

Blast Effects of a Silane Vapour Cloud Explosion

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1 Introduction

Silane is a pyrophoric and highly-reactive gas with a wide flammable range in air (see [1] for a review). Its use has become increasingly widespread in the manufacturing of common glass products (such as LCDs, photovoltaic cells, thin-film transistors, and semiconductors) and is generally stored and dispensed to process equipment at high pressures (for e.g., 70 bar at the source and 7 bar at the equipment). An accidental release can result in serious consequences, and it is of interest to understand the behaviour of silane releases such that appropriate guidelines can be developed for safe storage and handling.

In general, silane can either autoignite immediately when exposed to air or undergo delayed autoignition when entrained and mixed in air [1-5]. The former is generally observed when the exit velocity of an impulsively-started jet of silane is below a critical value, which results in a jet fire that can produce significant levels of thermal radiation. In the latter case, silane can form a metastable mixture in air and then autoignite following a certain time delay, which varies with the composition of the silane-air mixture. This can lead to bulk autoignition or can trigger a SWACER-like mechanism (as in the transition from deflagration to detonation [6]); therefore, the resulting vapour cloud explosion is characterized by very high flame speeds that can result in serious blast damage.

Both thermal and blast hazards should be considered when specifying separation distances for safe storage and handling, both; however, the present paper will focus only on blast effects due to a silane vapour cloud explosion (VCE). Although the exact composition and size of a silane vapour cloud resulting from an accidental release cannot be determined a priori, an attempt was made by the authors to formulate a methodology that can be used to determine credible worst-case releases and the corresponding blast effects [7]. In the present paper, results from field trials are presented and compared to estimates made using the methodology presented previously in Chao et al. [7].

2 Theoretical Considerations

The methodology used to estimate blast effects from an accidental release of silane has been discussed in detail in [7], and only important aspects are outlined in the present paper. In general, the strength of a blast wave depends on the amount of chemical energy contained in the vapour cloud and on the rate at which that energy is released. Therefore, the first step to determine blast effects is to estimate the amount of silane that is dispersed upon an accidental release. Using this value, the concentration distribution within the vapour cloud can be approximated using the simple model described in [8,9].

Maximum Flammable Mass

The total mass of silane that is released depends on the ignition delay, which is unknown and impossible to estimate; however, for a free-jet release that is typical of an accidental release, the vapour cloud grows with time and approaches a quasi-steady concentration distribution, decreasing from 100% at the release orifice down to 0% at infinity. The mass of flammable gas between the lower and upper flammability limits in this quasi-steady distribution can then be used as a conservative estimate of the maximum flammable mass in the cloud when the ignition delay is unknown (see sketch in Fig. 1a). It is evaluated using a similar approach to that developed in [10] for accidental high-pressure releases of hydrogen through small orifices. Using this method, a supercritical underexpanded jet of silane can be approximated by an equivalent isentropic expansion through a notional nozzle such that the classical relations for concentration decay in a turbulent jet can be used (see sketch in Fig. 1b). For cases where the release is partially obstructed or confined (which can significantly increase the amount of flammable mass in a quasi-steady cloud), a factor of 7 is applied to the flammable mass of silane as a conservative approximation (see [11] for details).

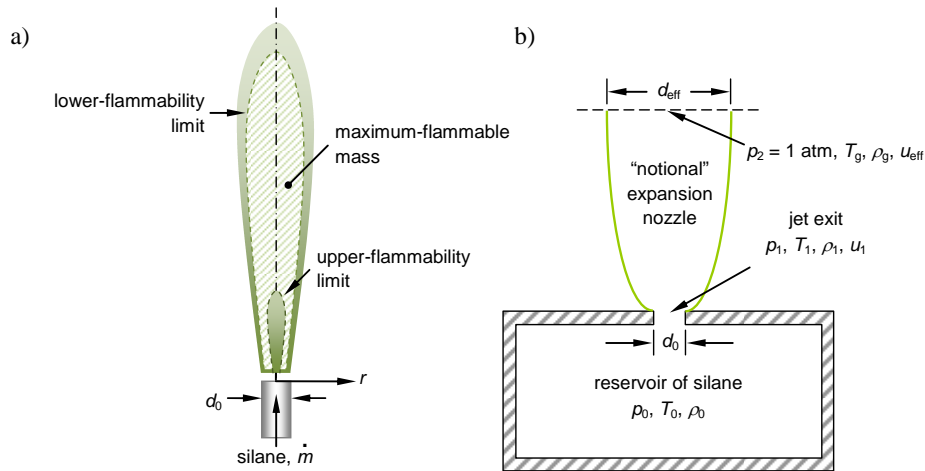


Figure 1. Sketch of a) lower and upper and upper flammability limits in a silane jet from a choked orifice and b) notional expansion of a supercritical silane release.

Blast Effects

Once the maximum flammable mass of silane is estimated, it can be assumed that it forms a hemispherical vapour cloud in air with a nonuniform concentration distribution. The maximum concentration is taken to be at the centre of the vapour cloud and decreases linearly with the radius of the hemisphere. Only the chemical energy from the portion of the cloud bounded between the upper and lower explosibility limits is considered (see Fig. 2).

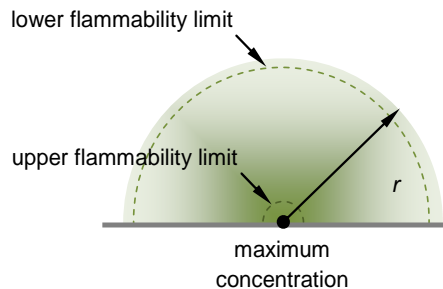


Fig. 2: Distribution of silane concentration in assumed-hemispherical vapour cloud.

Given a flame speed and an average expansion ratio, the blast overpressure and impulse as functions of distance from the explosion centre can be determined (see [12] for details). It should be noted that for the case of silane-air, one can choose a sufficiently high visible flame speed of the order of 500 m/s, which is typical for bulk autoignition or even a detonation (there exists very little difference in the resulting blast effect when flame speeds greater than 500 m/s are chosen).

3 Experimental Details

A series of field trials were conducted whereby silane was released into the open atmosphere from a 44-L cylinder through a 6.1-m long stainless steel tube with an inside diameter of 10 mm. The release orifice was located 0.46 m above the ground. Such a long length of tubing was used in order to locate the source cylinder sufficiently far away from the explosion centre behind a concrete bunker. The initial pressure in the source cylinder was varied from 5.2 to 10.4 MPa in order to obtain different mass flow rates and, hence, different values for the maximum flammable mass of silane that was released. The silane cylinder was placed on a load cell in order to measure the change in mass during each release.

Both unobstructed and obstructed releases were tested. In the unobstructed cases, ignition was promoted by a smoldering ember placed 7.6 m downstream of the release orifice. For the obstructed releases, an obstacle array was placed either 0.5 or 1.2 m away from the release orifice. The obstacle array consisted of a set of 2 x 5 vertical cylinders (230 mm in diameter with 200 mm spacing) with a 0.9 by 1.2 m vertical flat plate mounted 0.5 m behind the back row of cylinders. A smoldering ember was placed on top of the vertical flat plate in order to promote ignition.

The trajectory and overpressure of the blast wave was measured using Kistler piezoelectric pressure transducers (type 211B); see Fig. 3 for a sketch of transducer locations. A high-speed video camera (at 1,000 fps) was also used.

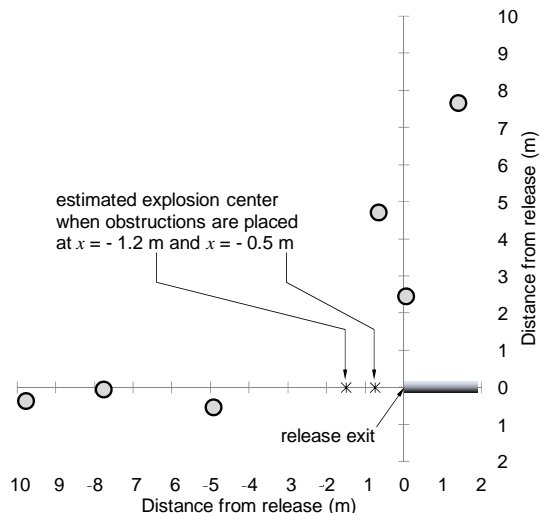


Figure 3. Layout of pressure transducer location (denoted by the grey circles) with respect to the release exit at $(x,y) = (0,0)$.

4 Results and Discussion

Select frames from a high-speed video of a typical obstructed release are shown in Fig. 4. In the first frame at $t = -142$ ms, a release of high-pressure silane (at $p_0 = 8$ MPa) begins as the cylinder valve is opened, indicated by the bright light in the photograph. Ignition is effected by the smoldering ember at $t = 0$ ms; in the second frame at $t = 1$ ms, a flame kernel can be clearly seen at the edge of the silane cloud that forms around the obstacle array. The flame slowly propagates away from the piloted

ignition centre until bulk autoignition suddenly occurs at $t = 8$ ms (shown in the third frame of Fig. 4). This is characterized by a significant increase in luminosity in the photograph. It should be noted that the explosion centre is taken to be at the centre of the VCE upon bulk autoignition; in the case shown, the explosion centre is found to be 0.75 m from the release exit.

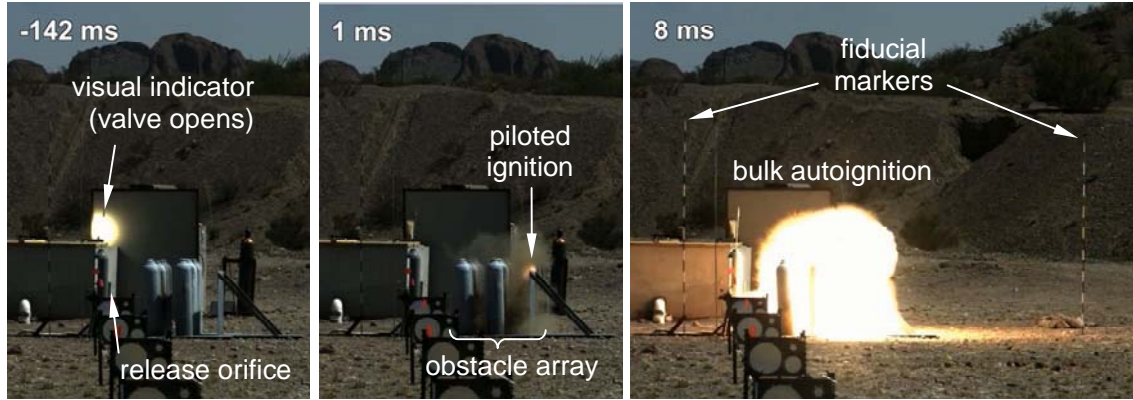


Figure 4. Select frames from high-speed video of an obstructed release of silane; valve opens at -142 ms, piloted ignition occurs at 1 ms, and subsequent bulk autoignition occurs at 8 ms.

Typical blast wave trajectories and pressure histories in the axial and radial directions of the release are shown in Fig. 5 for an obstructed case. In the axial direction (see Fig. 5a), a maximum overpressure of 0.21 bar is measured at 4.2 m from the explosion centre and decays to 0.17 and 0.11 bar at 7.0 and 9.0 m, respectively. In the radial direction (see Fig. 5b), the pressure transducers were located closer to the explosion centre; hence, larger overpressures were recorded (a maximum overpressure of 0.58 bar was found at 2.6 m and decayed to 0.32 and 0.11 bar at 4.7 and 8.0 m, respectively). These measured values are consistent with the average shock strength determined from the blast wave trajectory.

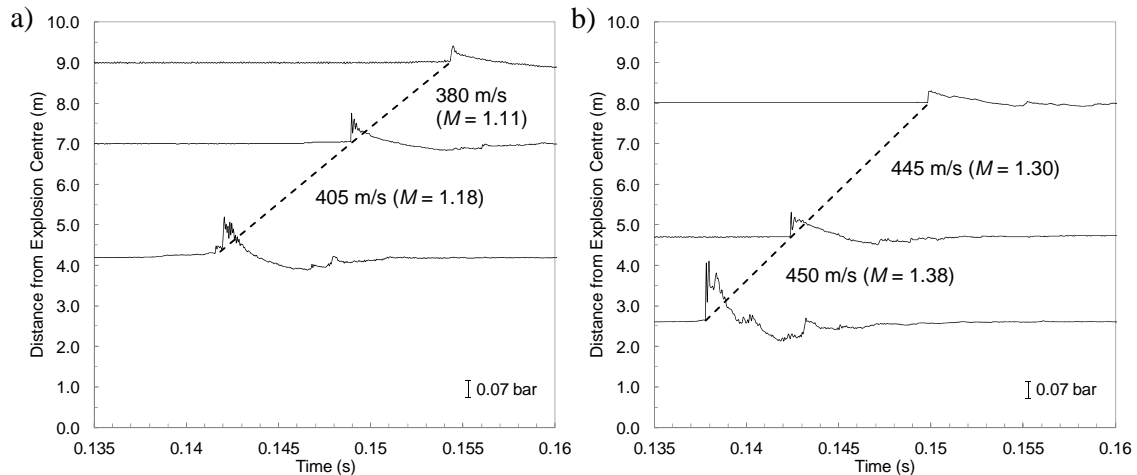


Figure 5. Blast wave trajectories (dashed lines) and pressure histories (solid lines) in the a) axial and b) radial directions from the exit orifice.

The measured maximum overpressure and positive impulse (determined by taking the area below the pressure curves) are shown in Fig. 6 (for the same release shown in Fig. 5). The blast effects can be clearly seen to decay with distance from the explosion source. Two different estimates of the blast effects (using the methodology described in [7]) are shown for comparison in the figures. The first

estimate is made using a discharge coefficient of $c_d = 0.4$ (denoted by the solid line in the figure); the agreement with the experimental results is fairly close.

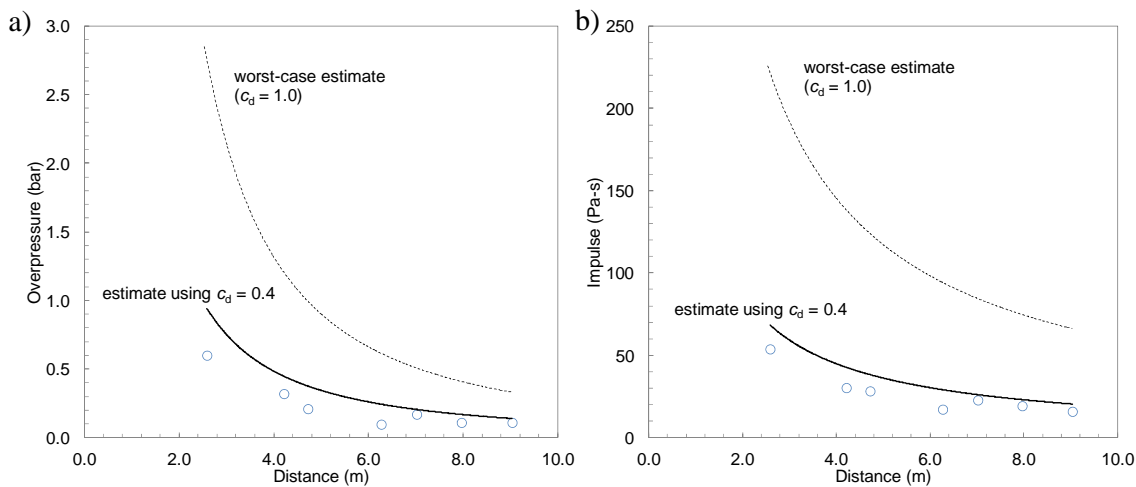


Figure 6. Blast effects (i.e., a) overpressure and b) impulse) of a silane VCE with estimates made using $c_d = 0.4$ (solid line) and $c_d = 1.0$ (dashed line).

It should be noted that this value of c_d is specific to this particular experimental setup only and cannot be generalized to other scenarios. It was selected in order to match the pressure decay in the source cylinder of silane during the release (assuming isentropic flow from an infinite reservoir), which occurred from a pressurized cylinder through a very long tube (with a length-to-diameter ratio greater than 600), resulting in considerable friction losses. This scenario does not necessarily emulate a real accidental silane release where a pipe may rupture or a pressure relief device may fail; however, it does provide an adequate means to control the release of silane while maintaining a sufficient separation distance between the explosion centre and the source cylinder.

The second estimate (denoted by the dashed line in the figure) is made by setting the discharge coefficient to unity. In this particular case, the blast effects are significantly over predicted in comparison to the experimental results. However, because details of an accidental release are unknown, it is impossible to select an appropriate discharge coefficient that is applicable in any given situation. Therefore, when specifying guidelines for safe separation distances, this approach can be used as a means to determine a credible worst-case scenario.

5 Concluding Remarks

In general, the ignition behaviour of silane is unpredictable when releases are not carried out under carefully controlled conditions. In an accidental release where the conditions are not known and cannot possibly be controlled, it is essentially impossible to define an appropriate ignition time delay (and hence, size) of a silane vapour cloud in air. This is taken into consideration in the methodology that was previously developed by the authors to estimate the resulting blast effects a silane VCE. In comparison to experimental results from large-scale field trials, the estimates made using this methodology agree fairly well when the discharge coefficient is selected to match the details of the release. When the discharge coefficient is set to unity, this methodology appears to yield conservative estimates that can be used as a credible worst case.

6 Acknowledgments

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References

- [1] Britton LG. (1990). Combustion hazards of silane and its chlorides. *Plant/Operations Prog.* 9:16.
- [2] Cruice WJ. (1978). Effects of releases of silane mixtures in ambient air. Hazards Research Corporation Report 4007.
- [3] Tsai HY, Wang SW, Wu SY, Chen JR, Ngai EY, Huang KPP. (2010). Experimental studies on the ignition behavior of pure silane released into air. *J. Loss Prev. in the Proc. Ind.* 23:170.
- [4] Tamanini F, Chaffee J. (1996). Ignition characteristics of releases of 100% silane. SEMATECH Technology Transfer 96013067A-ENG, March 7.
- [5] Tamanini F, Chaffee J. (1996). Effects of leak size and geometry on releases of 100% silane. SEMATECH Technology Transfer 96083168A-ENG, September 30.
- [6] Lee JHS, Moen IO. (1980). The mechanism of transition from deflagration to detonation in vapour cloud explosions. *Prog. Energy Combust. Sci.* 6:350.
- [7] Chao J, Bauwens CR, Dorofeev SB. (2010) Estimating blast effects from an accidental release of high-pressure silane. Proceedings of the 23rd International Colloquium of Dynamics of explosions and Reactive System. Irvine, USA. July 24-29, 2011.
- [8] Dorofeev SB. (2007). Evaluation of safety distances related to unconfined hydrogen explosions. *Int. J. Hydrogen Energy.* 32:2118.
- [9] Dorofeev SB. (2007). A flame speed correlation for unconfined gaseous explosions. *Proc. Saf. Prog.* 26:140.
- [10] Houf W, Schefer R. (2007). Predicting radiative heat fluxes and flammability envelopes from unintended releases of hydrogen. *Int. J. Hydrogen Energy.* 32:136.
- [11] Sposato C, Tamanini F, Rogers WJ, Mannan MS. (2003). Effect of plate impingement on the flammable volume of fuel jet releases. *Proc. Saf. Prog.* 22:201.
- [12] Dorofeev SB. (1996). Blast effect of confined and unconfined explosions shock waves. In: Sturtevant B, Shepherd J, Hornung H, editors. *Proc. 20th ISSW*, vol. 1, Singapore: Scientific Publishing Co.; p. 77-86.