Liquid Hydrogen: Safety and Design Considerations Webinar Q&A

Key words: plume, vapor, ignition, venting, pressure, tank

The information in this document provides answers to the questions that were raised during the Center for Hydrogen Safety February 7, 2023 webinar.

1	**What rationale is used for Plume dispersion study and placing the hydrogen detectors?** Hydrogen detectors are not usually used outdoors due to the variability of wind and weather, the one place outdoors for hydrogen detection is for hydrogen dispensing to the public at the hose. In the case of the Video shown in the class we had sensors distributed around the entire spill pad and at a range of heights because of the problems mentioned above.
2	**With regards to plume dispersion, will the h2 gas be mixed with the water vapor cloud or reside above/below the water vapor?** Initially the H2 Vapor is more dense than air and will drop towards the ground, but it will rapidly become buoyant. In the low wind condition the GH2 rises with the vapor cloud and for the most part is resident in the cloud. In the higher wind condition the hydrogen is blown by the wind and is resident with the cloud for awhile, but then will be seen rising above the cloud and still influenced significantly by the wind.
3	**Is that fire exposure setback measured in terms of radiant heat output?** It is not, but the vent stack design outlet is based on radiant heat exposure.
4	**How much risk reduction is typically targeted through the safety controls on these vessels?** This is difficult to assess since a quantitative risk assessment is difficult to conduct and in general, we talk about tolerable risk or accepted residual risk. That being said, the design for the cryo-vessels that were discussed is very robust and the history of use of these designs has been excellent with very few if any incidences due to a design feature.
5	**Can you speak to the typical inspection/testing requirements of the safety circuit (rupture disks / relief devices)?** The typical change-out or retest period is 5 years within the industrial gas industry. Annual inspection is recommended.
6	**Have you encountered any instances where hydrogen ignited following burst disk rupture in LH2 applications?** Yes, high-velocity cold H2 gas has ignited during a rupture disc activation.
7	**Usually, we provide a pressure gauge between rupture disk and safety valve. I did**

	not see it in the picture you have shown. Was it provided and if not, why? A pressure gauge is not usually provided as one set (safety valve and rupture disc) and is always online by design. If the diverter valve connecting the (2) sets of relief devices is in the center position, both sets are online. For the secondary stack with a rupture disc and a locked open valve, a pressure gauge is installed.
8	**Can you please discuss the criticality of H2 system cleanliness, recommended cleanliness levels for components, and best practices when opening up H2 systems for maintenance/service?** The cleanliness of an H2 piping system is based on its end use, not usually for safety. For instance, if a moderately clean system is required, oxygen cleanliness may be specified. Electronic grade oxygen systems are the next-level cleanliness. Safety-related cleanliness is based on particulate and filtering. Particulate may cause regulators and safety valves to not operate correctly.
9	**Can safety systems cope with large damage to the outer layer and/or total loss of vacuum?** Yes, the safety system is sized for these higher flow rates. The spring-loaded safety valves are sized for lower flows, such as runaway pressure build or loss of vacuum. Higher flow requirements, such as loss of vacuum combined with fire, are handled by the rupture discs, sized for such an event.
10	**Vent loses are expensive and we're seeing some stations venting from the vaporizers but this venting is not happening during fueling. Is this necessary for pressure release?** Gases can be stored in theory, forever, as long as the system integrity is not compromised. However, all cryogenics are "use it lose it" unless a refrigeration loop is provided (almost never). Thus, a gas use must be available to use all the heat leak for an LH2 system. In some cases, this is not possible. For instance, for fueling applications, if a gas compressor is not installed, the gas formed in the tank and during cryogenic pump operation will vent from the tank vent stack. If a compressor is installed, the waste gas can be compressed into storage tubes and used for fueling. In cases of purging or cooling down tanks, the gas is wasted. For LH2 tanks at low pressure (less than 100 psig) using gas, the hydrogen losses can be eliminated by gas use first circuits and tank sizing. The tank size is a big part of the gas generated.
11	**Could you please re-explain the design basis and functionality of the pressure build regulator?** The pressure regulator controls the liquid flow from the tank to the pressure build (PB) vaporizer. As the tank pressure falls, the pressure regulator opens and when the tank low end pressure set point is reached, the regulator closes. The set point of this regulator should be at least ~10 - 20 psig or ~1 barg above the use pressure

	since the house-line regulator needs this pressure to supply hydrogen and control accurately. The set point of the pressure build circuit depends largely on the required use pressure and the system house-line pressure drop which is driven by peak flow rate, pressure, and temperature. The PB design circuit requires knowledge about peak use flow from the tank, which in turn drives the size of the vaporizer heat transfer and the flow rate through the PB circuit. The flow through the PB circuit is based on the replacement of the withdrawn liquid with gas at pressure and temperature to maintain constant tank pressure. As the liquid is removed from the bottom of the tank, the same volume of the liquid removed must be replaced with the same volume of gas. Since density varies significantly with pressure (for both saturated liquid and gas), the flow through the pressure build unit is greatly affected by gas and liquid density which is affected by pressure/temperature of the fluids.
12	**What is H2 purity requirement?** H2 purity varies based on source (GH2 or LH2) and requirements. You can buy higher purity but it costs more. For GH2 the Compressed Gas Association (CGA) has typical purities; see G-5.3 Commodity Specification for Hydrogen. Standard gas is 99.95% with LH2 standard purity at 99.9998% by volume. Impurities tested for are typically H2O, O2, CO, CO2, and hydrocarbons, to name a few. Not all impurities are tested for (as there are many), but the expected ones are typically tested.
13	**What is the Media used to Vaporize H2 in the Economizer?** Ambient air vaporizers using ambient heat, the heat in the environment is used to warm the cold gas.
14	**Also, any design experience regarding radiation for H2 vent stacks that may auto-ignite?** Hydrogen fires have very low radiation and that actually can be an issue since you do not feel the heat from the hydrogen flame until you are very close to the flame. The temperature of the flame, however, is very high so if the flame contacts materials around the vent stack they are likely to melt or ignite.
15	**For the LH2 tanks, what stainless steel was used (is it SS316L) and are the tanks multilayered?** Typically, the material used is 304 SS. 316 SS or 316L can be used but due to cost, it is typically only used for higher purity systems (electronics grade). All tanks manufactured today are multilayered. Typically, perlite tanks are only available, as used tanks.
16	**What are the typical boil off rates for bulk stored hydrogen?** Boil-off is based on every piece of equipment and operation that is wetted by LH2 or cold gas. The LH2 tanks rates vary based by tank size. The heat transfers occur on the tank

	surface area, connections into/out of tank, and the tank supports. Typical heat transfer is defined by Normal Evaluation Rate (NER). This is a daily rate based on tank gross size. This does not change appreciatively if the tank is full or almost empty. Typical NERs range from 1.5%/day (1500 – 3000 gal tanks) to ~1%/day for larger tanks.
17	**Can you speak about controls regarding dispersing of H2 cloud through the vent stack given the risk of LEL and UEL limits?** The reason that the standards related to venting and vent design are written the way they are, is to control the risks so that the H2 is discharged above the roof-line, away from ventilation intakes, and away from electrical ignition sources. There may be configurations or vent rates that are beyond what the standards are considering and therefore all vents should be analyzed for compliance to the standards, but also consider any special conditions.
18	**Would they consider bird screens for the vent stack outlets?** Yes, bird screens are acceptable and may be needed. The openings must be large enough to allow the required flow rate. The screens have been 1/4" SS rounds welded to the outlet, not always traditional screening.
19	**Does residual liquid in supply trailer cause return transport problems?** The DOT has requirements for transporting hydrogen to assure: 1. The tanker does not become liquid full through cryogenic liquid expansion through warming. 2. The tanker does not vent over the road by using the requirements of guaranteed rated holding time (RHT) as defined in DOT 178.338-9 for a given pressure. Because of the low temperature of the LH2 at the beginning of the trip, the volume of gas space when empty, and the guaranteed RHT, venting of LH2 tankers on the road is not usually an issue and is only allowed in an emergency. If such a case occurs, the drivers must find a location to safely vent the trailer.
20	**Is the top of the vent stack closed or open?** It can be both. Vertical release openings are capped with open-able caps (flappers/silicone on caps (tube rupture discs) and side vents are uncapped.
21	**Reg. vaporizers, do they exist for high pressure applications so that liquid hydrogen can be pump at say 600# pressure and then vaporized rather than applications at near ambient temperature?** High-pressure vaporizers are available up to very high pressure (i.e.,10,000 psig). The design uses a thick-walled stainless-steel tube for the wetted surface, inserted into an aluminum outer tube with extruded fins for heat transfer surface area. A heat transfer paste media is applied between the SS outer wall of the inner tube and the aluminum wall inner wall of the outer tube

22	**What is your guess of losses from the liquefier to dispensing nozzle to LH2 HFS?** Losses in the LH2 industry have been estimated as high as 10% of the delivered product. Cool down and delivery losses are the highest, followed by tank and cryo-pump heat leak.
23	**Any anti-icing technology used for LH2 tanks?** Yes, anti-icing techniques are used where ice or liquid air create issues and include vacuum jacketed piping, insulated piping (not a good solution today), or just elevation to keep the ice from bridging to the ground.
24	**Top filling vs Bottom filling. Which method is safer and what are the pros and cons of each?** There is no correct, safer, fill solution. The safer and more economical solution minimizes or eliminates hydrogen venting, while controlling the tank pressure. Whichever fill type achieves this is the type used. For LH2, it is usually a matter of controlling the tank pressure. Bottom fill During the bottom fill process, the driver opens the bottom fill valve and fills the tank with liquid from the tank bottom. As the vapor space compresses, the tank pressure rises. This is typically used when the liquid in the tank is sub-cooled and the tank pressure is dropping during a fill. Top fill During the top fill process, the colder liquid entering the vapor space of the tank, condenses the warmer gas in the ullage space, reducing the pressure. This method is used when the tank pressure is rising during a fill or is too high when the driver arrives to minimize venting. However, if the tank is venting due to lack of use or increased heat leak, bottom filling causes less vent losses in the long run, as the warmer gas is vented and the energy in the warm gas is not put back into the liquid (as it is with top filling).
25	**Obviously, the physical construction of the piping systems, tanks, valves, pumps, etc. is very specialized. Could you list some of the major manufacturers of these items?** Chart is by far the largest supplier of cryogenic equipment. They have spent the last 20 years buying all the smaller specialized companies like LOX Equipment (Tankers and Cryogenic Tanks), Process Engineering (Cryogenic Tanks), Thermax (Vaporizers), and Howden, to name a few. Other companies include Nikisso Cryoquip, Cosmodyne, Taylor Wharton, Acme Cryogenics, Technifab, Eleet Cryogenics, Gardner Cryogenics, CTR, and many more.
26	**If there is a container failure is VCE or BLEVE possible?** Yes. This is especially possible if the vent system is plugged. Although many

	elements can plug a vent stack, water has the most potential. The only element that does not freeze at LH2 temperature is helium.
27	**How do drip trays mitigate the risk of liquid oxygen pooling?** Drip trays do not mitigate the risk of Liquid Air/enriched oxygen pooling but they do control the surface on which the liquid is in contact with and stops the liquid from running onto an incompatible material such as asphalt, vegetation, or oil soaked surfaces.
28	**LH2 storage spheres have sprinkler piping added but the smaller vertical cylindrical tanks don't - why?** By far the majority of the liquid hydrogen tanks do not have sprinkler systems. These are not required and usually unwanted.
29	**Are flares used instead of vents for liquid hydrogen? Is this a used practice? best practice? is it safer to flare the hydrogen to control effects instead of venting and taking the risk of late ignition and detonation?** Normally flaring is not done for hydrogen supply systems due to the small piping diameters and the variable flow rates. The largest stacks are the LH2 vent stacks on trailers and tanks for the main safety valves which are 3". Air in smaller stacks have not caused issues with 60 years of use in many systems. API 521 is the only code that addresses flaring, Flaring is also addressed in the NASA Safety Standard ANSI/AIAA G-095A-2017; however, while good advice on design of flare systems has been retained in the most current version, the recommendation for flaring above a certain discharge rate has been rescinded. There are no hydrogen standards recommending flaring hydrogen. The only place (we are aware of) that flares hydrogen is NASA. That is due to the large, continuous controller release that can occur (for example unloading a launch rocket storage tank for a scrubbed launch). This makes sense, as a large, cold unignited release can form a cloud and ignite explosively. It is easier to flare as the flow rate is fairly constant while the explosive danger is larger due to a large flow rate. NASA does not recommend venting without flaring if the H2 vent rate exceeds 0.3 kg/s, for this reason. Flaring dangers come from flame quenching, flame burnout, and flame dip. This requires many additional safeguards in the design. Even API 521 (5.7.4.3) indicates hydrogen requires a special design. Low gas exit velocities and buoyant flames are preferred for successful combustion of low-heating-value relief gas. High gas exit velocities are preferred for higher-heating-value hydrocarbon relief gases or for relief gases rich in hydrogen. Because of the high flame velocity, wide flammability range, buoyancy effects and noise, hydrogen flares require special design considerations. The manufacturer should be consulted for details. Flaring is typically a hydrocarbon function. API 521 recommends flaring most hydrocarbon, due to the pollution (5.7.3.1) and small potential for explosion upon flame quenching. Also, many facilities have a constant stream of flammables. The reactivity and flammability dissuade flaring when the "flaring poses more hazards than benefits", as stated in API 521 (section 5.2.1), which can be argued, which is

	the case with hydrogen in the industrial gas world. > Some compounds (e.g. ethylene oxide) have such high reactivity and flammability that flaring poses more hazards than benefits. Other options shall be considered for these compounds such as scrubbers, etc. Hydrogen is typically on the opposite end of the spectrum. Very low pollution with larger potential for explosion on re-ignition. Hydrogen vent stacks have traditionally been non-flared for the above reasons.
30	**Could you discuss the procedure with handling a vent that has ignited?** Let it burn unless the source of hydrogen can be isolated. Putting out the fire without isolating the source can cause the hydrogen to reignite, potentially explosively. Vent stacks should be designed for a fire.
31	**Liquid to gas (to 350 or 700atm)...what losses can we assume?** There are many variables needed to answer this question. It depends on the system design. With a compressor (expensive capital) the losses can be near zero. If the LH2 is not compressed but pumped, the losses will be higher. The tanks generate ~ 1/3 to 1/2 of their volume monthly in gas. A 20,000-gal tank will generate~ 600,000 scf/mo (vaporizer 6,000 gals of LH2). The pumps also generate hydrogen gas. A 20,000 gal LH2 tank system can generate 1,000,000 scf/mo of losses including the pump losses. There are also losses in every delivery.
32	**What are good options (if any) for a safe type of piping insulation other than vacuum jacketing (VJ) for LH2 or very cold super-critical H2 lines, which don't need to have such a low conductivity as VJ and which may be lower cost than VJ ?** There are no good options besides VJ, that we are aware of. For external insulation, the issues are a hydrogen leak under the insulation (flammability of hydrogen) oxygen-rich air condensing on the piping, and the cryopumping air (and moisture) into the insulation. Flammability of the insulation of concern in the 1st two cases and increased heat transfer is of concern for moisture cryopumping when the insulation integrity is breached. Most foam insulations are made from hydrocarbons (polyurethane foam) that burn from either a hydrogen fire or react with oxygen to burn as well.
33	**Do LH2 systems require lightning protection for a vertical tank and vent stack?** The vent stacks must be grounded. The thick wire used acts as lightning grounding. In theory, the vent stacks are large lightning rods due to their height and being metallic.
34	**Are there any non-metallic materials that are compatible with LH2?** Teflon (PTFE) is the most used gasket material with hydrogen. A list of materials commonly used is given on slide 11 in the presentation. This list includes PTFE, CTFE, and glass-filled PTFE.
35	**What is a safe cooling rate (°F/min) for the first fill of LH2 Tank to prevent**

	embrittlement? Are there any standards that give guidance on this matter? LH2 cool-downs take hours and it depends on the tank size and purge methods used. Typically, a temperature-sensing device on the inner vessel is not available and fog out of the vent and liquid on the level gauge are used as a cool-down indicator. Larger tanks (20,000 + gals) take longer than smaller tanks. Horizontal tanks take longer than vertical tanks. There is a weight factor in the cool-down time in deg ^{o}F/hr. Cool-down takes place in several steps. 1. Purge the nitrogen from the tank with warm hydrogen or cold gaseous hydrogen from the delivery trailer (without solidifying the nitrogen in the tank). This purge can help with the cool-down. 2. Once purged use cold gas from the delivery trailer to start/continue the cool-down. This is a slower cool-down than using liquid so the deg ^{o}F/hr. is slower than liquid. 3. Start pressure transfer of LH2 into the tank very slowly through the bottom fill. 4. Once the inner vessel exhibits cooling (cold from the vent stack), some liquid is put into the top fill. 5. Do not pump off until liquid is indicated on the liquid level gauge. The general cool-down takes anywhere from 4 -12 hours depending on the tank size (1500 - 25,000 gals). Doing the math, the average cool-down (which is not indicative of the process – slower at the beginning, slightly quicker towards the end) ranges from 125 deg/hr. to 42 deg ^{o}F/hr. The tank may take another 24-48 hours to fully cool-down the inner vessel and insulation.
36	**Is the secondary containment needed for equipment handling LH2?** No there are no recommendations to contain LH2 in the case of a release. It is not advisable to trap LH2 as it vaporizes rapidly.
37	**What is a typical boil off rate per day for a trailer and a tank with LH2?** See question 16 for tanks. Trailers are worse as they travel over the road, and the vacuums and supports lose heat transfer integrity from vibration and other over the road equipment movement.
38	**What about surge protection in LH2 system?** Not sure if this is electrical or piping. No surge protection is usually used for either. Surging in piping can be an issue in heat exchangers, especially non-ambient (e.g., steam). If the LH2 in the exchanger finds a “hot spot” in the exchanger, a pressure wave can develop and cause flow both upstream and downstream. This eventually causes a pressure void which then refills and the process starts again. This can be dampened by a liquid orifice or regulation but it is difficult to fix.

39	**Do NFPA 2 setbacks for LH2 already account for hazards associated with plumes?** They account for the leakage and interaction between other exposures. They do not take into account the distance for deflagration.
40	**What is a typical % of vapor generated when loading liquid hydrogen into the trucks?** Typically, almost no vapor is generated at a fill. That is because the tanker being loaded has some remaining LH2 and it is already cold. Small amounts of gas generation can occur from vacuum jacketed pipe, and container heat leak. Fill losses are usually minimal as the small amount of gas generated can be recovered at the plant via refrigeration.
41	**Are the safety requirements of liquid hydrogen and cryo-compressed hydrogen the same?** Mostly the same. Cryopumps require additional safeguards for the higher pressure and temperature effects of running cryo-compressed warm.
42	**You talked about LH2 storage having 2 vent stacks for redundancy. Are systems with only 1 vent stack common? Or is it a common practice to have 2 vent stacks per tank?** The addition of the 2^{nd} stack developed over the last 20 years. Originally, one stack was common in the 70, 80's, and 90's. Although the frequency of a tank BLEVE occurring is low, the effects are catastrophic. As the stacks are a single source of failure, 2 have become more of the norm.
43	**How comprehensive is the material data for tank and pipe materials down at liquid hydrogen temperatures? Is there a suitable data source that can be used to inform parameters for physics modeling of component design for liquid hydrogen environments?** NIST.gov has thermodynamic properties of LH2. Hydrogen (nist.gov) Material data is fairly available. Materials are chosen based on the ability to perform in the cold while maintaining the necessary tensile strength for the pressure. Other design parameters include melting point and permeation of hydrogen. 304 or 316 SS are the best metals for LH2. Although Aluminum is used for storage vessels, there is concern about the melting of aluminum from a small or large hydrogen fire. See: Technical Reference for Hydrogen Compatibility of Materials | Hydrogen Tools (h2tools.org)
44	**How is the changing density of H2 in a drum factored into the level instruments? What level of uncertainty does this add?** Level readings on a tank are not accurate and more analogous to a fuel gauge in a car. Level readings should not be used as absolute measures or for flow

	calculations. Not only does the density change based on temperature and pressure, but the liquid and gas stratify, making a non-uniform mixture. The accuracy from the density change can be off by as much 30%. That is why full is determined by a full try-cock valve set at 90-95 % full. Once liquid flows out of this valve, as measured by temperature, the tank is full.
45	**Besides NASA, what industries and companies have the most experience in handling and storage of liquid hydrogen?** Industrial gas companies have the most experience, as they deal with many types of systems, and with designs, maintenance, and deliveries, etc. These are companies like Praxair/Linde, Air Products, Messer, and Air Liquid/Airgas. The 2nd tier are the companies that provide the equipment but do not deal with daily issues such as Chart, CTR, Eleet Cryo. The next most experienced are companies that deal with hydrogen and own their own equipment. These are companies like NASA, Boeing, etc.
46	**I've noticed that natural gas pipeline utilities are developing an interest in getting more involved. What recommendations can you give these potential new players?** Become part of the hydrogen community. Volunteer for codes and standards committees (NFPA and CGA) and hire an expert in the area.
47	**For liquid hydrogen transportation, will the train be considered as a transfer method or is that already been applied in some countries? Thanks.** It is possible but not probable unless venting hydrogen is acceptable, and the vehicles to be filled must be close to the train (the fill lines are vacuum jacketed). The issue with density reduction, liquid growth, and vent losses must be addressed.
48	**Are there examples of LH2 storage systems located in relatively populated areas? For example, the H2 filling stations.** Yes, LH2 is in many cities. Besides fueling stations, LH2 is typically in industrial areas with fewer in residential areas.
49	**What are the best ways to find leaks in LH2 systems (snow, ice, rain from connections)?** LH2 leaks are not usually leaking LH2 but cold GH2. LH2 changes phase very quickly and easily. Visible icing is a good way to look for leaks in cold piping. Portable analyzers and soap solution are also used. Sound can be used, but by then the leaks are larger. Leak tape has been introduced in the last several years and can be applied.
50	**Is a Flash Back Arrestor allowed on the Vent Stack?** It is not allowed due to the large pressure drop associated with it. The European

	Industrial Gas Association specifically disallows it. The Compressed Gas Association (CGA) is silent on the subject but does indicate that pressure drop must meet API 520 and ASME. The vent stacks are designed for deflagrations using thicker walled pipes within CGA and EIGA documents. Flames do not typically flow back into the stack as the only oxygen in the stack is there at the initiation of flow. After that there is no oxygen for combustion.
51	**Since NFPA2's setback table tops out at 75,000 gal, what approach are you seeing for larger onsite storage volumes?** Anytime that you get beyond the standard then special analysis must be considered that accounts for all design choices, ignition mechanisms, and possible outcomes of ignition.
52	**Do you assume welding of pipes for cryo H2 is leak tight, or are there any standards that specify the failure leak rates/sizes for different diameters of welding?** Weld and weld inspection are addressed in ANSI/AIAA G-095A-2017, which further references ASME B31.12 and B31.3.
53	**I'm asking about surge in LH2 pumping system? Is there any protection required?** For pump systems, there are always large surge tanks (gas containers) downstream of the vaporizer. This is not only for surging (as the piston sends liquid down the line and then reloads), but also as the usage flow rate does not usually match the pump flow rate. This design handles any surge issues.
54	**Is there an emergency shutdown link between the tanker and the stationary tank?** Normally there is not. There is one on the tanker (to close the delivery liquid line) and one on the tank (to isolate the flow from the tank). All other circuits have no shutdowns on them and these shutdowns are not connected.
55	**Is it better to use a concrete wall to separate LH2 tanks or is it better to just use distance between tanks?** Distance is safer (opinion). Concrete walls (fire barrier walls) are used when there is not enough distance. The design/use of any barrier walls must be evaluated for its potential to cause confinement of the H2 and to reflect deflagration pressure waves.
56	**What type of gas is used for purging liquid hydrogen pumps?** If they need to be purged, helium for cold (less than -200 deg °F) and nitrogen for warm -200 deg °F or warmer)
57	**What is typical design pressure of transport tanks for LH2?** This varies by the industrial gas company. Most are at 150-160 psig while some are

	at 50 psig or less. The lower pressure vessels usually require pumps to offload. The high pressure containers use a pressure cascade to deliver.