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Are Unconfined Hydrogen Vapor Cloud Explosions Credible?

James Kelly Thomas, Craig Eastwood, and Martin Goodrich
Baker Engineering and Risk Consultants, Inc., 3330 Oakwell Court, Suite 100, San Antonio, TX 78218-3024; KThomas@BakerRisk.com (for correspondence)

Published online 26 May 2014 in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/prs.11685

Owner/operators of chemical processing and petroleum refining sites often ask whether unconfined hydrogen vapor cloud explosions (VCEs) can actually occur. This question normally arises during the course of a consequence-based facility siting study (FSS) or a quantitative risk assessment (QRA). While it is generally recognized that a hydrogen release within a process enclosure could lead to an explosion, the potential for an external hydrogen release to cause a VCE is not as widely recognized and is often questioned. This uncertainty appears to stem from the impression that a hydrogen release always ignites quickly and near the point of release such that a flammable cloud does not have time to develop prior to ignition and/or that a hydrogen release never produces a flammable cloud of any significant volume due to its positive buoyancy. Unfortunately, neither impression is correct. Hydrogen releases are actually susceptible to delayed ignition, and hydrogen releases can form significant flammable gas clouds near grade level. Unconfined hydrogen VCEs can and do occur. Furthermore, given the potential for rapid flame acceleration associated with hydrogen, the consequences of a hydrogen VCE can be severe. Consideration of such events in FSS and QRAs is, therefore, warranted.

Prior accidental hydrogen VCEs are reviewed to establish that such events do occur. Selected hydrogen VCE tests are also discussed to establish the potential severity of such events. Moosemiller and Galindo [10th Global Congress on Process Safety, 2014 Annual AIChE Meeting, New Orleans, LA, March 30–April 2, 2014] reviewed the ignition characteristics of hydrogen relative to the potential for a delayed ignition, and only the conclusions from that article are presented here. Example dispersions, using both simplified dispersion and computational fluid dynamics methods, are presented to illustrate the flammable gas volumes that can be created by hydrogen release scenarios. Blast load predictions are presented to illustrate the range of loads that could result from a hydrogen VCE due to such a release. © 2014 American Institute of Chemical Engineers Process Saf Prog 34: 36–43, 2015

Keywords: hydrogen; vapor cloud explosion; accident; ignition; dispersion

INTRODUCTION

Owner/operators of chemical processing and petroleum refining sites often ask whether unconfined hydrogen vapor cloud explosions (VCEs) can actually occur. This question normally arises during the course of a consequence-based facility siting study or a quantitative risk assessment (QRA). While it is generally recognized that a hydrogen release within a process enclosure (e.g., a building) could lead to an explosion, the potential for an external hydrogen release to cause a VCE is not as widely recognized and is often questioned. This uncertainty appears to stem from the impression that a hydrogen release always ignites quickly and near the point of release such that a flammable cloud does not have time to develop prior to ignition and/or that a hydrogen release never produces a flammable cloud of any significant volume due to its positive buoyancy.

While the practices and policies of specific petroleum refining and chemical processing facility owner/operators are confidential and hence cannot be discussed within the context of this article, it can be stated that some facility owner/operators do not consider unconfined H_2-air VCEs as credible events. A number of other owner/operators do consider such events, but they limit the associated release sizes to small values compared to those normally considered for typical hydrocarbon releases. Others treat hydrogen releases essentially the same as typical hydrocarbon releases. A similar range of treatments exists in the recommendations provided by consultancies engaged in explosion hazard analyses, facility siting studies, and QRAs of such facilities.

It is noted that the Factory Mutual (FM) Global data sheet for the evaluation of VCEs [1] specifically excludes consideration of VCEs due to gaseous hydrogen releases, irrespective of the hydrogen pressure or temperature, although it does call for the evaluation of liquid hydrogen releases. The FM Global data sheet does note that 3% of the VCEs reported in a VCE incident database were due to hydrogen or synthesis gas. It is further noted that FM Global's goals with respect to VCE evaluation may be different than those associated with facility siting studies and QRAs performed by facility owner/operators, but such considerations are beyond the scope of this article.

The focus of this article is on unconfined hydrogen VCEs. Since it is generally accepted that hydrogen released within an enclosure (i.e., a structure with roof and full walls) can result in an explosion, accidental explosions of that type are not addressed in this article. Of course, a hydrogen explosion within an enclosure still requires delayed ignition. It is also assumed that hydrogen-hydrocarbon mixtures are widely viewed as credible unconfined VCE scenarios, and hence are not addressed in this article.

The terms "congestion" and "confinement" are used within this article relative to the flame speed achieved in a

Table 1. Approximate congestion and confinement levels for accidental H_2 VCEs.

Accidental H_2 VCE	Section No.	Congestion Level	Confinement
Polysar Sarnia	2.1	Mixed (low and medium)	Partial (shed roof)
Jackass Flats	2.2	None	None
Silver Eagle Refinery	2.3	Mixed (low and medium)	None
Muskingum River	2.4	Very low	Partial (shed roof)
"H_2 Incidents" Database	2.5	Varies (none to medium)	Varies (none to partial)
MCA Case History	2.6	None	None
NASA H_2 Incidents	2.7	Mostly none (multiple cases)	Mostly none (multiple cases)
Hanau, Germany	2.8	Mixed (low and medium)	None
Sodegaura, Japan	2.9	Mixed (low and medium)	None

VCE. Congestion is typically present within refining or processing areas in the form of piping, structural supports, instrumentation, conduit, and other similar items. Congestion induces turbulence in the flow field ahead of the flame, and hence increases the combustion rate and accelerates the flame front. Confinement is typically present in the form of limited solid decking or roofing, larger vessels, and/or small enclosures within the region of interest. Confinement restricts the free expansion of the product gas and hence accelerates the flame front. The presence of this type of limited confinement does not denote "fully confined" (e.g., as with a VCE within an enclosure), and a VCE is still "unconfined" even when such limited confinement is present.

ACCIDENTAL HYDROGEN VCEs

Zalosh and Short [2] reviewed over 400 accidents involving hydrogen from a variety of sources covering the time period from 1965 to 1977. The referenced report provides details only for selected accidents. Zalosh and Short concluded that the data "indicate that hydrogen explosions have been a more serious problem than other types of hydrogen accidents in terms of the number of incidents, casualties, and reported property damage." Their analysis showed that slightly more than half the hydrogen incidents were explosions, and that explosions accounted for three-quarters of the injuries and fatalities. Three-quarters of the incidents reviewed involved hydrogen gas, with most of the remaining incidents involving liquid. Hence, the analysis of Zalosh and Short [2] would indicate that a significant fraction of the incidents involved explosions of hydrogen gas, and that explosions caused a disproportionally large fraction of the casualties.

Perhaps the two most well publicized accidental unconfined H_2 VCEs are the Polysar Sarnia [3] and Jackass Flats [4,5] incidents. These two events were also reported in the summary provided by Lenoir and Davenport [6]. Lenoir and Davenport also reported an unconfined H_2 VCE in 1975 at a hydrogen unit in Watson, CA involving 300 kg of H_2, but because the source cited by Lenoir and Davenport is private communication, no further information is available; this event is also included in the incident collection provided by Gugan [7]. More recent accidental unconfined H_2 VCEs occurred at the Silver Eagle refinery in Woods Cross, UT [8], although few details related to that event have been published, and at the Muskingum River power plant [9]. A number of additional incidents are summarized in the "H_2 Incidents" database [10], although the information sources for these incidents are not reported and not a great deal of information is provided for any specific incident. The Manufacturing Chemists' Association (MCA) Case History collection [11] also describes an accidental unconfined H_2 VCE. Ordin's review of accidents involving hydrogen in NASA operations [12] identifies a number of unconfined H_2 VCEs. Limited information is also available on the unconfined H_2 VCEs which occurred in Hanau, Germany [13] and Sodegaura, Japan [14]. Each of these incidents is discussed separately below. Table 1 summarizes the congestion and confinement present in each of these incidents; note that most of the congestion and/or confinement levels assigned in this table are judgments based on the description provided in the referenced source, as the authors did not personally investigate many of these incidents.

Other unconfined H_2 VCEs are identified in databases or noted in the literature, but without sufficient details or information to confirm that the VCE involved pure hydrogen and was unconfined, and hence are not discussed in this article. It is also noted that there are other accidental unconfined H_2 VCEs the authors are aware of, either by being directly involved in the incident investigation or based on discussions with owner/operators of petroleum refining and/or chemical processing plants. However, the information related to those incidents is confidential and cannot be discussed at this time. Nevertheless, it should be understood that the number of accidental unconfined H_2 VCEs reported in the literature is only a small fraction of the number of such events which actually occur. This complication, of course, is not restricted to accidental VCEs involving hydrogen.

Polysar Sarnia

This incident was reported by MacDiarmid and North [3], and occurred at the Styrene I plant (Litol benzene process unit) within Polysar's petrochemical complex located in Sarnia, Canada. A release of hydrogen occurred due to a partially failed gasket (1/8-in., 3-mm-thick) on a compressor located within an open-sided (i.e., partially enclosed) shed and operating at about 700 psi (48 bar). It is noted that since the compressor shed was open-sided, it is not considered an enclosure (i.e., fully enclosed) for the purposes of this article. The delay between the start of the release and ignition was 10–15 s. Approximately 30 kg of hydrogen was released. The resulting VCE caused extensive structural damage in the near-field and resulted in several fatalities and several injuries. Fortunately, the incident occurred on a plant holiday or more plant staff would likely have been injured or killed. Broken glass and minor structural damage was observed out to roughly 3,300 ft (1 km). It was concluded that a detonation had occurred (i.e., that a deflagration-to-detonation transition, DDT, occurred).

MacDiarmid and North [3] reported that the damage to a building located 500 ft (150 m) from the explosion was consistent with a blast overpressure of 1.1 psi. Based on the Baker–Strehlow–Tang (BST) VCE blast curves [15], this blast overpressure would be consistent with a vapor cloud detonation involving 37,000 ft^3 (1,050 m^3) of stoichiometric H_2-air mixture and a blast duration of 24 ms. The corresponding hydrogen mass is 57 lbm (26 kg), which is a high fraction of the hydrogen mass reportedly released (i.e., 30 kg). It is noted that a detonation would be predicted using the BST VCE blast load prediction method for most open-sided compressor sheds [16]. The overpressure estimate based on building damage is, of course, approximate. Reducing the "target" overpressure at this standoff distance by half would reduce the required hydrogen mass down to 5 kg. Furthermore, in reality, some of the gas-mixture would have been combusted as a deflagration prior to the DDT, which would increase the cloud size and hydrogen mass required to achieve the prescribed load. In any case, these comparisons indicate that a significant fraction of the hydrogen released from through the compressor gasket failure participated in the VCE.

Jackass Flats

This incident was reported by Reider et al., [4,5]. Rocket motors were being tested and hydrogen was one of the fuels tested. One test without deliberate ignition of the hydrogen was performed to evaluate the resulting noise (i.e., sound pressure) levels. The hydrogen was released from storage at an initial pressure of 3,400 psi (23.6 MPa) through a convergent-divergent nozzle venting upward into the atmosphere, and flowed for a period of 13 s prior to an unintentional ignition. It was estimated that about 200 lbm (90 kg) of hydrogen, or approximately 10% of that released, was involved in the VCE [5], while the remainder of the hydrogen was diluted below the flammability limit. The VCE was reported to be a deflagration, causing limited damage to the surrounding buildings. A VCE occurred in this case without the cloud encountering any congestion (flow directed upward) due to preignition turbulence in the rocket exhaust.

Silver Eagle Refinery

The U.S. Chemical Safety Board (CSB) is currently investigating a recent accidental unconfined H_2 VCE that occurred at the Silver Eagle refinery in Woods Cross, UT. Details related to this event have not yet been published. The CSB has released a statement [8] that the hydrogen release was associated with the failure of a 10-in. (25 cm) diameter pipe off a reactor in the distillate dewaxing unit, which was undergoing catalyst regeneration. The hydrogen released was at 630 psi (43 bar) and 800°F (430°C). The released hydrogen was reported to have ignited quickly, most likely from an open-flame furnace near the release location. The VCE was reported to have caused severe damage to two homes and minor damage to other homes in a residential neighborhood near the refinery.

Muskingum River Power Plant

An unconfined H_2 VCE occurred at the Muskingum River power plant in 2007 due to the failure of a rupture disk on a hydrogen storage tank vent line during refilling from a truck [9]. The storage tank was located outdoors. Hydrogen released from the vent line for 3–10 s before it was ignited and exploded. The VCE killed the driver, injured 10 others, and caused extensive damage to adjacent buildings.

"H_2 Incidents" Database

A number of additional hydrogen explosion incidents are summarized in the "H_2 Incidents" database [10], although the information sources for these incidents are not reported and not a great deal of information is provided for any specific incident. The"H_2 Incidents" database, which is managed by the Pacific Northwest National Lab with support from the U.S. Department of Energy, is a voluntary reporting tool for events involving either hydrogen or hydrogen-related technologies. A summary of the relevant incidents from this database is provided as Table 2.

Incident #287 in the list is the Polysar Sarnia incident discussed earlier in this article, and incident #129 appears to be of a similar nature (i.e., partially enclosed hydrogen compressor). Incident #148 (vent stack discharge) is similar to both the MCA Case History discussed below, and other similar events that have occurred but which have not been reported in the literature. The authors are also aware of events similar to Incident #169 (burst disk on hydrogen cylinder pressure relief line) which have not been reported in the literature.

MCA Case History

The MCA Case History collection [11] describes an accidental unconfined H_2 VCE involving a release from a H_2 gas vent stack. The explosion was reported to have caused severe damage to several buildings near the facility. No further details on the release (e.g., release quantity, ignition delay, etc.) are provided in this reference.

NASA Hydrogen Incidents

Ordin reviewed accidents involving hydrogen in NASA operations [12]. It is noted that Ordin concluded that hydrogen released to the environment ignited in 62% of such releases. Ordin identified a number of unconfined H_2 VCEs. Most of the unconfined H_2 VCEs reported by Ordin involved the intentional or unintentional release of hydrogen through vent pipes, with the vented hydrogen discharging for some period of time prior to ignition. Several of the VCEs were reported to be detonations, with equivalent TNT masses ranging up to 20 lb_m (9.1 kg) of TNT.

Hanau, Germany

The unconfined H_2 VCE which occurred in Hanau, Germany in 1991 involved the release of hydrogen from a 100-m^3 cylindrical storage tank which ruptured at a pressure of 45 bar [13]. The hydrogen released from the pressurized tank created a flammable cloud which was ignited and resulted in a VCE. The blast wave caused significant property damage in the vicinity and window damage to buildings near the plant.

Sodegaura, Japan

The unconfined H_2 VCE which occurred in Sodegaura, Japan in 1992 involved the release of hydrogen from a heat exchanger [14,17]. The resulting VCE caused significant damage to the plant.

HYDROGEN VCE TESTS

Unconfined hydrogen VCE tests are only of passing interest for this article. For such tests, the hydrogen is generally released into a test rig in a controlled fashion with the intent that the hydrogen not be ignited prematurely. Hence, the fact that such tests are able to generate a cloud of flammable hydrogen-air mixture, ignite the mixture, and produce a VCE blast load is not surprising. Several tests performed recently are noted below since they illustrate the potential for a DDT with hydrogen-air mixtures in unconfined congested volumes. Note that these tests are intended only to be representative and to illustrate the potential severity of an H_2-air VCE, rather than provide an exhaustive review of the literature.

Shirvill and Roberts [18] tested hydrogen (as well as hydrogen-methane mixtures) in a congested 9.8 ft (3 m) × 9.8 ft (3 m) × 6.6 ft (2 m) high rig with congestion formed by 1-in. (2.54 cm) diameter pipes. A vertical array was placed in the bottom half of the rig, and a horizontal array in the top half. The mixture was ignited by a spark near the rig

Table 2. Unconfined hydrogen VCEs reported in the "H_2 Incidents" Database.

Incident No.	Incident Date	Facility Description	Release Description	Pressure (psig)	Release Details	Damage	Other Information
129	2001	H_2 Generation Plant, compressor (partially enclosed)	Internal piping explosion fails piping system	1,800	n/a	• Blew bldg. cladding off end of building • Debris distributed for 65′	• Compressor enclosure (partially closed-in ends that can trap gas under roof) • 510 m^3/day production rate • Hydrogen "self-ignited"
148	n/a	Compressor (external)	Vent stack from relief valve	2,700–2,900	"large" flow	Property damage • "Considerable damage"	• Release oriented horizontally
169	2002	Unknown (likely power plant)	Burst disk on pressure relief line from 6-pack of tubes (23′ L, 2′ D)	2,100	14,500 scf	• Property damage	• Vent pipe contained two 90-degree bends, secured with single u-clamp
185	1989	Fuel oil refinery	Pipe end at outlet of HX on outlet of desulfurization reactor, leaked H_2	n/a	n/a	• Nearby HX damaged by blast	• Ignited by static
192	2007	Coal-fired power plant	Pressure relief disk	>1,500	n/a	• Fatality + property damage	• Loading H_2 storage • LikelyBeverly, OH incident (AEP plant)
227	2003	Hydrogen transport trailer	Cylinder damage	2,900	n/a	• Damaged car following trailer • Broken windows on nearby house	• Cylinders fell off the trailer
287	1984	Styrene plant, benzene unit	Burst flange	700	30 kg	• Two killed, Two injured′ • Shed roof and heavy door blown several hundred feet • Light damage to CR (75′away) • Window/door/masonry damage to office buildings out to 1,200′	• 10–15 s, operators heard a pop and loud hiss within compressor shed. • Witnesses saw "white flash"

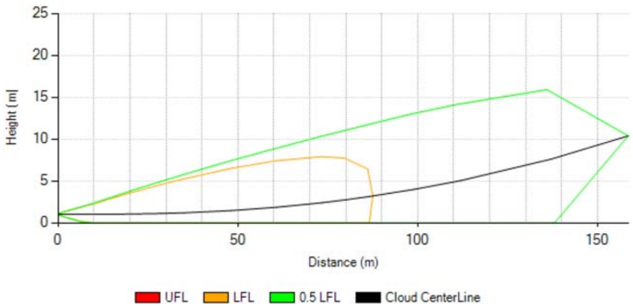

Figure 1. Flammable cloud from simplified dispersion analysis (SafeSite$_{3G}$®). [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

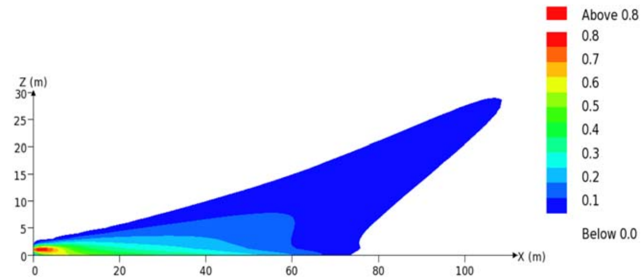

Figure 2. Hydrogen concentration contours for release into uncongested area (FLACS). [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

center. A near-stoichiometric H_2-air mixture underwent a DDT near the edge of the rig.

Thomas *et al*. [19] tested a lean H_2-air mixture in a 48 ft (14.6 m) × 12 ft (3.7 m) × 6 ft (1.8 m) tall rig with congestion formed by a uniform array of 2-in. (5 cm) vertical pipes (pitch-to-diameter ratio of 4.1, area and volume blockage ratios of 23% and 4.2%, respectively). Hydrogen-air mixtures were ignited at the rig center near grade level. Deflagrations resulted for hydrogen concentrations of 18% or less, a very fast deflagration was achieved at a concentration of 20%, and a DDT occurred with a concentration of 22%.

IGNITION OF HYDROGEN RELEASES

One rationale given for discounting the potential for an unconfined hydrogen VCE is that the released hydrogen will always quickly ignite (i.e., prompt ignition), so that a flammable hydrogen-air cloud of significant volume cannot be formed before the mixture is ignited. It is argued that the result of a hydrogen release will, therefore, be a small flash fire followed by a jet fire, rather than a VCE. Of course, the fact that accidental H_2 VCEs have occurred is evidence that this is not always the case. Nevertheless, it might still be argued that the probability of prompt ignition is so large (i.e., close to unity) that an H_2 VCE is not risk significant, regardless of the potential consequences.

The review provided by Moosemiller and Galindo [20] considered this issue, and concluded that the widely varying views of hydrogen ignition that prevail in the industry among subject matter experts appear to have a basis in the underlying physical phenomena at play near the point of release. They concluded that, depending on how the release occurs, very different ignition probability outcomes might be realized under otherwise identical conditions (i.e., material, pressure, temperature, ignition sources, etc.). It would therefore appear that the potential for delayed ignition is real, which is consistent with the actual occurrence of accidental unconfined H_2 VCEs discussed in the Accidental Hydrogen VCEs Section discussed above. It is noted that a survey of hydrogen release incidents cited by Moosemiller and Galindo [20] indicates that most hydrogen releases are ignited, and that explosions may be more frequent than fires, which both indicate that the likelihood of delayed ignition is not insignificant. However, many of these releases may have been inside enclosures. As noted earlier, Ordin [12] concluded that 62% of the hydrogen releases to the environment ignited, and that a number of incidents were unconfined H_2 VCEs.

DISPERSION OF HYDROGEN RELEASES

The other rationale given for discounting the potential for an unconfined hydrogen VCE is that the released hydrogen will not form a flammable hydrogen-air cloud of significant

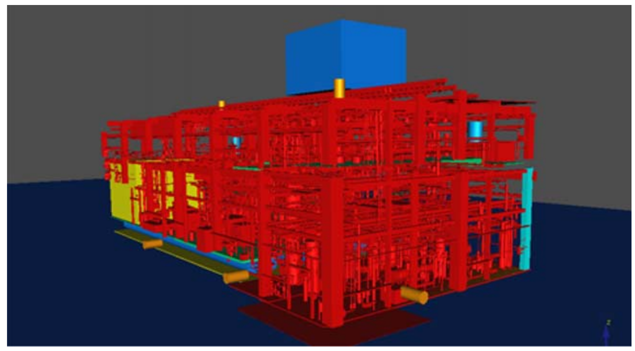

Figure 3. Process module solid model. [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

volume since hydrogen is buoyant. In simplified terms, it is argued that the released hydrogen will quickly rise and "float away." Of course, the fact that accidental H_2 VCEs have occurred is evidence that this is not always the case. Nevertheless, it might still be argued that this is true for most cases and hence an H_2 VCE is not risk significant, regardless of the potential consequences.

The buoyancy of a hydrogen release is only relevant outside of the momentum controlled portion of dispersion, which is true of any positively or negatively buoyant gas. Hence, large release rates (i.e., releases with significant momentum) can form significant flammable volumes prior to buoyancy, whether positive or negative, exerting a significant influence. Light gases, such as hydrogen, will form clouds that "lift" once the resulting mixture velocity slows, and heavy gases will form clouds that tend to "slump" when the mixture velocity slows. The relevant point, of course, is how much flammable volume can be formed within a congested environment prior to buoyancy effects coming into play. A hydrogen release will obviously simply "float away" if the release is very small. The relevant question is whether this will happen if the release is in the range normally considered for facility siting studies and QRAs.

To illustrate, consider a release of hydrogen through a 2-in. diameter hole at 1,400 psig (97 bar) and 550°F (288°C). The prescribed release conditions give a release rate of 8.4 kg/s. The dispersion analyses performed to evaluate the resulting flammable cloud assumed a wind velocity of 3 m/s and Pasquil stability class D. A horizontal release direction at a height of 1 m was assumed. Figure 1 shows the flammable gas concentration contours for a side-view of the cloud as

Table 3. FLACS analysis case parameters and resulting flammable volumes.

Case No.	Module Present?	Release Rate (kg/s)	Release Height (m)	Release Location	Flammable Vol. Within Module (m^3)	Flammable Vol. Within Module (% module)	Total Flammable Cloud Volume (m^3)	Flammable Vol. Ratio (Total/In Module)
1	No	8	1	n/a	n/a	n/a	8,500	n/a
2	Yes	8	5.5	Center	1,300	15	8,300	6.6
3	Yes	8	5.5	Edge	2,700	33	9,600	3.6
4	Yes	8	2	Edge	3,700	46	11,000	2.9
5	Yes	16	2	Edge	4,400	55	22,000	5.1

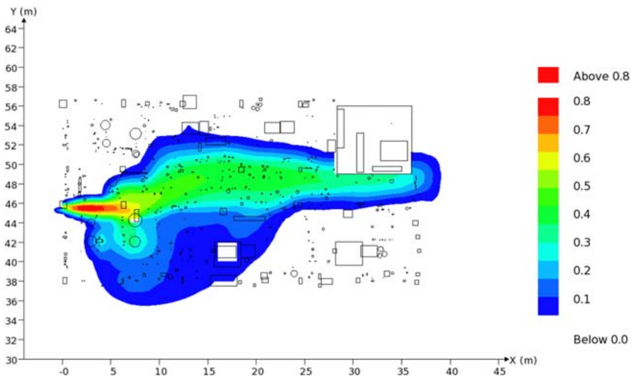

Figure 4. Hydrogen concentration contours, Case 4 (horizontal slice). [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

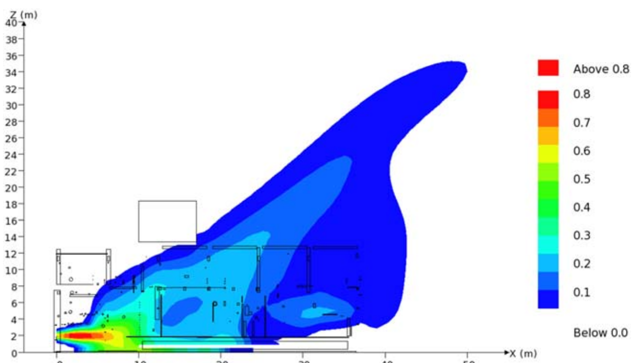

Figure 5. Hydrogen concentration contours, Case 4 (vertical slice). [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

predicted by BakerRisk's SafeSite$_{3G}$® code [21]. The dispersion analysis performed by SafeSite$_{3G}$® does not consider the impact of congestion or confinement due to process equipment, piping, and other obstacles on the dispersion process. As shown in Figure 1, the distance to the lower flammability limit (LFL) is about 90 m from the release point, and the cloud does not begin to noticeably "lift" (i.e., reflect the mixture's positive buoyancy) until roughly 60 m, after the centerline hydrogen concentration has been reduced to about 7%. Of course, even with an elevated initial temperature release, the positive buoyancy of the mixture is not large once the hydrogen concentration is diluted to low concentrations.

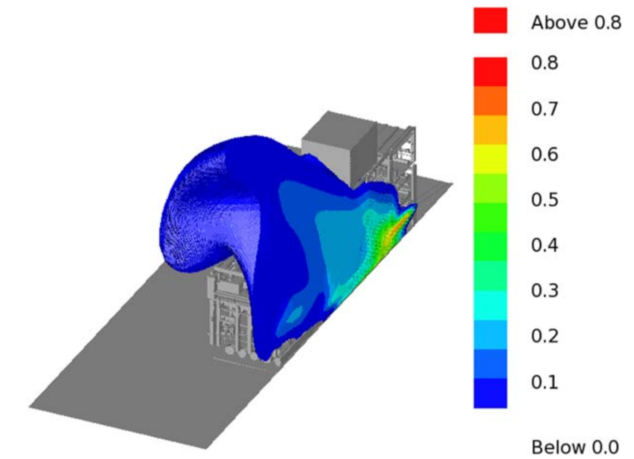

Figure 6. Hydrogen concentration contours, Case 4 (perspective view). [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

The FLACS computational fluid dynamics code was employed to illustrate the impact of congestion on the dispersion and the resulting flammable cloud formation. First, the same release conditions discussed above were used in a FLACS simulation with no congestion present (i.e., as with the SafeSite$_{3G}$® analysis). The hydrogen concentration contours for this release are shown in Figure 2; the concentration contours shown in this figure are expressed in terms of hydrogen mole fraction (i.e., 0.1 is 10% H_2) and the contour shown extends to the LFL (0.04). As can be seen in Figure 2, the distance to the LFL predicted by FLACS is similar to that predicted by SafeSite$_{3G}$®, as shown in Figure 1, and the flammable cloud shapes are similar.

Second, the congestion associated with a typical process module was used to illustrate the impact of congestion on the flammable cloud resulting from this same release case. The process module is shown in Figure 3. The module dimensions are approximately 120 ft (36.7 m) long, 62 ft (18.9 m) wide, and 38.4 ft (11.7 m) high (volume of 290,000 ft^3, 8,120 m^3). The module represents a mixture of low and medium congestion areas, with very limited regions which are confined (i.e., via the presence of large pieces of equipment and limited areas of solid decking). The release location was initially set at 18 ft (5.5 m) off the ground, near the midheight of the module. Release locations at the middle of the module and at the edge of the module were evaluated, with the release oriented in the same direction as the wind. The release at the edge of the module was then evaluated at a release height of 6.6 ft (2 m), with both the nominal release rate (8 kg/s) and double this value. The analysis case parameters and the resulting flammable cloud volumes are summarized in Table 3. Depending on the release location, flammable cloud volumes equivalent from 15 to 46% of the module volume are predicted for the 8 kg/s release case and 55% of the module volume at twice this release rate. The largest flammable volume within the module with the 8 kg/s release is almost half the flammable volume with no congestion present (i.e., Case 4 compared to Case 1). As shown in Table 3, the total flammable volume ranges from 2.9 to 6.6 times that within the module.

The hydrogen concentration contours for Case 4 are shown in Figure 4 (horizontal slice through the plane of the release), Figure 5 (vertical slice through the plane of the release), and Figure 6 (perspective view); the concentration contours shown in these figures are expressed in terms of hydrogen mole fraction (i.e., 0.1 is 10% H_2). As shown in these figures, the distance to the LFL from the release point is roughly 40 m near grade level, about half that for the release into an uncongested environment (see Figure 2). However, while the congestion does serve to decrease the forward momentum of the release and hence allow buoyancy forces to play a larger role, a large flammable cloud still results from this release. Furthermore, a large portion of the flammable cloud is outside the process module. This is relevant since, if the flammable cloud were ignited inside the module and accelerated such that a DDT occurred, the detonation could propagate into the portion of the flammable cloud outside the module such that it could also contribute to the explosion energy [19,22].

HYDROGEN VCE BLAST LOADS

The Dispersion of Hydrogen Releases Section served to establish that flammable H_2-air clouds of significant volume can be formed from relevant releases and the Ignition of Hydrogen Releases Section established that delayed ignition of such clouds can occur. This is consistent with the fact that accidental H_2 VCEs have occurred, as discussed in the Accidental Hydrogen VCEs Section. It is therefore relevant to consider the magnitude of the blast loads that could result from an unconfined H_2-air VCE.

The blast loads from an unconfined H_2-air VCE depend on: (1) flame speed, (2) explosion energy, and (3) standoff distance. Flame speed is directly related to the rate of energy release. The flame speed will depend on the level of congestion and confinement present within the region occupied by the flammable cloud along with the hydrogen concentration. Even moderate levels of congestion are sufficient to trigger a DDT for hydrogen concentrations that are not well away from stoichiometric (i.e., lean or rich mixtures); for example, tests described in the Hydrogen VCE Tests Section showed that a DDT could occur with moderate congestion levels without any confinement at a hydrogen concentration of 22%. The flame speed for a detonation is well above the sound speed in air (i.e., in the range of Mach 5 for a near-stoichiometric mixture). The flame speed will be much lower if the level of congestion and confinement in the volume of interest, coupled with the flammable cloud and congested volume scales and hydrogen concentration, are such that a deflagration results. A flame speed on the order of Mach 0.5 would be representative of such a case. The explosion energy is dependent on the explosion mode (i.e., deflagration vs. detonation). In the case of a deflagration, the explosion energy will be essentially limited to the portion of the flammable cloud within the congested/confined volume, with the portion of the gas mixture outside of this volume contributing little to the explosion energy. In the case of a detonation, essentially the entire flammable cloud can contribute to the explosion energy, since the detonation wave can propagate out of the congested region into the unburnt portion of the cloud in the open [22,23]. The standoff distance is simply the distance between the target of interest (e.g., an occupied building) and the explosion.

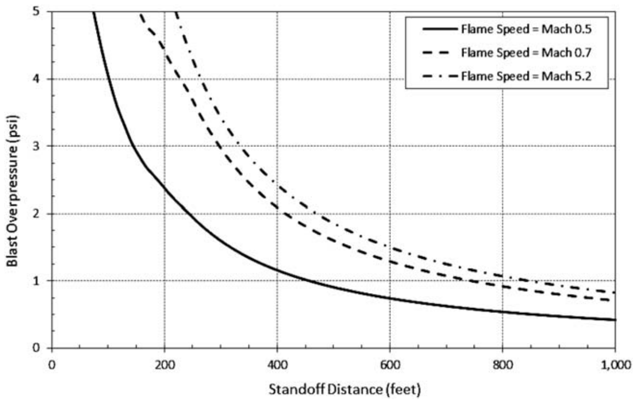

Figure 7. Blast Overpressure versus Distance (4,000 m^3 H_2-air flammable gas cloud).

As a simple illustration, consider the blast loads for the flammable volume within the module based on the FLACS dispersion analysis discussed in the Dispersion of Hydrogen Releases Section. That analysis showed that it is likely that a flammable volume of roughly 4,000 m^3 (140,000 ft^3) within the module could be achieved for reasonable hydrogen release sizes. Larger volumes would result from larger congested volumes coupled with larger release rates and/or less favorable weather conditions. The flammable cloud was assumed to be at a uniform stoichiometric concentration, which is conservative. For the purposes of this illustration, the blast loads were calculated using BakerRisk's VCloud code [24], which utilizes a single-zone BST approach [16]. Flame speeds of Mach 0.5 (i.e., moderately fast deflagration), Mach 0.7 (i.e., very fast deflagration) and Mach 5.2 (i.e., detonation) were evaluated. A detonation (i.e., a DDT) would be predicted for hydrogen releases at medium levels of congestion [16], as would be present within many processing areas. A detonation could propagate into unburnt fuel outside of the congested region [22,23], as was discussed previously.

The calculated blast overpressure for a 4,000 m^3 stoichiometric H_2-air mixture is shown in Figure 7 as a function of standoff distance. The blast overpressure is greater than 1 psi out to 400 ft (120 m) for the lower end of the flame speed range examined, and out to roughly double that distance for a detonation. The blast durations at the 1 psi overpressure for these cases range from about 60 ms (Mach 0.5) to 40 ms (detonation), which reflects the limited cloud size considered. The overpressures in the mid- to far-field for the very fast deflagration and detonation cases are similar, as expected. A larger difference between these two cases would result if the portion of the flammable cloud outside the congested volume were considered, since as shown in Table 3, a large portion of the flammable volume was outside the process module for the cases considered. These results serve to illustrate that the credible hydrogen releases can produce damaging blast loads, particularly when a combination of the release and congestion/confinement would support a DDT.

CONCLUSIONS

Despite the impression by some that unconfined hydrogen-air VCEs are not credible events, unconfined hydrogen-air VCEs can and do occur. Hydrogen does not always immediately ignite upon release. Hydrogen's buoyancy does not prevent the formation of a large flammable mixture for release rates of interest for explosion hazard analyses; credible hydrogen releases can form significant flammable gas clouds. VCEs of hydrogen-air mixtures can produce damaging blast loads, particularly when the combination of the release and congestion/confinement would support a DDT. Hydrogen releases leading to VCEs should, therefore, be considered in explosion hazard analyses, facility siting studies, and QRAs where hydrogen is utilized within a facility.

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