected) and use of plastic tubing were eliminated and replaced with a hard-piped system. The small quantity of hydrogen gas being purged through the sample cylinder was also redirected such that it was released near the top of the hood and immediately adjacent to the hood exhaust duct work. A locking device was then provided for the remaining two sample cylinder quick-disconnect fittings to prevent them from separating without first removing the locking device.

https://h2tools.org/lessons/unintentional-uncoupling-compressed-gas-quick-disconnect-fitting

I-5. Aug 06, 2008: Vent Line Leak

A hose clamp failed on a low-pressure vent line from a hydrogen reactor experiment and effluent was leaked into the laboratory. Hydrogen in the effluent stream triggered the low-level hydrogen alarm. The hose clamp was re-secured and other hose clamps were checked for proper tightness.

https://h2tools.org/lessons/low-pressure-vent-line-leak

I-6. Sep 1, 1992: Technician Fatally Burned When Leaking Hydrogen Ignites

A laboratory technician died, and three others were injured when hydrogen gas being used in experiments leaked and ignited a flash fire. The incident occurred in a 5700-square-foot, single-story building of unprotected non-combustible construction. The building was not equipped with automatic gas detection or fire suppression systems.

Employees in the laboratory were conducting high-pressure, high-temperature experiments with animal and vegetable oils in a catalytic cracker under a gas blanket. They were using a liquefied petroleum gas (LPG) burner to supply heat in the process.

Investigators believe that a large volume of hydrogen leaked into the room through a pump seal or a pipe union, spread throughout the laboratory, and ignited after meeting the operating LPG burner some 10 to 15 feet away. The flash fire engulfed the people in the room.

Other employees used portable fire extinguishers to extinguish the localized fires caused by the flash fire. The fire department received notification at 2:36 p.m. Because the fires were extinguished by the time they arrived, firefighters provided emergency care to the injured. Damage was estimated at $25,000.

https://h2tools.org/lessons/laboratory-technician-fatally-burned-when-leaking-hydrogen-ignites

I-7. Dec 31, 1969: Technician Accidentally Removes Critical Bolts

A technician accidentally loosened critical bolts holding a fitting to the top of a hydrogen tank, which caused a large hydrogen leak in the dewar. The fitting contained various instruments, and when the third bolt was loosened, hydrogen gas exited through an opening in the seal. The Viton or neoprene O-ring was blown out of its groove and was immediately frozen, making it impossible to reseal the fitting cover. The area was evacuated, the dewar was vented, and the gasket was replaced. The ullage space was not purged with helium gas during the gasket replacement, which may have been responsible for small leaks that developed during the transfer.

The fitting containing the instruments was mounted on a flange, which was in turn secured to another flange. Long bolts and short bolts were used to retain the components. The bolt heads were identical and not identified, hence leading to the error in loosening the wrong bolts. The leaks that occurred after the gasket was replaced were probably due to moisture condensation on related vent valve components.

https://h2tools.org/lessons/technician-accidentally-removes-critical-bolts-dewar-fitting

I-8. May 3, 2004: Fire in Fuel Cell Test Stand

A small electrical fire occurred from an apparent electrical short circuit inside a fuel cell test stand. Subsequently, the electrical fire caused a nearby hydrogen line made of flexible tubing to melt, and exposed and then ignited leaked hydrogen.

The electrical fire was easily extinguished. The hydrogen flame was extinguished by snuffing the flame, shutting off the gas lines and power to the test stand. No one was injured, but damage was incurred in the test stand.
https://h2tools.org/lessons/small-fire-fuel-cell-test-stand

I-9. Jan 1, 1982: Use of "Quick-Disconnect" Fittings Results in Laboratory Explosion

A researcher was using numerous compressed gases in his lab. To facilitate reconfiguring his experimental apparatus, he installed "quick-disconnect" fittings on flexible tubing connected to his compressed gas cylinders/regulators. He also fitted all the equipment that needed gas with complementary "quick-disconnect" fittings.

On the day of the incident, he needed to purge his infrared spectrometer with nitrogen as the element heated up. He mistakenly attached the "quick-disconnect" fitting from a cylinder of 10% nitrogen and 90% hydrogen to the "quick-disconnect" fitting on his spectrometer. As soon as the gas started flowing and he switched on the element, the instrument exploded, destroying a $6,000 piece of equipment. Only minor damage was done to the rest of the room, and there were no injuries.

https://h2tools.org/lessons/use-quick-disconnect-fittings-results-laboratory-instrument-explosion

I-10. Jun 28, 2010: Explosion in University Biochemistry Laboratory

A hydrogen explosion occurred in a university biochemistry laboratory. Four persons were taken to the hospital for injuries and were treated and subsequently released. All the exterior windows in the laboratory were blown out and there was significant damage within the laboratory. One sprinkler was activated that controlled a fire associated with a compressed hydrogen gas cylinder. First responders from the local community and the university campus arrived quickly on the scene. Once the injured were attended to and the site secured, response efforts focused first on assessing potential hazards. Campus personnel worked into the night to board up windows, isolate utility services, and clean up debris.

The laboratory researchers work with soil bacteria that cannot survive in the presence of oxygen. As a result, research work is conducted inside a plastic chamber in which the chemical constituents in the air can be controlled. The explosion occurred during the setup of one of these chambers. The chamber is essentially a plastic bag with a volume of approximately 2 cubic meters. The setup procedure calls for using nitrogen to purge normal atmospheric air out of the bag three times, leaving a very small amount of residual oxygen present. The remaining small amount of oxygen is then removed by reaction with hydrogen in the presence of a palladium catalyst to form water.

Hydrogen was mistakenly introduced into the plastic bag as part of the first purge. As a result, the hydrogen concentration reached an explosive level inside the bag due to the relatively large presence of oxygen. The ignition was most likely triggered by an electrical source inside the chamber or when the palladium catalyst became too hot. The amount of hydrogen involved could not have exceeded 1 pound, which is the capacity of the compressed gas cylinder when full.

The investigation uncovered several procedural and design items that contributed to the explosion:

1. One of the first steps of the procedure is to ensure that the lines leading from the nitrogen and hydrogen compressed gas cylinders are tight and do not contain any leaks. This was done by opening the tanks to pressurize the lines but leaving the end valve in the "off" position. Research technicians then applied soapy water to each connection to see if there are any bubbles that would indicate a leak. When this check was completed, the research technicians forgot to turn the hydrogen tank back off prior to beginning the three purges with nitrogen.
2. Both compressed gas cylinders were connected to the chamber through a common tube via a "T" connector. A valve on the end had to be held open manually to introduce gas into the plastic bag. Normally, there would be a toggle switch inside the "T" connection that would be used to allow nitrogen or hydrogen, but not both, to be introduced into the chamber. At some point in the past, the right parts were unavailable, so that the "T" connection in use at the time of the explosion did not have a toggle switch. Had the toggle switch been present, the explosion would have been unlikely to have occurred.

The following corrective actions were identified. (1) Replace the use of pure hydrogen with a 95:5 mixture of nitrogen and hydrogen. (2) Use of "T" connections between gases should be eliminated. (3) All laboratory personnel should receive refresher training.

https://h2tools.org/lessons/hydrogen-explosion-university-biochemistry-laboratory

J. Fueling Station Incidents

J-1. Feb 24, 2006: Incorrect Check Valve Installation

A contractor was replacing a needle valve and a check valve on the nitrogen purge line to the dispenser because of a small leak at the connection between the needle valve and the check valve. On reinstalling the valves, the contractor installed the check valve backwards, causing the pressure disk in the regulator to fail, venting about 1000 psig hydrogen into the air for about 10 seconds. This was found during testing of the contractor's work before the system was returned to normal service.

https://h2tools.org/lessons/incorrect-check-valve-installation

J-2. Jun 11, 2007: Fueling Hose Fails

A sidewall burst failure occurred in a high-pressure polytetrafluoroethylene-lined hose. The 4.0-m hose was in service for approximately 2 years, primarily for 70 MPa fueling of hydrogen at ambient conditions ranging from -40 °C (-40 °F) to 50 °C (122 °F). The total number of fills during its service life was estimated to be 150. In addition to the high-volume fill events, pressure cycling occurred as part of the routine test procedures and operational protocols. These additional pressure-cycling occurrences were approximated 200-250 cycles. During each filling cycle, the hose could bend during connections, as required by the situation. Failure of the hose occurred while temporarily connected to a gas booster, after 1-2 hours of service at 75 MPa. There were no tight bends in the hose during its final service application and no vibration present in the assembly.

Examination of the hose provided additional information. Failure of the hose occurred approximately 30 cm from the crimped end fitting. The hose contained three distinct kinks, or bent areas, all within the immediate area of the failure. However, the burst area did not show any obvious signs of previous damage or flaws. Some strands of the metal braiding exhibited corrosion attack, as well as gouge-type mechanical damage, but no fatigue characteristics or discontinuities were noted on the failed strands that were examined.

High-pressure fueling hoses should be examined daily for signs of external damage, including corrosion, abrasion, cuts, and kinking. High-use fueling hoses should be replaced every 6 months.

https://h2tools.org/lessons/fueling-hose-fails

J-3. Sep 19, 2007: Fitting Failures for Fueling Equipment

Two fitting failures ocurred in the filling systems of the fueling equipment. Both fittings were installed in the system thermal chamber experiencing ambient temperatures of -40 °C (-40 °F) to 50 °C (122 °F). They were connected in high-pressure lines used for 70-MPa hydrogen fueling.

The first fitting, a 0.25-inch national pipe tapered (NPT) hose connection, was in service for approximately 1 year with no signs of leakage. The failure was noticed when the system was pressurized during a filling sequence. The failure was discovered by an audible hissing noise during leak checking. The system was depressurized and the fitting removed and replaced. The system was re-pressurized with no further leakage.

When technicians attempted to reconnect a second fitting for a double-ferrule high-pressure connection, it would not re-seal. The nut would not spin freely on the tubing and had created gouge marks. The fitting was replaced and no further leakage occurred.

For the use of mechanical fittings in hydrogen service, administrative controls should be in place, as in this case, to ensure that leak testing is conducted on a regular basis. It should never be assumed that every fitting is tight. Additional discussion of best practices for fittings and joints can be found in the Hydrogen Safety Best Practices Manual.

https://h2tools.org/lessons/fitting-failures-fueling-equipment

J-4. Sep 19, 2007: Needle Valve Failure in Hydrogen Service

The subject needle valve was used primarily for manual filling to control the flow rate of hydrogen from storage banks to the 70-MPa test system. The valve was installed on the exterior of the thermal chamber in ambient temperatures of -5 °C (23 °F) to 30 °C (86 °F). The gas flowing through the valve was at conditioned temperatures of -40 °C (-40 °F) to 50 °C (122 °F). The valve was in service for approximately 2 years and 400 fill operations.

Failure occurred during a test under an open valve condition. When attempting to close the valve, the technician was unable to completely close the valve despite increasing the turning force. An upstream ball valve was closed to isolate the flow.

Investigation determined that internal galling has caused the failure rendering the needle valve unusable. The galling was caused by a stainless steel stem acting against a stainless steel seat. This failure mode had been observed before and the manufacturer had been previously notified. The valve was replaced with a new needle valve to continue with the test program.

https://h2tools.org/lessons/needle-valve-failure-hydrogen-service

J-5. Aug 2, 2004: Leak at Breakaway Fitting

A vehicle fill was initiated by the operator. During the hose pressurization step, a leak was observed at the breakaway fitting. The operator pressed the emergency stop to terminate the fill. The fitting was an SAE straight thread and was likely loosened by torque applied to the fueling hose. After the incident, additional means were applied to these fittings to restrict loosening, a cover was installed to deflect any leakage, and a different style nozzle was used to restrict hose torque. In addition, different fittings have now been deployed.

https://h2tools.org/lessons/leak-breakaway-fitting

J-6. Dec 19, 2004: Leak on Liquid Hydrogen Tank at Fueling Station

A valve packing started to leak during cold ambient temperatures. A technician was dispatched. He first reduced the pressure to minimize the release and then re-tightened the packing to stop the leak. The fueling station staff included inspection on monthly preventive maintenance plan and evaluated alternate materials for better cold-weather performance.

https://h2tools.org/lessons/leak-lhy-tank-fueling-station

J-7. Oct 05, 2009: Leak on Compressor

A vehicle fill depleted the high-pressure hydrogen inventory. The compressor turned on to refill the storage by compressing 60 psig gas from a liquid hydrogen tank up to the 5500 psig storage pressure. After running about 2 hours, a crankshaft bearing started to fail. This allowed greater movement of the shaft, which led to a shaft seal leaking hydrogen. The compressor shut down on low suction pressure and then the system was shut down using the e-stop by the emergency responders.

A gas detector was added in close proximity to the compressor shaft and a vibration switch is under consideration. Additional predictive measures are being considered to predict bearing failure. In addition, the manufacturer has been contacted and the bearing design is being analyzed to see if it can be improved.

https://h2tools.org/lessons/leak-compressor-fueling-station

J-8. Jan 22, 2009: Breakaway Separation During Fueling

During a 70-MPa fueling, the fueling hose breakaway separated. The separation occurred without any extraneous forces other than the pressure of the gas internal to the fueling hose. Upon investigation, it was determined the pull force set point was incorrectly adjusted. No further issues were identified.

Corrective actions included replacing the breakaway with a new one, which restored normal operation of the dispenser. Verify and periodically inspect the pull/separation force adjustment if the breakaway is so equipped.

https://h2tools.org/lessons/breakaway-separation-during-fueling

J-9. Aug 25, 2008: Hydrogen Delivery Truck Causes Hydrogen Leak at Fill Station

A hydrogen leak occurred at a hydrogen fill station when a vendor's hydrogen fill truck trailer pulled away after filling and caught an improperly stored hydrogen fill line. The driver of the hydrogen truck trailer did not properly stow the hydrogen fill line after filling and failed to verify that the hydrogen fill line was clear of the trailer prior to departure. As the driver pulled away from the fill station, the hydrogen fill line caught on the trailer and subsequently pulled on the hydrogen fill station's ground storage tubes' distribution manifold. The force of this pull bent the hydrogen distribution manifold and hydrogen began leaking from a threaded connection and from the hydrogen fill line. The truck trailer driver reported hearing a "pop and hissing sound," stopped the truck movement, and then promptly left the truck to report the incident at approximately 6:45 p.m.

The local fire department was contacted, and the building was evacuated. The fire department arrived by 8:00 p.m., along with the hydrogen vendor's service technician, to isolate the hydrogen leak. The hydrogen leak at the plant's hydrogen ground storage system was stopped by closing the individual valves on each hydrogen storage tube, thereby isolating the distribution manifold. At 10:00 p.m., the all clear was given. Hydrogen operations were restored to the plant the next day by removing the damaged hydrogen ground storage unit and replacing it with a hydrogen tube trailer with concrete barriers installed to provide protection. The hydrogen leak from this event caused no hydrogen fire/explosion or personnel injuries.

https://h2tools.org/lessons/hydrogen-delivery-truck-causes-hydrogen-leak-fill-station-due-improperly-stored-hydrogen

J-10. Aug 21, 2008: Fire at Hydrogen Fueling Station

A fire began in the compression skid for a high-pressure hydrogen fueling station. The initial source of fire was likely a release of hydrogen from a failed weld on a pressure switch. The initial fire cascaded to three stainless steel line failures, release of glycol coolant, and release/combustion of compressor oil. Non-metallic seals and hoses containing hydraulic fluid and coolant melted/burned and caused leakage of the fluid, which was mostly consumed by the fire. The local fire department responded and contained the situation by shutting off the power supply and spraying water on nearby equipment. The compressor skid was a loss and the fire caused moderate damage to surrounding equipment.

The failed pressure-switch component was replaced with a better design. Shutoff valve location and/or redundant shutoff valves at storage vessels are important for containment to prevent escalation. Consider design features within equipment skids to reduce the likelihood of cascading events.

https://h2tools.org/lessons/fire-hydrogen-fueling-station

J-11. Mar 13, 2012: Hydrogen Cylinder Leak at Fueling Station

An alarm sounded at a recently inaugurated hydrogen fueling station in a major metropolitan area. One out of a total of 120 high-pressure hydrogen cylinders, which was located on the roof of the fueling station, failed in service. Gaseous hydrogen was leaking from a screw fitting of the cylinder, but the hydrogen was not ignited. Three hydrogen gas sensors detected the leakage and triggered an alarm that resulted in an immediate emergency shutdown, isolating the leaking high-pressure cylinder bank from the other three banks and notifying the local fire department. No personnel were allowed to enter the roof area, approximately 7-9 meters above ground level.

The police isolated the area around the fueling station within a radius of 200 meters. The maximum content of the leaking cylinder bank was determined to be ~ 70 kg of hydrogen at 800 bar. The leak rate at the high-pressure storage bank was ~5 kg/hr.

After 2.5 hours, the hydrogen supplier's technician manually opened a bypass line to let the hydrogen escape through a vent line. This action was taken from the ground-floor control room well outside the hazard area.

About 4 hours later, the leaking high-pressure bank was essentially empty, with a pressure of around 1 bar. The cylinder with the failed polytetrafluoroethylene (PTFE)-sealed screw fitting was sealed with a plug with the intention of never using it again. There was no threat to employees or the public from this incident.

Corrective actions identified were: (1) The hydrogen supplier installed a fire-resistant material board adjacent to the high-pressure hydrogen storage banks to prevent any potential jet flames from affecting adjacent high-pressure cylinders. (2) The hydrogen supplier installed a semi-automated sprinkler system to cool the high-pressure hydrogen storage banks to prevent jet flames from affecting other hydrogen cylinders. (3) The alarm system was refined to send automated messages to relevant personnel informing them of gas/fire alarms.

https://h2tools.org/lessons/hydrogen-cylinder-leak-fueling-station

J-12. May 04, 2012: Pressure Relief Device Fails

A pressure relief valve failed on a high-pressure storage tube at a hydrogen fueling station, causing the release of approximately 300 kilograms of hydrogen gas. The gas ignited at the exit of the vent pipe and burned for 2-1/2 hours until technicians were permitted by the local fire department to enter the station and stop the flow of gas. During this incident, the fire department evacuated nearby businesses and an elementary school, closed adjacent streets, and ordered a high school to shelter in place.

There were no injuries and very little property damage. The corrugated roof on an adjacent canopy over a fueling dispenser was slightly singed by the escaping hydrogen flame, causing less than $300 in damage.

The station's operating systems worked as they were designed to function in an emergency. All equipment and fuel supplies were completely isolated, and all storage vessels were well within acceptable and safe pressure and temperature limits prior to and throughout the incident.

After a thorough analysis of the incident was conducted, corrective actions were taken to replace pressure relief valves, heighten vent stacks, modify response procedures, and improve communication protocols with first responders. A considerable amount of time was taken to review the station design, evaluate emergency action plans and procedures, meet with the public, train first responders, and conduct follow-up drills with employees and first responders. The station reopened 9 months after the incident and has been fully operational since that time.

Three root-causes were noted during the investigation: (1) the use of incompatible materials in the manufacturing of the PRD valve, (2) improper assembly resulting in over-torquing of the inner assembly, and (3) over-hardening of the inner assembly materials by the valve manufacturer.

https://h2tools.org/lessons/pressure-relief-device-fails-fueling-station

J-13. June 10, 2019: Fueling Station High Pressure Storage Leak

A hydrogen leak originating from a tank within a high-pressure storage unit serving a hydrogen vehicle fueling station resulted in fire and explosion. Emergency responders arrived on scene within 7 minutes and contained the fire within 3 hours. No damage was reported to the separate forecourt hydrogen dispenser or to other major station components within the station backcourt compound. No personnel injuries resulted directly from the fire and explosion, but a nearby vehicle airbag was triggered due to the explosion pressure, with minor injuries to the vehicle occupants. Immediately after the explosion, all potentially affected hydrogen stations were idled until the root cause was determined.

The root cause of the incident was subsequently identified as an assembly error of a specific plug in a hydrogen tank in the high-pressure storage unit. The inner bolts of the plug had not been adequately torqued. This led to a hydrogen leak, creating a mixture of hydrogen and air that ignited. The source of ignition has not been positively identified. An inspection and integrity verification program for the high-pressure storage units with similar plugs was implemented, including check and re-torque of tank plugs. Additional measures implemented include revised assembly, verification, and documentation of procedures as well as increased automated leak detection frequency. Dependent on site, additional ignition control measures are considered, including loose gravel removal/smooth surface around the high-pressure storage unit, additional backcourt compound ventilation, and higher extent use of explosion-proof components.

https://h2tools.org/lessons/fueling-station-high-pressure-storage-leak

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

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

The 17-member panel has over 400 years of 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 500 projects covering vehicle fueling stations, auxiliary power, backup power, combined heat and power, industrial truck fueling, portable power, mobile applications, and R&D activities.

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

HYDROGEN
Safety Panel