High-Pressure Hydrogen Hazards

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In the previous paper of this series, risks associated with potential hydrogen vapor cloud explosions were discussed, which is perhaps the most recognizable type of hydrogen hazard. However, hydrogen is stored and transported in high-pressure vessels and pipes, which represents additional inherent hazards. This paper focuses on hazards associated with hydrogen in high-pressure applications.

The sudden release of high-pressure hydrogen gas represents several potential hazards and risks. An accidental failure could result in injuries to personnel nearby if fragments or projectiles are thrown from the failed vessel or pipe. Sudden release of high-pressure hydrogen gas could also cause a blast wave that could injure personnel. Secondary debris impacted by projectiles or blast waves can result in injuries as well. In addition, an accidental release of high-pressure hydrogen gas can result in damage to infrastructure and equipment in the vicinity. Not only can this cause significant business interruption and repair costs, but it also can cause knock-on effects, such as subsequent failure of another pressure vessel if it is impacted by flying debris.

Types of Hazards

High-pressure hydrogen gas typically represents three main types of potential hazards: projectiles, blast waves, and pipe whipping.

Projectiles

Projectiles can be thrown if there is a failure in the material of the vessel. Projectiles could be a small fitting (Figure 1), such as a gauge or pipe that connects to the body of a pressure vessel, an end cap, or fragmentation of the vessel body. Failure modes can be thread stripping, bolt or weld failure, fracture due to material deficiency, over-pressurization, or other similar occurrence.[2] Vessel body fragmentation has been studied extensively for some time, and guidelines for hazard evaluations on this topic can be found in available references.[3]

High-Pressure Hazard Accidents[1]

Pressure sensor diaphragm rupture on hydrogen compressor. The sensing diaphragm of a pressure transducer (PT) supplied on an outdoor hydrogen compressor unexpectedly ruptured and released ~0.1 kg hydrogen to atmosphere. At the time of the incident, personnel were alerted by a loud 'pop' and dust disturbance. The facility monitoring system detected a loss of the PT signal and initiated equipment shutdown.

Hydrogen bottle rupture. A 2000-psia-rated gas cylinder (nominal size 10"×1.5") 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 since the cylinder was being filled in a test vault that was designed for high-pressure bursts.

Swagelok fittings under high pressure. After initial pressurization of a tubing run at 5200 psi, pipefitters realized they could not maintain the required test pressure of 5000 psi. Immediate troubleshooting of the 3/8" stainless steel tubing (0.065" wall thickness) run revealed a leak near the far end of the run at the Swagelok fitting and cap. The pipefitters removed the cap from the Swagelok fitting at the far end of the run, believing the balance of the tubing run to have been bled off. However, when the pipefitter loosened the cap, the Swagelok, ferrules, and cap were still under high pressure and blew off the end of the tubing run, becoming a projectile.

Over-pressurization of laboratory ball mill. Upon pressurization of a 70-ml reactor to 80 atm, a 270° rupture occurred around the perimeter of the reactor. The blow-out of the reactor resulted in a very loud noise, and the contents of the ball mill were thrown all over the lab. Since the pressure inlet valve is situated near the top of the ball mill, the person's hand was in the path of the lift-off of the top of the reactor and the person received a deep, 3-cm cut on the palm of the right hand.

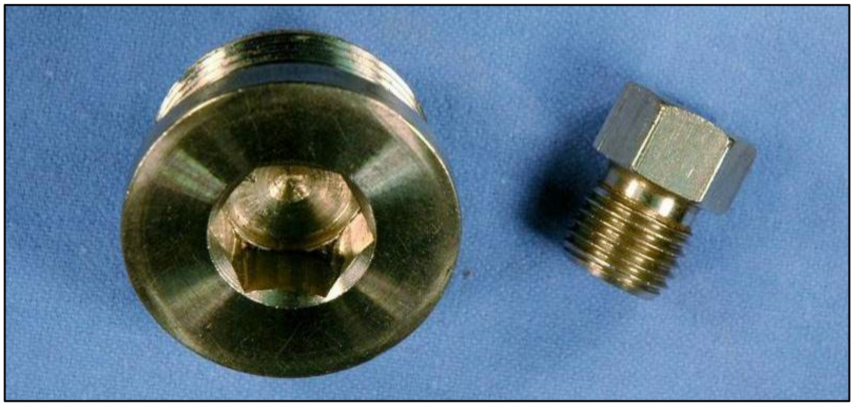


Figure 1. Typical Pressure Vessel Fitting

Methods are provided in the open literature to estimate the velocity of projectiles launched from high-pressure releases.[4] In general, the velocity of a threaded component is calculated as a function of its mass, diameter, and the distance it is pushed until it escapes the vessel or pipe body. Oftentimes, the push distance is taken as the length of threads. The projectile is accelerated as it travels through this portion of the body until it is launched into the open. For high-pressure hydrogen gas, the projectile typically continues to accelerate for a small distance after it clears the body as well.

Research recently conducted by BakerRisk for the Pressure Testing Research Cooperative (PTRC) has shown that these methods are conservative, sometimes by a significant margin. The PTRC is a consortium of companies who jointly sponsor research on a variety of topics related to hazards and safety of high-pressure systems. Specifically, the PTRC helps interested participants better understand and predict hazards in their pressure test facilities, learn how to effectively improve testing safety, and mitigate test fragment hazards with effective protective structures. The pressure vessel used in PTRC tests is shown in Figure 2, and an exemplar steel plate barricade perforated by a projectile is shown in Figure 3.

Figure 2. PTRC Test Pressure Vessel


Front View
Back View

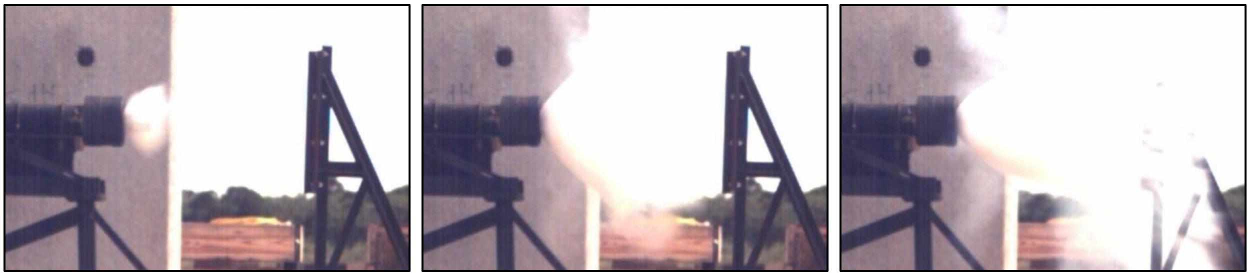
Figure 3. Projectile Perforation of a Steel Plate

Blast Waves
When gas-filled vessels or pipes fail, the escaping gas can cause a blast load. A discontinuity between the high pressure and the ambient air causes a shock wave to propagate away from the source, which might threaten personnel or nearby structures. The severity of the blast increases with pressure and charge volume, as well as with reduced standoff.

The manner in which a pressure vessel or pipe fails has a significant effect on the blast loads released to the surroundings. If it fails catastrophically by bursting the main body, the blast loads will be nearly equal in any given direction from the source (provided the vessel or pipe does not have a significantly elongated geometry, in which case the loads may vary appreciably close-in).

However, if a vessel fails by launching a fitting, plug, flange, or other such object formerly attached to the main body of the vessel, the blast loads will be focused such that pressures will be greater in the direction of the release and lesser in the opposite direction. In the far-field, the blast loads tend toward being equal in all directions (i.e., a hemispherical distribution). This failure mode tends to produce blast loads that have a long duration due to the time it takes for the pressurized medium to escape the vessel.

Blast loads tend to be more acute for releases of lighter projectiles. Heavier, slower moving plugs cause the vent area to open more gradually, reducing the strength of the leading shock wave. If the object takes an appreciable amount of time to release from the vessel, the magnitude of the blast pressures will be less than if an object is thrown from the vessel instantaneously. Images from test video for a sudden release of high-pressure gas are shown in Figure 4. Note the gas emitting from the vessel is visible due to the sudden expansion and cooling of the gas, which caused water vapor in the surrounding air to condense and form a cloud.[2]



Time = 0 ms Time = 3 ms Time = 6 ms

Figure 4. Blast Wave from Release of High-Pressure Gas[1]

It has been suggested that the blast loads ensuing from a pneumatic pressure vessel failure can be approximated by equating the stored energy to an equivalent TNT charge weight.[4,5] However, test results indicate that this simplified approach is accurate for a limited range of test conditions. Therefore, a more precise computational fluid dynamics (CFD) model is recommended for most applications. An example of a CFD model of a blast wave ensuing from a sudden release of high-pressure gas is shown in Figure 5.

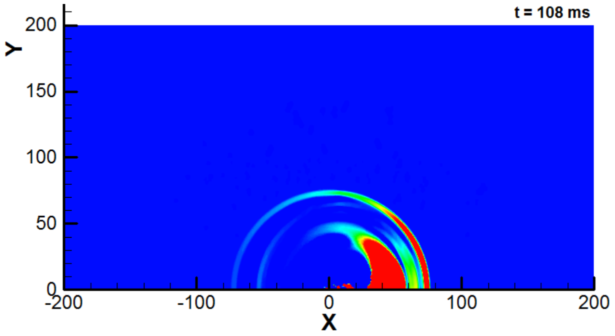


Figure 5. Blast Pressure Fringe Plot from End of a Horizontal High-Pressure Gas Pipe

Pipe Whipping

High-pressure hoses and tubes can fail, and in doing so they tend to whip and thrash around, sometimes violently. This type of pipe whipping can result in personnel injuries and damage to nearby infrastructure. Images from a test video performed for the PTRC to demonstrate pipe whipping are shown in Figure 6.

Time = 0 ms Time = 200 ms Time = 1000 ms

Note: End of pipe is shown in the yellow circle

Figure 6. Pipe Whipping Test[1]

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[1] Videos for this and other tests can be viewed at www.youtube.com/@bakerrisk946

Regulations and Requirements

Few regulations and requirements exist regarding protection from high-pressure hydrogen hazards. ASME Standard PCC-2 Repair of Pressure Equipment and Piping addresses some aspects of this topic.[6] Specifically, this Standard specifies minimum safe standoff distances for various biological hazards (e.g., eardrum rupture, lung damage) and structural failures (e.g., glass windows, brick walls) for gas testing, as well as for fragments that may be thrown. However, the methods used for these assessments are based on converting the stored energy of the high-pressure system to equivalent weight of high explosives (i.e., TNT), which is known to over-predict the overpressure and under-predict the impulse for a blast wave from a high-pressure release. PCC-2 mentions that barricades may be used to mitigate hazards from high-pressure releases, but it does not currently offer any guidance on how barricades should be designed.

The UK's Health and Safety Executive (HSE) has published Guidance Note GS4 Safety requirements for pressure testing.[7] That document provides guidance on procedures for high-pressure systems as well as managing risks associated with related hazards. It references another HSE document, HSE Contract Research Report 168 Pressure Test Safety, which provides significant background and detail on quantifying high-pressure hazards as well as determining barricade designs.[4]

Mitigation Options

Hazards from high-pressure hydrogen gas systems can be mitigated in a variety of ways. Some of the most common and practical approaches are discussed in this section.

Exclusion Zone

Implementing requisite standoff between the pressurized items and the people and infrastructure in need of protection is typically the least expensive mitigation option, provided that the necessary space is available.

Exclusion zones need to be provided for projectiles, pipe whipping, and blast waves. Standoffs for projectiles can be calculated based on an assumed trajectory for a given projectile. Projectile standoff is often taken as the distance the projectile may travel until it hits the ground. Standoffs for pipe whipping are determined based on how far the pipe may swing in any direction. Standoffs for blast waves are determined by developing a CFD model of the high-pressure release and finding the separation distance to an overpressure criterion. Typically, a criterion of 2.3 psi is used for this purpose, which is the threshold for human eardrum rupture.[8]

Barricades

Sometimes, the space needed to implement a safe standoff exclusion zone is not available. In this case, use of barricades can be an appealing mitigation solution. Accordingly, barricades must be designed to contain both projectiles and blast loads.

Projectile impacts result in two primary barricade response modes: perforation and structural response.

Perforation is a puncturing of a material by an object that creates a hole, as shown in the example in Figure 7. This is commonly a localized response based on the barricade thickness and material properties. There are several analytical procedures of varying accuracy for calculating the perforation thickness threshold of various materials.[9, 10, 11] However, the mass and velocity of pressure vessel projectiles tend to be outside the bounds of validated ranges used to develop the predictive equations in most of these procedures. For this reason, tests were performed for the PTRC to validate and improve upon the perforation models.

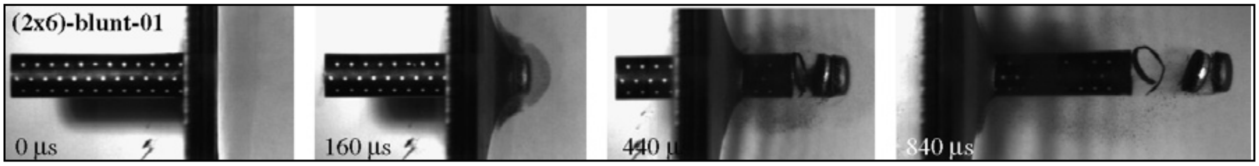

Figure 7. Example Projectile Perforating a Plate[12]

Designing for structural response involves evaluating deflections of a structural component in a more global sense. These deflections can result from a projectile impact or blast loads. Structural barricades should be designed to prevent failure in this response mode so that these hazards are contained and so that the barricade does not become a secondary debris hazard to personnel in the area. Structural barricades should be designed so that they can exhibit ductility in response to these impacts. Oftentimes this involves ensuring that a component's connections and supporting framework can withstand the response reactions transferred to them by the impacted component.

Barricades can be designed for structural response in several ways. One approach is to model each component as an equivalent spring-mass system in a single-degree-of-freedom (SDOF) approach. The nonlinear dynamic SDOF methodology described in standard texts is a widely accepted approach for estimating damage to structural components subjected to time-varying blast loading and/or projectile impacts. The SDOF approach is a government and industry accepted methodology that has been described in many guidelines.[13,14,15]

Structural barricades can also be evaluated numerically using finite element analysis (FEA) models. If an FEA approach is used, then a first principles-based code that can solve the dynamic response either implicitly or explicitly is recommended. This can be used to model both projectile impacts and blast loading applications. If done correctly, an FEA model should be more accurate than a simplified analytical approach. It will also provide more information for the modeler, regarding the dynamic response of the structural barricade. However, most first-principles-based FEA codes cannot adequately model the localized perforation mechanics of a projectile impact. Therefore, this response mechanism should be modeled using the previously described analytical methods. Alternatively, there are some smooth particle hydrodynamics (SPH) numerical codes that have been shown to effectively model localized perforation mechanics for some projectile impact applications. An example of an SPH model is shown in Figure 9.[16]

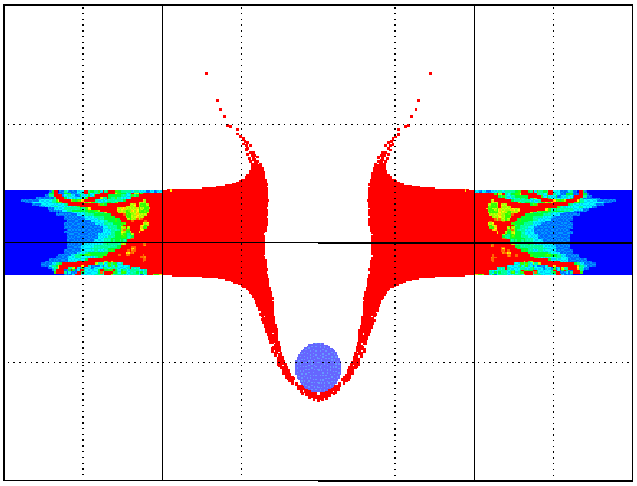

Figure 8. SPH Model of Projectile Perforation

An example of an FEA model is shown in Figure 10 in which a projectile impacts a barricade. For this case, the projectile was a long cylinder that had an initial velocity, and the barricade was a system of steel plates supported by a steel tube framework. As seen in the figure, the FEA model shows the dynamic response of the barricades and projectiles in terms of displacements, strains, and other such engineering parameters. It also reveals how a projectile might ricochet off a barricade. Published response criteria can be used in addition to the numerical results to determine appropriateness of a barricade design through use of an FEA model.

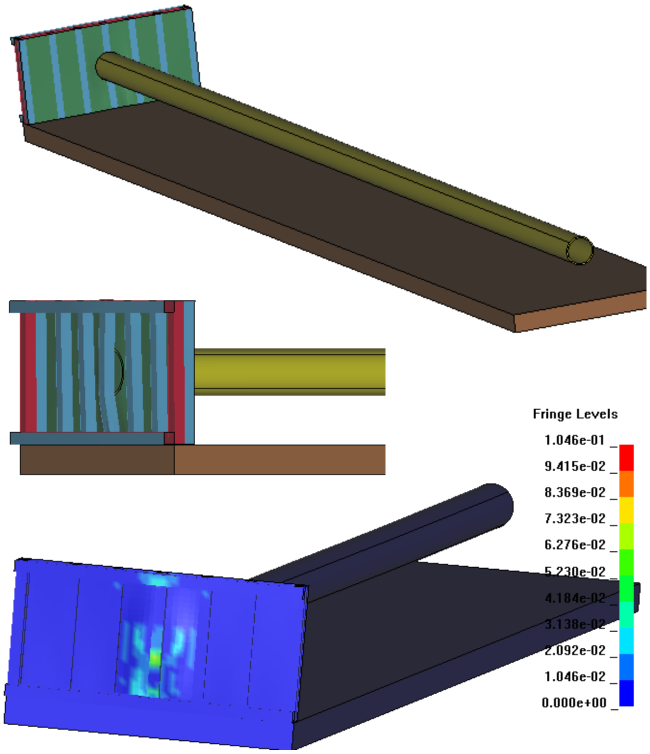

Figure 9. FEA Model of Projectile Impact

Several types of barricades have been used for protection from high-pressure hydrogen. If projectile protection for only a certain direction is needed, then a screen may be sufficient. If full protection from projectiles and blast loads is required with a limited available exclusion zone, then an enclosure may be used. Many facilities prefer to have these types of barricades designed and constructed off-site in a turnkey approach to minimize interruptions to their operations, such as with BakerRisk's SAFE™ (Shock And Fragment Enclosure) products.[17] Some examples of high-pressure barricades are shown in Figure 11.

Prefabricated SAFE™ Chamber

Portable Screen

Figure 10. Barricade Examples

Hose Restraints

Hose whipping hazards can be mitigated through two options: whip checks and anchors.

Whip checks are safety cables that connect hoses across a coupling to prevent the hoses from flying around in the event that the connection fails.[18] While use of a whip check does not eliminate the hazard, it enhances protection by limiting how far the hose may thrash around and how far high-pressure gas may jet away from the equipment. An example of a whip check is shown in Figure 12. Whip socks are similar to whip checks and typically contain braided wrappings that are installed around the end of a hose, which are connected to eyelets that can be secured.

Another option to mitigate hose whipping is to install anchors at regular intervals along a hose or pipe.

Hose anchors typically consist of a small steel plate that covers the top of the hose and is anchored to a structural support with bolts on both sides of the hose. The anchor limits the distance that a hose can thrash around as it is limited to the distance between the anchor spacings.

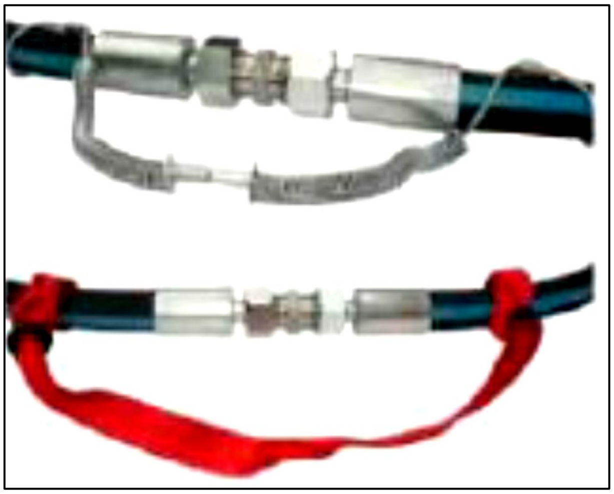

Figure 11. Whip Check Example[7]

Conclusions

The hydrogen industry requires systems operating at high pressures, which present various types of hazards to both personnel and infrastructure. With few regulations and requirements available to ensure safety in this industry, this paper can assist in understanding some of the hazards and some options for mitigation. The next paper in this series will further discuss consequences of hydrogen hazards through some full-scale field tests of hydrogen releases and explosions.

References

1 https://h2tools.org/lessons/high-pressure-100-bar, accessed May 2023.

2 Edel, M., Ketchum, D., and Falcon, J., “High Pressure Testing Hazards,” PVP2009-77439, Proceedings of the 2009 ASME Pressure Vessels and Piping Conference, Prague, Czech Republic, 2009.

3 Baker, W.E., et al, “Workbook for Predicting Pressure Wave and Fragmentation Effects of Exploding Propellant Tanks and Gas Storage Vessels,” NASA Contractor Report 134906, No. NAS3-19231, 1977.

4 Pressure test safety, Contract Research Report 168, Health and Safety Executive, 1998.

5 Safety in pressure testing, Guidance Note GS4, Health and Safety Executive, 1998.

6 Repair of Pressure Equipment and Piping, PCC-2, ASME, New York, 2022.

7 Safety requirements for pressure testing, Guidance Note GS4, 4th Ed., Health and Safety Executive, 2012.

8 Baker, W., et al, *Explosion Hazards and Evaluation*, Elsevier, New York, 1983.

9 Recht, R. and Ipson, T., “Ballistic Performance Dynamics,” *ASME Journal of Applied Mechanics*, 1963, pp. 384-390.

10 Kennedy, R., “A Review of Procedures for the Analysis and Design of Concrete Structures to Resist Missile Impact Effects,” Holmes and Narver, Inc., ELCALAP Seminar, 1975.

11 A Manual for the Prediction of Blast and Fragment Loadings on Structures, U.S. Dept. of Energy, DOE/TIC-11268, 1992.

12 Dey, S., et al, “On the ballistic resistance of double-layered steel plates: An experimental and numerical investigation,” Intl. Journal of Solids and Structures, Vol. 44, March 2007, p. 6701-6723.

13 Biggs, J., *Introduction to Structural Dynamics*, McGraw-Hill Publishing Company, New York, 1964.

14 Structures to Resist the Effects of Accidental Explosions, U.S. Dept. of Defense, UFC 3-340-01, 2008.

15 Design of Blast Resistant Buildings in Petrochemical Facilities, 2nd Ed., American Society of Civil Engineers, New York, 2010.

16 Bogosian, D. and Gerber, B., “Analytical Predictions of Fragment Penetration through Hollow Concrete Masonry Units,” 75th Shock and Vibration Symposium, Virginia Beach, VA, 2004.

17 https://www.bakerrisk.com/products/safe-shock-fragment-enclosure/, accessed May 2023.

18 https://www.corrosionpedia.com/definition/6124/whip-check, accessed May 2023.