Health and Safety Executive

Risk assessment for VCE scenario in an aerosol warehouse

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Risk assessment for VCE scenario in an aerosol warehouse

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In 2006, Dr Graham Atkinson of HSL was asked by HSE to review the risks from fires in large aerosol stores (Atkinson, 2007). Atkinson reviewed incident statistics and reports and concluded that the greatest risk to people from such fires was from explosions, not from the fire itself. He postulated a vapour cloud explosion (VCE) mechanism, whereby a fire of material elsewhere in the warehouse from the aerosols could give rise to a hot air layer close to the ceiling. Aerosols stored close to the ceiling could then fail and release their flammable contents, but not be immediately ignited by the fire. A large flammable vapour cloud could then form, which would give rise to a VCE when ignited. The report led to considerable discussion between HSE and the British Aerosol Manufacturers' Association (BAMA) about whether the proposed VCE scenario is realistic. Critiques of the Atkinson report were produced by Phoenix Loss Prevention Ltd (2007) and the BRE Centre for Fire Engineering at the University of Edinburgh (BRE, 2009). No other studies have been identified which address this issue.

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EXECUTIVE SUMMARY

Objectives

In 2006, Dr Graham Atkinson of HSL was asked by the HSE to review the risks from fires in large aerosol stores (Atkinson, 2007). Atkinson reviewed incident statistics and reports and concluded that the greatest risk to people from such fires was from explosions, not from the fire itself. He postulated a vapour cloud explosion (VCE) mechanism, whereby a fire of material elsewhere in the warehouse from the aerosols could give rise to a hot air layer close to the ceiling of the storage warehouse. Aerosols stored close to the ceiling could then fail and release their flammable contents, but not be immediately ignited by the fire. A large flammable vapour cloud could then form, which would give rise to a VCE when ignited. A VCE is defined (HSE, 2003) as "A cloud of vapours which when ignited cannot expand freely and results in a significant overpressure and explosion." In these circumstances any structures which provides partial confinement and/or congestion can prevent free expansion of the vapour cloud .It is not proven that this postulated scenario could actually occur, but the consequences could be severe if it did.

The objectives of the current work are to consider the likelihood and hence the risk of the VCE scenario at a large aerosol store. Discussions had suggested that the likelihood/ risk may be very low but a systematic analysis is required to document assumptions and reach a conclusion. The work has been done in conjunction with a small Steering Group with a membership from HSE, HSL and the British Aerosol Manufacturers' Association (BAMA).

Main Findings

1. An approximate risk assessment methodology has been developed based on the identified possible barriers to a warehouse VCE scenario which may or may not be present at individual warehouses. Two cases might in theory give rise to a VCE:

    a. A fire external to the warehouse which creates a hot air layer within the warehouse, capable of causing aerosol cans to rupture and release their contents without the contents catching fire ;

    b. An internal fire involving other slow burning material stored in the warehouse, remote from the aerosols, that creates a hot air/smoke layer capable of causing cans to rupture and release their contents.

2. At least about 50 tonnes of Liquefied Petroleum Gas (LPG) would need to be stored in aerosols to give rise to a release of 2 tonnes of LPG in a VCE scenario. 50 tonnes of LPG equates to the lower tier threshold specified in the Control of Major Accident Hazard Regulations (COMAH).

3. The quantity of LPG in a vapour cloud which could give rise to a warehouse VCE scenario may be less than the 2 tonnes used as an example by Atkinson (2007), perhaps by an order of magnitude. Thus it is likely that warehouses containing less than about 5 tonnes of LPG in aerosols would be too small for a VCE to be credible. The study identified barriers, which if present and functioning correctly would be expected to prevent a VCE.

4. Several barriers, if present, are capable of eliminating the VCE scenario. These are:

    - Less than about 5 tonnes of LPG stored in aerosols (Barrier 1)

    - Aerosols all stored in cardboard boxes (Barrier 2)

- Aerosols stored only at low level (Barrier 4).

- A significant percentage of powder aerosols are stored (Barrier 9)

5. Several barriers, if present, are capable of eliminating one of the two causes of the VCE scenario. Those which would eliminate the external fire case are:

   - Warehouse too large (> about 50 tonnes LPG stored in aerosols) (Barrier 5).

   - No combustible materials close to the outside of the warehouse so that an external fire is not possible. (Barrier 12).

   - Construction of the warehouse such that its external walls are firewalls.(Barrier 13).

   Those which would eliminate the internal fire scenario are:

   - No mixed storage (no other combustible material stored in the warehouse) (Barrier 6)

   - Other material that is not slow-burning (Barrier 8).

   - No dedicated aerosol storage area within the warehouse, i.e. aerosols are intermingled with the other combustible material throughout the warehouse (Barrier 12).

   - Firewall between the dedicated aerosol store and the rest of the warehouse (Barrier 13).

6. Other engineered barriers if present, whilst they will not 'eliminate the possibility' of a VCE will significantly reduce the likelihood and may therefore form part of an 'as low as reasonably practicable' (ALARP) demonstration. These are:

   - Structural integrity of warehouse providing protection from an external fire (Barrier 7)

   - Sprinkler System (Barrier 10)

   - Smoke vents or roof lights which would be expected to fail in a fire (Barrier 14).

7. The average individual risk of fatality from a VCE at any warehouse is estimated to be within the 'broadly acceptable' range. Specific warehouses with few of the identified barriers are likely to have VCE risks within the 'tolerable if ALARP' range.

Recommendations

This report may be used to assess any individual warehouse in terms of its likelihood of the VCE scenario. Whilst noting that the postulated VCE scenario is not proven, BAMA proposes using the barrier approach developed in this report as the basis for an industry guide to help operators of warehouses assess the potential of product stored in individual warehouses to give rise to a VCE. This assessment would highlight any additional barrier that might be implemented in the warehouse where the risk of a VCE was found to be unacceptable. Such guidance will also be of value to HSE inspectors.

1 INTRODUCTION

1.1 VCE SCENARIO

In 2006, Dr Graham Atkinson of HSL was asked by HSE to review the risks from fires in large aerosol stores (Atkinson, 2007). Atkinson reviewed incident statistics and reports and concluded that the greatest risk to people from such fires was from explosions, not from the fire itself. He postulated a vapour cloud explosion (VCE) mechanism, whereby a fire of material elsewhere in the warehouse from the aerosols could give rise to a hot air layer close to the ceiling. Aerosols stored close to the ceiling could then fail and release their flammable contents, but not be immediately ignited by the fire. A large flammable vapour cloud could then form, which would give rise to a VCE when ignited. The report led to considerable discussion between HSE and the British Aerosol Manufacturers' Association (BAMA) about whether the proposed VCE scenario is realistic. Critiques of the Atkinson report were produced by Phoenix Loss Prevention Ltd (2007) and the BRE Centre for Fire Engineering at the University of Edinburgh (BRE, 2009). No other studies have been identified which address this issue.

1.2 OBJECTIVES

The objectives of the current work are to consider the likelihood and hence the risk of the VCE scenario at a large aerosol store. Discussions had suggested that the likelihood/ risk may be very low but a systematic analysis is required to document assumptions and reach a conclusion.

1.3 STEERING GROUP

A Steering Group was set up to oversee the current work. This comprised:

Brian Fullam, HSE –replaced by– Iqbal Essa - HSE from June 2010

Laurence Cusco, HSL

Paul Jackson, BAMA

Paul Davidson, Unilever

2 DEVELOPMENT OF BARRIER DIAGRAM

2.1 METHODOLOGY

It was apparent that a fairly high level risk assessment methodology would need to be used because of the lack of quantified data for risk assessment frequency calculations. Layer of Protection Analysis (LOPA) is one such high level approach (CCPS (2001), Amey Vectra (2002), IEC (2004)) which simplifies the risk assessment and is conducive to the recording of assumptions. It was therefore decided to use a methodology based on LOPA, even though it may not be possible or desirable to follow a codified LOPA methodology rigorously.

The basis for such a LOPA-like analysis is a “bow-tie” (Philley, 2006) or equivalent diagram which identifies the initiating events and the barriers which prevent the hazardous outcome (in this case a VCE) from being realised. The barrier diagram in Figure 1 was developed in the following way:

- Brainstorming the logic and barriers with the Steering Group.
- The authors developed the information obtained in the brainstorm and information supplied by BAMA on CD into a prototype barrier diagram.
- Comments on the prototype diagram were obtained at a meeting of the BAMA Safety Operational Committee including many helpful comments on the logic and suggestions of additional barriers.

2.2 OVERVIEW OF BARRIER DIAGRAM

The diagram is shown as Figure 1. Events are shown in yellow (for initiating events) and orange (for outcomes whose frequency might be estimated). Barriers are shown in blue and are further defined in Table 1.

Three possible initiating events have been identified:

(a) A fire external to the warehouse which provides sufficient heating within the warehouse to fail aerosol cans, but without causing an immediate source of ignition within the warehouse. Thus any flammable material released from ruptured aerosol cans could form a cloud.

(b) A fire within the warehouse but of a material which is not from the aerosol dispensers. This fire would need to be slow burning and produce a hot smoke layer close to the roof of the warehouse which could cause aerosol cans to fail and produce a flammable vapour cloud away from the fire itself so that the flammable material would not immediately ignite upon release. A typical fuel for this type of fire might be compressed bales or rolls of cellulosic materials or similar non-volatile materials. In general, unless tightly compacted, packaging materials will create a fire of sufficient rapid growth to invalidate the possibility of a VCE.

(c) A fire in the aerosol storage itself. This has been discounted as a possible cause of a flammable cloud which could lead to a VCE. Either the fire would be controlled by the sprinklers, or other fire protection system (this is if ‘Temperature too low’ in barrier number 17), or the fire were not controlled and thus would escalate. In such a case, any flammable material released from failed aerosols would immediately ignite and feed the fire so as not to give rise to a cloud of vapour forming. This is

‘Temperature too high’ in barrier number 16. It is not believed that there is any intermediate case between these two extremes and therefore it is not credible for a fire in the aerosol storage to cause a VCE.

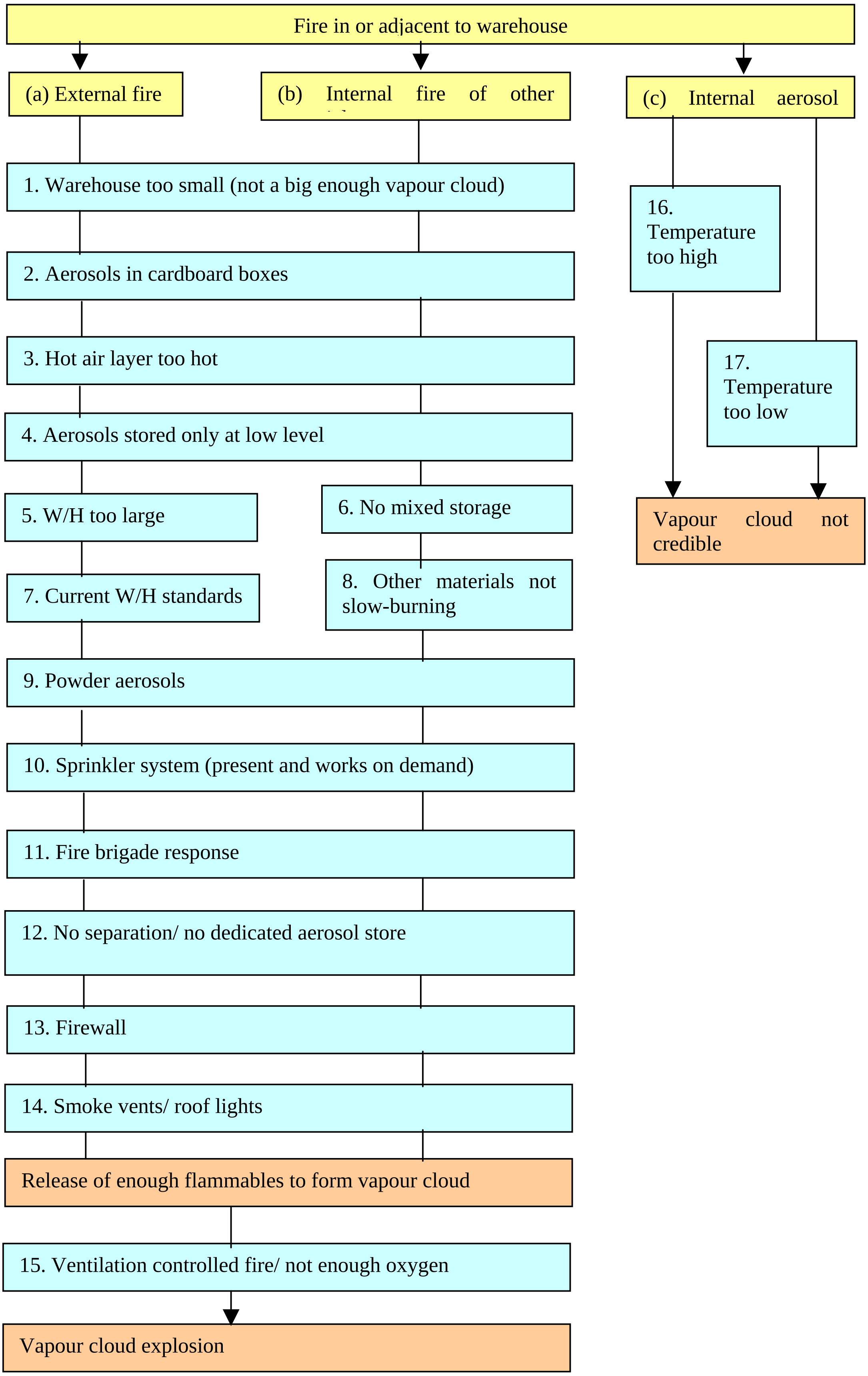


Figure 1: Barrier diagram for VCE in a warehouse containing aerosols

Table 1 Summary of barriers

Barrier number	Description
1	If the warehouse is too small (does not contain enough aerosols), then not enough cans could fail to give a significant vapour cloud. This is related to: • The number of cans in the building, • The percentage of aerosol pallets at the top of the racking (in the hot air layer). Atkinson (2007) estimated that approximately 1 million aerosols would be needed to get 2 tonnes of flammable vapour in a vapour cloud. This implies a COMAH top tier warehouse. However section 3.3 and Appendix B suggest that smaller clouds might also be capable of causing a VCE.
2	If aerosol cans are in cardboard boxes, this will provide enough insulation to prevent failure until the cardboard ignites (after which, flammables from any failed can will be immediately ignited).
3	This barrier encompasses things which would prevent a hot air layer from producing a large cloud of LPG due to failed cans. This includes: • Once the stretch wrap melts, the pallet will collapse and cans will fall from the top of the racking and no longer be within the hot air layer. How many in a pallet might fail (likely to be a relatively low number as it takes time for heat to conduct into the centre of the pallet load (Phoenix, 2008), whereas when the shrink wrap gets hot enough the pallet will collapse and cans will fall out of the hot air layer. • The Phoenix report also argues that the plume/ hot layer will reach a temperature high enough to ignite the released contents.
4	Aerosols stored only at low level (and therefore not in a hot air zone that could form below the ceiling).
5	Warehouse too large (for external fire to cause a VCE). The inclusion of this as a barrier was because of the understanding that an external fire could only cause sufficient heating in a relatively small warehouse. Even for smaller warehouses, Appendix A suggests that this barrier would largely apply.
6	No mixed storage, e.g. aerosols stored in a segregated room with only aerosols stored in that room.
7	Structural integrity of the building such that there would be protection from an external fire. In practice if the outside wall of the warehouse is concrete or even brick and impervious to heat, in such cases the external fire scenario will not result in a VCE.
8	Other materials stored in the warehouse are not slow-burning. A slow-burning material that burns like charcoal would be needed, i.e. slow burning with no embers in the smoke. Embers would tend to ignite any failed cans and escalate the fire to the aerosol storage.
9	Two-phase aerosols containing powder will self-ignite due to static when they burst and therefore would not allow a hot un-ignited flammable layer to build up.

10	A suitable sprinkler system is provided in the warehouse. Sprinkler systems installed in warehouses storing aerosol dispensers to the code deemed reliable enough to ensure that the risk of property loss is reduced to a reasonable level will have sprinkler heads that activate at about 70°C. As it would be necessary for the ambient temperature to be about 80°C to burst the aerosols, then the sprinklers would operate before the aerosol dispensers start to burst and the cooling effect will prevent burst, or at the very least disrupt the formation of a hot layer.
11	The fire brigade may fight a slow burning fire and extinguish it. However, they might not wish to approach a warehouse containing aerosols, even if the aerosols are not yet burning. They would be expected to tackle an external fire.
12	For an external fire there would need to be flammable material which could cause a significant fire close to the warehouse. This may be the case for a significant number of warehouses and the range chosen is likely to be conservative. For an internal fire, the aerosols would need to be stored separately from the material which was burning in order that material from failed cans did not ignite immediately. Where there are large quantities of aerosols, separate storage in a caged area is likely, but to prevent ignition prior to a VCE significant separation distance would be needed.
13	It is not expected that the external walls of a warehouse will be firewalls and therefore this offers only limited protection against an external fire. For internal fires, recently constructed warehouses (since 2004) might have a fire wall for separation.
14	If there are sprinklers there are unlikely to be smoke vents as they reduce the efficiency of the sprinklers. However, many insurers ask for both and some companies comply with this. However, a high proportion of warehouses have roof lights (energy saving). If polycarbonate, these melt at around 150 – 200^{o}C and become effective roof vents. A VCE is unlikely in such cases.
15	Fires inside buildings tend to become ventilation controlled fairly soon and remain so until ventilation occurs due to the roof failing (which will vent the hot air layer). If this is so then it is likely that the fire will be ventilation controlled and there will be no oxygen to support a VCE.
16	This relates to a fire of aerosols. Any such fire (if not controlled by the fire protection system) will fail aerosol cans but will immediately ignite the material released. Therefore a vapour cloud cannot form.
17	This relates to a fire of aerosols. If the fire protection system (sprinklers) operates correctly, then the fire will be controlled and will neither cause a hot smoke layer nor cause failure of further aerosols. A flammable cloud will not form.

3 QUANTITY OF LPG REQUIRED TO CAUSE A VCE

3.1 INTRODUCTION

Atkinson (2007) used the TNO GAMES methodology, which uses the TNO multi-energy method, to estimate consequences for a flammable cloud containing 2 tonnes of LPG. He assumed a source strength (one of the inputs to the method) of 10. This is a high value and 7 is more usual for chemical industry applications unless the flammable material is more reactive than a hydrocarbon or there is very considerable confinement/ congestion. However, except close to the source of the explosion, both strength 7 and strength 10 yield similar results. For 2 tonnes of LPG, Atkinson predicted the effects as a function of distance as shown in Table 2.

Table 2: Damage effects from a warehouse VCE involving 2 tonnes of LPG (from Atkinson, 2007)

Overpressure	Effect	Range (metres)
300 mbar	Complete destruction of most houses and office buildings	130
50 mbar	Roughly 50% window breakage	500
10 mbar	Limit of significant window breakage	2000

3.2 VCE MODELLING

For the current report, Lisbona carried out sensitivity modelling using the TNO multi-energy method as implemented in the consequence modelling software PHAST (DNV, 2007). He used a source strength of 7 and a range of masses of LPG (n-butane was assumed) in the cloud. All of the cloud was assumed to be within a confining/congesting structure. Results are shown in Figure 2. These apply to a worst case cloud composition (close to a stoichiometric mixture of LPG and air) and lower overpressures will result if the mixture is richer or leaner. Although results have been presented from the multi-energy model in Figure 2, it is recognised that it is not fully applicable to warehouses, where there is significant confinement. Models such as Shell Scope (Puttock et al, 2000) would be more applicable but their use was beyond the remit of this study. It expected that the results in Figure 2 are roughly indicative of possible effects, but any directional effects from specific geometries are missed.

The results are consistent with those of Atkinson (2007). The results also show that the effects within the warehouse would be devastating. Figure 2 suggests that there is no lower limit to the quantity of LPG involved in terms of the overpressure produced by the explosion, although the distance at which significant effects occur decrease with decreasing quantities of LPG. Any lower limit to the quantity of LPG involved is therefore more of a function of the ability to form cloud large enough to be sufficiently contained and congested to give rise to a VCE. This is considered in the next section.

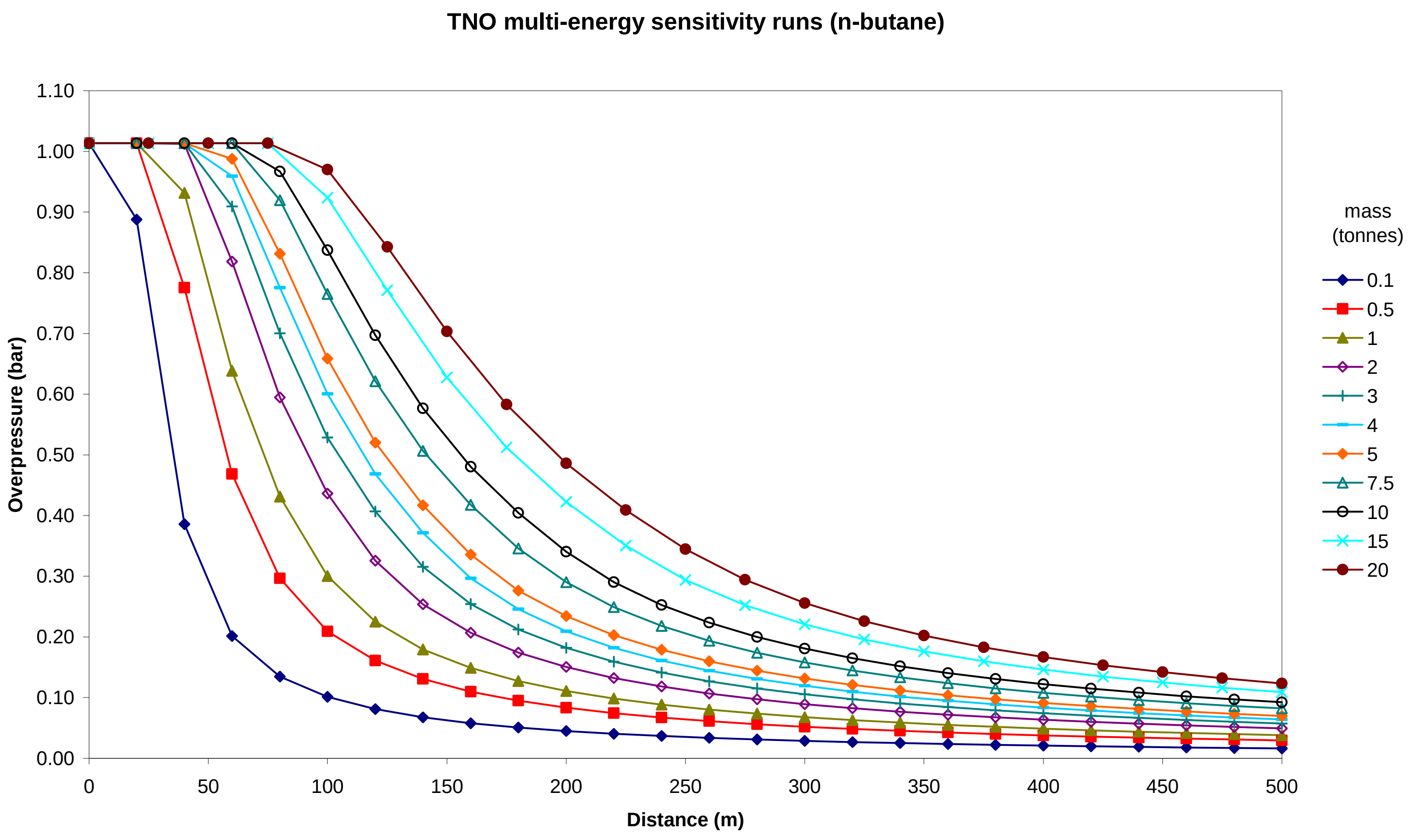


Figure 2: VCE modelling results showing overpressure vs distance for different quantities of LPG

3.3 CREDIBLE CLOUD SIZE

Kletz (1977) suggested, based on empirical evidence from incidents, that a VCE was unlikely for vapour clouds containing less than 2 tonnes of flammables. However, he was considering outdoor events of loss of containment. Smaller quantities can give substantial overpressures if containment is present.

For an ignited cloud of flammable vapour to give rise to a VCE, it must be:

- Mixed with air and with a composition within the flammable range (otherwise it cannot be ignited); and

- Within a containing and/or congesting structure which will give rise to turbulent mixing as the vapour cloud burns and expands (otherwise a flash fire with no overpressure effects, rather than a VCE, would result upon ignition).

Mixing with air is considered separately within Barrier 15 in Figure 1.

The walls and ceiling of the warehouse provide some degree of containment, which will prevent the cloud from expanding. The construction of many warehouses is panels on a steel frame and the panels will be expected to fail and vent the explosion at a fairly modest overpressure, depending on the construction. This may reduce the overpressure effects from those shown in Table 2 and Figure 2, but would not be expected to prevent a VCE because:

(a) The explosion will be well underway before failure of warehouse wall panels; and

(b) Congestion also contributes to producing overpressure effects.

Congestion is provided by the racking and spaces between the pallets within the racking, and the cloud therefore needs to be large enough to encompass reasonable numbers of pallets.

Appendix B estimates the size of the cloud in an approximate way, and suggests that even a cloud of 0.1 tonnes of LPG could form a large enough cloud for the racking and pallets to cause significant congestion.

This suggests that quantities of LPG less than 2 tonnes may be able to give rise to a VCE, but such VCEs would be less damaging than a 2 tonne VCE. It has therefore been assumed that a cloud containing an order of magnitude less LPG than 2 tonnes could still produce a VCE (although the likelihood and consequences would be less than for a 2 tonne cloud). Appendix C suggests that at least 50 tonnes of LPG in aerosols would need to be stored for a 2 tonne LPG cloud to be produced. This suggests that warehouses containing less than about 5 tonnes of LPG in aerosols would be too small for a VCE to be credible. Appendix A suggests that a VCE initiated by an external fire would be extremely unlikely even for larger amounts of LPG.

4 LIKELIHOOD OF A VCE

4.1 QUALITATIVE ASSESSMENT

The quantification of likelihood or frequency always introduces uncertainty. However, a qualitative assessment based on the barrier diagram in Figure 1 reveals that there are some barriers whose presence would eliminate the possibility of a VCE. These barriers are listed in Table 3. If any one of the barriers for "external fire" and any one of the barriers for "internal fire of another material" are provided in a reliable way, then this would be expected to prevent a VCE.

Table 3: Barriers whose presence would eliminate a VCE

Barriers for external fire	Barriers for internal fire of other material
1. Less than about 5 tonnes of LPG stored in aerosols	1. Less than about 5 tonnes of LPG stored in aerosols
2. Aerosols all stored in cardboard boxes	2. Aerosols all stored in cardboard boxes
4. Aerosols stored only at low level	4. Aerosols stored only at low level
5. Warehouse too large (an approximate scoping calculation is given in Appendix A suggests that warehouses storing more than 50 tonnes of LPG in aerosols would be too large; and that those storing more than 5 tonnes may be too large)	6. No mixed storage (no other combustible material stored in the warehouse)
9. Significant percentage of powder aerosols is stored. Powder aerosol pallets would need to be distributed throughout the warehouse so that there would be sufficient at high level to provide a reliable early source of ignition.	8. Other material not slow-burning (this needs further definition but an example of a slow-burning material would be charcoal which burns slowly and without embers in the smoke).
12. No combustible materials close to the outside of the warehouse so that an external fire is not possible.	9. Significant percentage of powder aerosols is stored. Powder aerosol pallets would need to be distributed throughout the warehouse so that there would be sufficient at high level to provide a reliable early source of ignition.
13. Construction of the warehouse such that its external walls are firewalls.	12. No dedicated aerosol store, i.e. aerosols are intermingled with the other combustible material throughout the warehouse (as recommended by Atkinson (2007)
	13. Firewall between the dedicated aerosol store and the rest of the warehouse

The most appropriate way of preventing a VCE would therefore be to provide one or more barriers from Table 3. If, for any reason, none of these barriers were present, then the likelihood of a VCE could be minimised by providing as many as possible of the other engineered barriers shown in Figure 1. These other barriers are listed in Table 4.

Table 4: Other engineered barriers that could reduce the likelihood of a VCE

Barriers for external fire	**Barriers for internal fire of other material**
7. Good structural integrity of the warehouse (this provides a more limited version of the benefits of barrier 13 – firewall).	10. Sprinkler system
10. Sprinkler system	14. Smoke vents or roof lights which would be expected to fail in a fire.
14. Smoke vents or roof lights which would be expected to fail in a fire.	

4.2 QUANTITATIVE ASSESSMENT

An attempt has been made to quantify the frequency of warehouse VCE events, but this has necessitated considerable judgement and estimation of frequencies. The assessment is provided in Appendix D but contains considerable uncertainty. More justification for frequency and probability values would normally be required in a major hazards risk assessment than is available in the assessment in Appendix D.

Nevertheless, it has been possible to conclude that, on average for the warehouse population, the risk of VCE is likely to be so low as to be in the ‘broadly acceptable’ region as defined by the HSE (2001) publication ‘Reducing Risks Protecting People’. For individual warehouses which do not have any of the barriers defined in Table 3, the risk could be in the ‘tolerable if ALARP’ region. This means that consideration would need to be given to whether the provision of more risk reduction (more barriers from Tables 3 or 4) is reasonably practicable.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1. An approximate risk assessment methodology has been developed based on the identified possible barriers to a warehouse VCE scenario which may or may not be present at individual warehouses. Two cases might in theory give rise to a VCE:

    a. A fire external to the warehouse which creates a hot air layer within the warehouse, capable of causing aerosol cans to burst and release their contents forming a vapour cloud before ignition occurs;

    b. An internal fire of other slow burning material stored in the warehouse, remote from the aerosols, that creates a hot air/smoke layer capable of causing cans to burst and release their contents.

2. At least about 50 tonnes of LPG would need to be stored in aerosols to give rise to a release of 2 tonnes of LPG in a VCE scenario. 50 tonnes of LPG equates to the COMAH lower tier threshold.

3. The quantity of LPG in a vapour cloud which could give rise to a warehouse VCE scenario may be less than the 2 tonnes used as an example by Atkinson (2007), perhaps by an order of magnitude. It is therefore likely that warehouses containing less than about 5 tonnes of LPG in aerosols would be too small for a VCE to be credible.

4. The study identified barriers, which if present and functioning correctly would be expected to prevent a VCE.

5. Several barriers, if present, are capable of eliminating the VCE scenario. These are:

    - Less than about 5 tonnes of LPG stored in aerosols (Barrier 1).
    - Aerosols all stored in cardboard boxes (Barrier 2).
    - Aerosols stored only at low level (Barrier 4).
    - A Significant percentage of powder aerosols are stored (Barrier 9).

6. Several barriers, if present, are capable of eliminating one of the two causes of the VCE scenario. Those which would eliminate the external fire case are:

    - Warehouse too large (> about 50 tonnes LPG stored in aerosols) (Barrier 5).
    - No combustible materials close to the outside of the warehouse so that an external fire is not possible. (Barrier 12).
    - Construction of the warehouse such that its external walls are firewalls.(Barrier 13).

    Those which would eliminate the internal fire scenario are:

    - No mixed storage (no other combustible material stored in the warehouse) (Barrier 6).
    - Other material not slow-burning (Barrier 8).

- No dedicated aerosol storage area within the warehouse, i.e. aerosols are intermingled with the other combustible material throughout the warehouse (Barrier 12).

- Firewall between the dedicated aerosol store and the rest of the warehouse (Barrier 13).

7. Other engineered barriers if present, whilst they will not 'eliminate the possibility' of a VCE, will significantly reduce the likelihood, and therefore may form part of an 'as low as reasonably practicable' (ALARP) demonstration. These are

   - Structural integrity of warehouse providing protection from an external fire (Barrier 7).

   - Sprinkler System (Barrier 10).

   - Smoke vents or roof lights which would be expected to fail in a fire (Barrier 14).

8. The average individual risk of fatality from a VCE at any warehouse is estimated to be within the 'broadly acceptable' range. Specific warehouses with few of the identified barriers are likely to have VCE risks within the 'tolerable if ALARP' range.

5.2 RECOMMENDATIONS

This report may be used to assess any individual warehouse in terms of its likelihood of the VCE scenario. Whilst noting that the postulated VCE scenario is not proven, BAMA proposes using the barrier approach developed in this report as the basis for an industry guide to help operators of warehouses assess the potential of product stored in individual warehouses to give rise to a VCE. This assessment would highlight any additional barrier that might be implemented in the warehouse where the risk of a VCE was found to be unacceptable. Such guidance will also be of value to HSE inspectors.

6 APPENDIX A: SCOPING CALCULATION: WAREHOUSE SIZE FOR EXTERNAL FIRE

If the warehouse contains 1 million cans and there are approximately 2500 cans per pallet[1], then number of pallets = 400

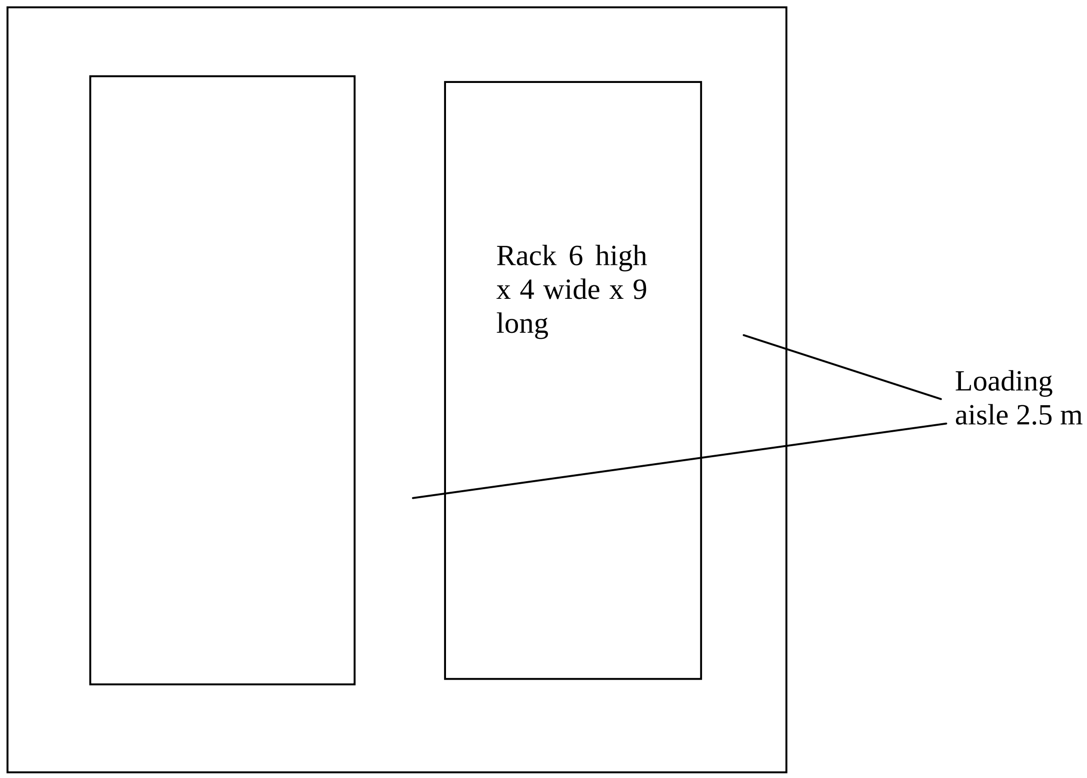
FM Global Standard 7-31 gives examples of racked storage 5 high with 2 pallets having a dimension of 2.4 metres and each pallet being 1.5 metres high.

If rack is 6 high, total height of rack = 6 x 1.5 = 9 m + 1.2 m space to ceiling. So total height approx 10 metres

Just as an example to approximate the size of the building, assume racks are 4 deep with 2 racks either side of loading aisle which is 2.5 m wide. Racks would be approx 9 pallets long.

Total width = (3 x 2.5) + 2 x 2.4 x 2 = 12 m

Length of building = (2.5 x 2) + (9/2 x 2.4) = 15 m



[1] *This may be an overestimate, as for this number of cans to be on a pallet, they would need to be relatively small (no more than 150 ml). The overestimate should be conservative as it will underestimate the size of the warehouse.*

This section of the warehouse would therefore constitute a fairly small warehouse. However, unless there were firewalls, it would be open to the rest of a much bigger warehouse, with the aerosol area segregated and in a caged area.

www.engineeringtoolbox.com gives convective heat transfer coefficients to air as being in the range 10-100 W/m^2K. Natural convection would tend to be at the lower end of the range and 10 W/m^2K has been assumed.

As a worst case (minimum size), consider a warehouse of dimensions 15x12x10 m.

Assume the 15x10m wall is all at a temperature of 250^0C. (Above this temperature, cardboard boxes would ignite. However as cardboard should not be next to the wall a higher temperature may be appropriate and will be considered later).

Consider heat transfer to a layer of air close to the wall which is rising by natural convection and producing a hot air layer at the ceiling. Aerosol cans will burst if heated to about 80 – 90^oC and stretch wrap fails at about 100^oC. Therefore consider the air layer being heated is at 80^oC (this assumption will maximise the calculated heat transfer rate).

Heat transfer rate = U A ΔT = 10 x (10x15) x (250 – 80) = 255000 W = 255 kW

Volume of 3 metres depth at ceiling level = 15 x 12 x 3 = 540 m^3

Mass of air = 540 x 1.2 = 650 kg

Air specific heat capacity is approximately 1 kJ/kgK

Time to heat 650 kg air from 20 to 80^oC = (650 x 1 x (80 – 20))/255 = 150 seconds
= 2.5 minutes

This is an underestimate because there will be mixing between the hot air layer at the surface and the rest of the room. There will also be heat transfer into the walls, racking and aerosol cans.

A very conservative calculation of heat transfer into the cans ignores the heat transfer rate. The specific heat capacity of an organic liquid is also approximately 2.4 kJ/kgK

Time to heat 2 tonnes of aerosol can contents from 20 to 80^oC
= 2000 x 2.4 x (80 – 20)/255 = 1130 seconds = 19 minutes

Cans are approximately 30% of total weight (a 150ml can weighs 30g with 100 g of product) Specific heat of Aluminium = 0.9 kJ/kgK so

Time to heat the cans themselves = 2000 x 0.3 x 0.9 x (80 – 20)/255 = 127s = 2.1 minutes

This gives a total time of 19 + 2.1 = 21 minutes.

As cans rupture the temperature in the cloud will drop so the driving force into the pallets drops; therefore this will take even longer. Further, the need for heat transfer into the pallet through the insulating wrapping has not been considered in this calculation.

The contents of the aerosols would also need to be vaporised. Approximate latent heat capacity of an organic liquid is 500 kJ/kg

Time required = 2000 x 500/255 = 3900 s = 65 minutes

This suggests that for this very small warehouse, it would only be possible to fail enough cans to produce a 2 tonne vapour cloud after an absolute minimum of 1-2 hours. This might be reduced if the wall temperature were higher than 250^{o}C. Temperatures higher than 250^{o}C would however seem to imply that the fire was very close to the warehouse and it is likely that it might spread to the warehouse itself, thus providing a strong ignition source within the warehouse for flammable material and making a VCE less likely. It is also unlikely that the whole wall would reach a uniform high temperature.

The estimate of greater than 1-2 hours (for this warehouse which is about the minimum size which could lead to a 2 tonne flammable vapour cloud) seems of the right order. Virtually all warehouses would be larger than this, either because they store more aerosols or they also store other materials. This would increase the time required as the building volume increases more with size than the area of the largest wall. Therefore a big external fire would be needed which was not extinguished for several hours.

It therefore appears that a warehouse large enough to give a 2 tonne flammable vapour cloud will be too large for a hot air layer, sufficient to fail significant numbers of cans, to form.

Another consideration is that the total volume of this mini warehouse is 1800m^3 but 2 tonnes at UFL needs 9200m^3 (see Appendix B) therefore with a 10m ceiling height needs 920m^2 floor space (30.5m x 30m) or 4 times the size of the warehouse considered to contain the cloud below UFL. This means a much bigger warehouse and longer to form a hot air layer. For a stoichiometric concentration a ~23,000m^3 or 150m x 150m warehouse would be needed. Even if only 0.1 tonnes of flammable aerosol contents were involved, the warehouse would need to be 34m x 34m x 10m for the blast effects to be stoichiometric. These estimates assume no space taken up by product. If 30% of the volume is taken up by the product, the warehouse size needed grows by a further 50%. If the cloud was limited to a 3m hot layer then a further 3 times the floor area is needed. This is before taking account of the distance needed to provide separation from the fire.

The conclusion of these scoping calculations is that it is extremely unlikely (and virtually incredible) that a hot air layer that could fail enough aerosol cans to cause a VCE could be formed in a typical sized warehouse.

7 APPENDIX B: ESTIMATED CLOUD SIZE

7.1 CLOUD SIZE FOR 2 TONNES OF LPG

Assume 2 tonnes of LPG

If predominantly butane MWt = 58

Number of kmols = 2000/58 = 34.5

Volume (at 20 ^oC) = 34.5 x 24 = 828 m^3

LFL is 1.8 % (However, for the explosion overpressures given in Figure 2, the concentration would need to be stoichiometric not LFL, i.e. around 3.6% (15:1 by mass)).

Volume if whole cloud at LFL = 828/ 0.018 = 46,000 m^3

Volume of a sphere = $4/3\Pi r^3$

Diameter if spherical = 2 x $(46{,}000 \times 3/4/\Pi)^{0.3333}$ = 45 m

Since warehouses are not this tall (assume 12m for a smaller warehouse, 24m for a large one), the cloud will extend further horizontally than this. Even the diameter above is quite sufficient for the cloud to extend between several racks and therefore to be exposed to both confinement and congestion.

NB. This method is approximate only. It assumes that the whole cloud is at the same concentration which is the LFL. In practice, some parts of the cloud would be well above the LFL and some would be below the LFL. Also as stated above, for the explosion overpressures given in Figure 2, the concentration would need to be stoichiometric not LFL, i.e. around 3.6% (15:1 by mass)).

UFL is 9%
Volume if whole cloud at UFL = 828/0.09 = 9200 m^3
Diameter if spherical = 26 m

Ideally, the size of the cloud would be estimated using gas dispersion. However, simple dispersion models are inappropriate for an indoor situation with congestion and fire effects. Therefore these simple calculations are used to get a very approximate size for the flammable cloud.

7.2 CLOUD SIZE VARIATION WITH QUANTITY OF LPG

From the above, it can be seen that the cloud diameter is proportional to the cube root of the mass of LPG. This gives rise to the following table of cloud diameter (at LFL) versus quantity.

2	45	26
1	36	21
0.5	28	16
0.1	16	10

8 APPENDIX C: RELATIONSHIP BETWEEN SIZE OF CLOUD AND NUMBER OF PALLETS

8.1 METHOD 1

According to the Phoenix report (2008), only the 500-600 cans in the periphery of a the pallet can give rise to the flammable cloud, not the entire 2-3000 cans, as the rest are shielded from the hot smoke. This implies that approximately 0.25 of the cans in the hot smoke could burst as a result.

It is estimated that a pallet of aerosols could contain 200 kg of LPG. It could therefore release 0.25 of this, i.e. 50 kg.

To release 2 tonnes of LPG would require 40 pallets to be in the hot air layer.

If the racking stacked pallets 6 pallets high and only the top layer was involved in the hot air layer, then a total number of pallets in the warehouse of 40 x 6 = 240 would be required.

240 pallets @ 200 kg of LPG per pallet implies 48 tonnes of LPG stored in the warehouse, i.e. approximately 50 tonnes which is the lower tier COMAH threshold.

If higher racking were used then a larger quantity of LPG in aerosols would be required. If stacked 10 high, the number of pallets in the warehouse would need to be 400 and the quantity of LPG in aerosols would be 80 tonnes.

8.2 METHOD 2

Atkinson (2007) estimated that approximately 1 million aerosols would be required to give rise to a 2 tonne cloud of LPG. At 2,000-3,000 aerosols per pallet, this equates to 330 – 500 pallets. This estimate is therefore of the same order as the 240 – 400 pallets estimated using Method 1 above.

The two methods therefore yield similar results. There will be a lot of variation because of different LPG contents of aerosols and sizes of aerosol cans.

9 APPENDIX D: APPROXIMATE ESTIMATION OF FREQUENCY

9.1 MEASURES OF RISK

The measure of risk of interest is the frequency of a VCE per warehouse. There are several possible ways in which this can be calculated:

i. Average frequency per warehouse over the entire population of warehouses containing aerosols.

ii. Average frequencies for groups of types of warehouse with common characteristics

iii. Frequency for a particular warehouse with a particular set of barriers.

The barrier diagram in Figure 1 provides the basis of estimating the frequency for any of these but will be limited by the available input data.

9.2 INPUT ASSUMPTIONS

9.2.1 Initiating events

The initiating events in Figure 1 are further defined in Table 6. A range of frequencies has been assumed which reflects that warehouse construction and fire prevention standards have improved relative to the population of warehouse fire incidents that led to the frequency estimated by Atkinson (2007). In the absence of better data, the warehouse fire frequency has been divided equally between the three initiating events:

- External fire (outside the warehouse but adjacent to it)
- Internal fire (inside the warehouse) of a material other than aerosols
- Internal fire of aerosols

Table 6: Initiating events and assumptions

Event Number	Event	Discussion	Frequency range
(a)	Fire in or adjacent to warehouse	Atkinson (2007) derived a rate of 0.017 per year based on his review of incidents. BAMA has commented that this picture is based on events from several years ago; there were no such events in warehouses recorded since 1996 as standards have improved. It may be reasonable to take some account of improved standards in fire prevention (particularly since as discussed under barrier 1 in Table 2, relevant warehouses are likely to come under the COMAH regime); fire protection is included in the barriers. This has been reflected by making Atkinson's estimate the maximum value (rather than the middle of a range). A range of a factor of 5 has been assumed. Other sources of fire start frequencies to support the range proposed are as follows: 1) Upper value:Chemical warehouse fire frequency of approx 10^{-2}(from Fowler& Tyldesley, 1998), although generic value across all industry sectors, not specifically for hazardous goods warehouses. Atkins (2003) includes a literature review of warehouse fire start frequencies. Values are within the proposed range. They are not specific to hazardous goods warehouses but all values are around $1x10^{-2}$. Rahikainen and Keski-Rahkonen (1998) quote $8.1x10^{-6}/m^2$ in their survey across Finland. 2)Lower value:Hockey and O'Donovan (1997) suggest a frequency of about 10^{-3} /year for a large fire in a typical warehouse; for hazardous goods warehouses they suggest an order of magnitude lower, at about 10^{-4}/year (fire involving 100% inventory) with 10^{-3}/year being more representative of a smaller fire (10% inventory). Phoenix (2008) suggests using 0.005-0.01.	0.0034 – 0.017 per year

Event Number	Event	Discussion	Frequency range
(b)	External fire (external to warehouse)	It is necessary to determine the relative likelihood of each of these three mechanisms. BAMA considers that dedicated aerosol warehouses are very unusual. Therefore most warehouses contain other materials as well as aerosols. In the absence of better data could just divide the range for (a) by 3. It is understood that there is a generic warehouse fire frequency higher than the 0.017/yr derived for a warehouse fire. However, dangerous goods warehouses might be expected to have better security and fire prevention than the average warehouse and therefore have a similar frequency. External fires might be relatively unlikely except that arson is a common cause of warehouse fires. These arguments support dividing the frequency for (a) by 3.	0.0011 – 0.0056
(c)	Internal fire of other material than aerosols		0.0011 – 0.0056
(d)	Aerosol fire		0.0011 – 0.0056

Table 7: Barriers and assumed average probability of failure over all aerosol warehouses

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	**(c) Internal fire**
1	Warehouse too small	If the warehouse is too small (does not contain enough aerosols), then not enough cans could fail to give a significant vapour cloud. This is related to: • The number of cans in the building, • The percentage of aerosol pallets at the top of the racking (in the hot air layer). Atkinson (2007) estimated that approximately 1 million aerosols would be needed to get 2 tonnes of flammable vapour in a vapour cloud. This implies a COMAH top tier warehouse. Appendix C considers the number of cans and pallets required to give 2 tonnes of LPG. However section 3.3 and Appendix B suggest that smaller clouds might also be capable of causing a VCE. If the scope of the calculation is limited to warehouses that are large enough to have the potential for a VCE, then this barrier does not need to be included. However if the warehouse is small enough that any cloud would contain < 2 tonnes of LPG, then both the likelihood and consequences will be less. It is therefore suggested that a factor in the range 0.1 to 1 is applied for warehouses which are smaller than COMAH top tier.	1 For warehouses containing > 50 tonnes of LPG in aerosols (by definition from scope) 0.1 - 1 For warehouses containing 5 - 50 tonnes of LPG in aerosols	1 For warehouses containing > 50 tonnes of LPG in aerosols (by definition from scope) 0.1 - 1 For warehouses containing 5 - 50 tonnes of LPG in aerosols
2	Aerosols in cardboard boxes	Failure of cans thus producing an unignited cloud, will only occur if they are stored shrink-wrapped. If they are in cardboard boxes, this will provide enough insulation to prevent failure until the cardboard ignites (after which, flammables from any failed can will be	0.9 – 0.99	0.9 – 0.99

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	**(c) Internal fire**
		immediately ignited). For this to be a barrier, there would have to be too few aerosols stored shrink-wrapped to give the possibility of a significant vapour cloud, i.e. a large proportion of the aerosols would need to be stored in cartons (cardboard boxes). In the UK, aerosols are commonly stored shrink-wrapped unlike in mainland Europe where cartons are more often used. A probability (of enough aerosols not to be in cardboard boxes) in the range 0.9 to 0.99 is therefore proposed.		
3	Hot air layer too hot	This barrier encompasses things which would prevent a hot air layer from producing a large cloud of LPG due to failed cans. This includes: • Once the stretch wrap melts, the pallet will collapse and cans will fall from the top of the racking and no longer be within the hot air layer. How many in a pallet might fail (likely to be a relatively low number as it takes time for heat to conduct into the centre of the pallet load (Phoenix, 2008), whereas when the shrink wrap gets hot enough the pallet will collapse and cans will fall out of the hot air layer. • The Phoenix report also argues that the plume/ hot layer will reach a temperature high enough to ignite the released contents. There will therefore be a limited time during the fire development when the temperature is high enough to fail cans, but not high enough to melt shrink-wrap nor to ignite the can contents. (If the fire becomes	0.001 – 0.1	0.001 – 0.1

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	(c) Internal fire
		ventilation-controlled, that could limit further temperature rise but would itself prevent a VCE (see barrier 15)). It is difficult to quantify the risk reduction. However it seems clear that there will be at least some risk reduction from this barrier and that it could be substantial. A range of 0.001 to 0.1 is proposed although there is little evidence to support this.		
4	Aerosols stored only at low level	This is very unlikely to be the case for the COMAH warehouses which are being considered. If the pallets are stacked not racked then they would be limited to 4 pallets high = 6 metres and this would not come close to the roof. The unracked limit is 2 metres for shrink-wrapped aerosols. Therefore aerosols close to the roof is only an issue for racked storage or unusual designs (Permaflex was not racked). It is expected that all COMAH warehouses will be racked. Therefore the probability of failure of this barrier is 1. The probability could be lower for smaller warehouses and a range of 0.1 – 0.5 is proposed for warehouses which store sub-COMAH quantities of aerosols.	1 for COMAH warehouses 0.1 – 0.5 for sub-COMAH	1 for COMAH warehouses 0.1 – 0.5 for sub-COMAH
5	Warehouse too large	The inclusion of this as a barrier was because of the understanding that it would need to be a relatively small warehouse so that an external fire would cause sufficient heating within the warehouse. However,	0 for COMAH	N/A

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	**(c) Internal fire**
		Atkinson (2007) used 2 tonnes of flammables in the example in his report. This would imply a large warehouse, bigger than the COMAH top tier threshold. If heating one wall of the building it would be necessary to heat the air in the warehouse to a high enough temperature and for long enough, without exceeding 250^{0}C at which temperature cardboard would start to burn (and would then ignite failed cans). The criteria for a warehouse being too large are undefined. It may be possible to carry out some approximate scoping calculations based on the wall temperature closest to the external fire being at about 250^{o}C (above which cardboard would start to burn). The scoping calculation in Appendix A suggests that warehouses which are large enough to store more than 50 tonnes of LPG in aerosols would be too large for an external fire to raise the internal temperature sufficiently. A probability of 0 has therefore been assumed for the warehouse being too large to allow a hot air layer for a COMAH warehouse. Even for smaller warehouses, Appendix A suggests that this barrier would largely apply and hence the probability of failure is set to the range 0 to 0.001.	warehouse 0 - 0.001 for sub-COMAH	
6	No mixed storage	Warehouses containing nothing but aerosols are very rare. It is much more likely that there would be large caged areas in warehouses containing other goods. Storage will always be mixed if the warehouse is not dedicated to one of the aerosol brand holders. It is common to have household goods in mixed storage alongside aerosols. A	N/A	0.9 – 0.99

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	(c) Internal fire
		probability of failure of mixed storage of 0.9 to 0.99 has been assumed.		
7	Current warehouse standards	The structural integrity of the building will be a barrier as a high temperature is required for a fairly long time (several 10s of minutes) to cause cans to fail. If the building fails or sets on fire, then this would prevent an unignited cloud, either by venting and preventing cans from failing or by engulfing the flammables from failed cans in the fire. It is expected that most warehouses will be of a construction such that the warehouse fabric itself will not ignite. However failure of the warehouse cladding might be expected if the fire was right up against the wall (e.g. a pile of pallets stored against the side of the building. Good housekeeping should make this relatively unusual (but is accounted for in barrier 12 not here). Current warehouse standards would also prevent storage of aerosols on the second floor of a building such as at Permaflex. A probability range of 0.1 to 0.5 has been assumed for failure of this barrier.	0.1 – 0.5	N/A
8	Other materials not slow-burning	If the material was slow burning then a lot of material would be needed to achieve the 100 MW fire assumed by Atkinson (2007). Distribution centres concentrate on categories of goods but the mix of categories changes over time. DIY warehouses are also relevant. A material that burns like charcoal would be needed, i.e. slow burning with no embers in the smoke. Embers would tend to ignite any failed cans and escalate the fire to the aerosol storage. It is therefore considered extremely unlikely that a suitable slow	N/A	0.001 – 0.01

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	(c) Internal fire
		burning material would be present in sufficient quantities and the probability of failure of this barrier is taken as 0.01 – 0.001		
9	Powder aerosols	Two-phase aerosols containing powder will self-ignite due to static when they burst and therefore would not allow a hot unignited flammable layer to build up. Powder aerosols are assumed to be relatively unusual. It is also unlikely that all or most of the aerosols in a warehouse would be powder. However, only some powder aerosols are needed in the warehouse as they would provide a local source of ignition. The probability of failure of this barrier is therefore taken to be high and in the range 0.2 – 0.99	0.2 – 0.99	0.2 – 0.99
10	Sprinkler system	A sprinkler system has to be present and to work correctly on demand. Whether there are sprinklers depends on the insurers. A large percentage of larger warehouses have sprinklers as there are almost no insurers that do not insist in their installation. Companies who self-insure are highly likely to have sprinklers as self-insurance would be on the basis of very high levels of fire protection. Such sprinkler systems are set to operate at 70°C which is lower than the temperature at which aerosols will burst releasing their contents. Hauptmanns (2008) estimated the probability of failure on demand of a sprinkler system as 0.06). PD 7974 Part 7 gives the probability of successful sprinkler operation as being in the range 0.75-0.95, equating to a PFD of 0.05 to 0.25. A sprinkler system would be expected to activate in the case of an internal fire but may not in the case of an	0.25 – 0.5	0.05 – 0.25

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	(c) Internal fire
		external fire. For an external fire, the probability of failure of the sprinkler barrier has therefore been increased.		
11	Fire brigade response	The fire brigade may fight a slow burning fire and extinguish it. However, they might not wish to approach a warehouse containing aerosols, even if the aerosols are caged or are not yet burning. They would be expected to tackle an external fire. A fire would need to burn for some time to cause failure of a significant number of aerosols (Phoenix, 2008). Phoenix estimated that, in air/smoke at 250º C, 10 min would be needed for a single can to reach 80º C and burst. The 100MW fire scenario considered by Atkinson (2007) suggested that 28-40 minutes would be needed to burst a sufficient number of cans for a VCE. Fire brigade response may be possible within this time. Particularly for an internal fire, the fire brigade response of putting water on the fire and/or creating smoke vents in the roof will tend to reduce the temperature of the smoke layer. For an external fire, the fire brigade might also provide cooling of the walls of adjacent buildings. The probability of failure of the fire brigade response is therefore estimated as being in the range 0.1 to 0.5.	0.1 – 0.5	0.1 – 0.5
12	No separation	For an external fire there would need to be flammable material which could cause a significant fire close to the warehouse. This may be the case for a significant number of warehouses and the range chosen is	0.5 – 0.9	0.1 – 0.5

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	(c) Internal fire
		likely to be conservative. For an internal fire, the aerosols would need to be stored separately from the material which was burning in order that material from failed cans did not ignite immediately. Where there are large quantities of aerosols, separate storage in a caged area is likely, but to prevent ignition prior to a VCE significant separation distance would be needed. The probability of failure of this barrier has been taken as being in the range 0.1 to 0.5.		
13	Firewall	It is not expected that the external walls of a warehouse will be firewalls and therefore this offers only limited protection against an external fire. For internal fires, recently constructed warehouses (since 2004) might have a fire wall for separation. Whether there is a firewall depends on the age of the building and the value of the stock. Firewalls are therefore relatively unusual.	0.9	0.99 - 1
14	Smoke vents/ roof lights	If there are sprinklers there are unlikely to be smoke vents as they reduce the efficiency of the sprinklers. However, many insurers ask for both and some companies comply with this. However, a high proportion of warehouses have roof lights (energy saving). If polycarbonate, these melt at around 150 – 200^{o}C and become effective roof vents. Some have fibreglass roof lights which melt/ fail at higher temperature. Whereas smoke vents would be unlikely to operate for an external fire, a hot smoke layer at roof level	0.2 - 1	0.2 - 1

Barrier Number	**Barrier**	**Discussion**	**Range of probability of failure on demand (PFD)**	
			(b) External fire	**(c) Internal fire**
		would still be expected to fail polycarbonate roof lights. The melting point of these roof lights is still fairly high compared with the temperature required to fail an aerosol can. However, they might still have some effect in reducing the time available for cans to heat to the failure temperature. It is assumed that 50% of warehouses might have polycarbonate roof lights and that they have a failure to work in the range 0.1 to 0.5		
15	Not enough oxygen	Fires tend to become ventilation controlled fairly soon and remain so until ventilation occurs due to the roof failing (which will vent the hot air layer). If this is so then it is likely that the fire will be ventilation controlled and there will be no oxygen to support a VCE. It is more likely than not that the fire will be ventilation controlled, particularly in view of the time required for a significant number of cans to fail. The most likely event to stop the fire being ventilation controlled is the failure of the roof and as discussed under barrier 14, this would disperse the hot layer. (See also section 3.2.3 in the main text of the report). It is therefore proposed that a range of failure of there being enough oxygen of 0.01 to 0.1 is reasonable if the fire is internal. If the fire is external then there would be no consumption of oxygen within the warehouse so the probability of failure of this barrier is 1.	1	0.01 – 0.1
16	Temperature too high	This relates to a fire of aerosols. Any such fire (if not controlled by the fire protection system) will fail aerosol cans but will immediately ignite the material released. Therefore a vapour cloud cannot form.	N/A	N/A

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	**(c) Internal fire**
17	Temperature too low	This relates to a fire of aerosols. If the fire protection system (sprinklers) operates correctly, then the fire will be controlled and will not cause a hot smoke layer or cause failure of further aerosols. A flammable cloud will not form.	N/A	N/A

9.2.2 Barriers

Table 7 defines the barriers and proposes ranges of probability of failure of the barrier for case (i) in section 9.1: the estimation of an average frequency over all warehouses. For cases (ii) and (iii), Table 7 may still be of use if the barrier exists within the sample of warehouses or individual warehouse considered. If the barrier does not exist, then the probability of failure should be set to 1.

Table 7 contains some barriers where the probability of failure equates to the probability of the barrier not being present – if the barrier were present then it would prevent the VCE scenario. This is different from some other barriers, e.g. barrier 10 (sprinklers) where not only does the barrier have to be present, it also has to work on demand. The identified barriers which only have to be present to prevent a VCE are shown in Table 3 in Section 4 of the main report. Only one of these barriers would need to be present for each initiator to eliminate the VCE scenario.

9.2.3 Backdraft vs VCE

The probability assumed in Table 7 for barrier 15 (not enough oxygen) makes a distinction between a VCE and 'backdraft'. Backdraft can occur when a structural failure allows air into the fuel vapour which has been formed by the fire and may be above its autoignition temperature. This can be explosive but is a fireball (the rate of burning is limited by mass transfer/mixing between the fuel vapour and the air). A VCE however requires pre-mixing of the flammable vapour and air before ignition, so that once ignited a combustion front propagates through the flammable mixture. While both have significant thermal effects, the overpressure effects of a VCE are considerably greater than those of a fireball.

If backdraft were being considered, then failure of the roof or roof lights would be expected to cause a backdraft but would not be expected to cause a VCE.

9.3 ESTIMATED FREQUENCY OF VCE

A VCE frequency for each initiator can be derived by multiplying the frequency of the initiating event by the probability of failure of all of the applicable barriers.

9.3.1 Average frequency for all warehouses which are large enough to be applicable

This has been estimated using both the minimum and maximum values of the ranges in Tables 6 and 7. The results are shown in Table 8.

Table 8: Estimated average VCE frequencies for warehouses which are large enough

Initiating event	Estimated frequency per warehouse per year	
	Minimum	Maximum
(b) External fire	0 (for COMAH warehouses) 0(for smaller warehouses)	0 (for COMAH warehouses) 2.8×10^{-8} (for smaller warehouses)
(c) Internal fire of other material	1.8×10^{-16} (for COMAH warehouses) 1.8×10^{-18} (for smaller warehouses)	3.4×10^{-8} (for COMAH warehouses) 1.7×10^{-8} (for smaller warehouses)
Total	1.8×10^{-16} (for COMAH warehouses) 1.8×10^{-18} (for smaller warehouses)	3.4×10^{-8} (for COMAH warehouses) 4.5×10^{-8} (for smaller warehouses)

The frequencies shown in Table 8 relate to averages over the population of warehouses. It is possible that warehouses with few of the barriers in place could have higher frequency. Comparison with risk criteria is considered in section 9.3.4 below.

9.3.2 Frequency for groupings of warehouses

Although the average frequencies in Table 8 above are very low, there may be types of warehouse without some of the barriers in Figure 1. The frequency of VCE for such warehouses would be higher than for the average. Equally, any warehouses, which do have at least one of the barriers for each initiating event identified in Table 3, would have no risk of a VCE. This section concentrates on types of warehouse which may have higher than average frequency of VCE. Table 7 includes the estimated average frequency of barriers being present. If a barrier is not present for a type of warehouse, then the probability of its failure becomes 1. If one of the barriers identified in Table 3 is present, then the probability of its failure becomes zero (or else the probability of its being in working order, if appropriate). Table 9 gives the estimated probability of failure of each barrier if it is present.

Tables 10 and 11 give the estimated frequency of VCE for different combinations of barriers being present, for the initiating events of external fire and internal fire of another material, respectively. Only combinations which include none of the barriers identified in Table 3 have been considered as only these cases have a risk of VCE.

Table 9: Assumed probability of failure if the barrier is present

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	**(c) Internal fire**
1	Warehouse too small	If the scope of the calculation is limited to warehouses that are large enough to have the potential for a VCE, then this barrier does not need to be included.	0 – 0.1 For warehouses containing <5 tonnes of LPG in aerosols	0 – 0.1 For warehouses containing <5 tonnes of LPG in aerosols
2	Aerosols in cardboard boxes	Failure of cans to produce an unignited cloud will only occur if they are stored shrink-wrapped. If they are in cartons, this will provide enough insulation to prevent failure until the cardboard ignites (after which, flammables from any failed can will be immediately ignited).	0	0
3	Hot air layer too hot	There will be a limited time during the fire development when the temperature is high enough to fail cans, but not high enough to melt shrink-wrap nor to ignite the can contents. (If the fire becomes ventilation-controlled, that could limit further temperature rise but would itself prevent a VCE (see barrier 15)). It is difficult to quantify the risk reduction. However it seems clear that there will be at least some risk reduction from this barrier and that it could be substantial. A range of 0.001 to 0.1 is proposed.	0.001 – 0.1	0.001 – 0.1

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	(c) Internal fire
4	Aerosols stored only at low level	If the pallets are stacked not racked than they would be limited to 4 pallets high = 6 metres and this would not come close to the roof.	0	0
5	Warehouse too large	If the warehouse is large enough then an external fire cannot provide enough heating to produce a hot enough air layer at the ceiling. See Appendix A which suggests that a warehouse storing 50 tonnes of LPG in aerosols would be too large for a VCE to develop.	0	N/A
6	No mixed storage	Aerosol pallets are mixed within the other storage in the warehouse including the other flammable material which could give rise to a fire.	N/A	0
7	Current warehouse standards	This includes good structural integrity of the warehouse and preventing storage of aerosols in buildings with more than one storey such as at Permaflex.	0.1 – 0.5	N/A
8	Other materials not slow-burning	A material that that is slow burning with no embers in the smoke (such as charcoal) would be needed. Embers would tend to ignite any failed cans and escalate the fire to the aerosol storage.	N/A	0
9	Powder aerosols	All or a significant fraction of the stored aerosols are powder aerosols which will self-ignite on failure.	0	0
10	Sprinkler system	Hauptmanns (2008) estimated the probability of failure on demand of a sprinkler system as 0.06). PD 7974 Part 7 gives the probability of successful sprinkler operation as being in the range 0.75-0.95, equating to a PFD of 0.05 to 0.25. A sprinkler system would be expected to	0.25 – 0.5	0.05 – 0.25

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	**(c) Internal fire**
		activate in the case of an internal fire but may not in the case of an external fire. For an external fire, the probability of failure of the sprinkler barrier has therefore been increased.		
11	Fire brigade response	The fire brigade may fight a slow burning fire and extinguish it. However, they might not wish to approach a warehouse containing aerosols, even if the aerosols are not yet burning. They would be expected to tackle an external fire. A fire would need to burn for some time to cause failure of a significant number of aerosols (Phoenix, 2008). Particularly for an internal fire, the fire brigade response of putting water on the fire and/or creating smoke vents in the roof will tend to reduce the temperature of the smoke layer. For an external fire, the fire brigade might also provide cooling of the walls of adjacent buildings. The probability of failure of the fire brigade response is therefore estimated as being in the range 0.1 to 0.5.	0.1 – 0.5	0.1 – 0.5
12	No separation	For an external fire there would need to be no flammable materials close to the warehouse. For an internal fire, the aerosol pallets would need to be mixed throughout the warehouse with the other materials.	0	0
13	Firewall	It is not expected that the external walls of a warehouse will be firewalls and therefore this offers only limited protection against an external fire.	0.9	0

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	(c) Internal fire
		For an internal fire, if separate aerosol storage is surrounded by a firewall then this would prevent formation of a hot air layer.		
14	Smoke vents/ roof lights	If there are sprinklers there are unlikely to be smoke vents as they reduce the efficiency of the sprinklers. However, many insurers ask for both and some companies comply with this. However, a high proportion of warehouses have roof lights (energy saving). If polycarbonate, these melt at around 150 – 200^{o}C and become effective roof vents. Some have fibreglass roof lights which melt/ fail at higher temperature. Whereas smoke vents would be unlikely to operate for an external fire, a hot smoke layer at roof level would still be expected to fail polycarbonate roof lights. The melting point of these roof lights is still fairly high compared with the temperature required to fail an aerosol can. However, they might still have some effect in reducing the time available for cans to heat to the failure temperature. It is assumed that polycarbonate roof lights might have a failure to work in the range 0.1 to 0.5	0.1 – 0.5	0.1 – 0.5
15	Not enough oxygen	Fires tend to become ventilation controlled fairly soon and remain so until ventilation occurs due to the roof failing (which will vent the hot air layer). If this is so then it is likely that the fire will be ventilation controlled and there will be no oxygen to support a VCE. It is more likely than not that the fire will be ventilation controlled, particularly in view of the time required for a significant number of cans to fail. The most likely event to stop the fire being ventilation controlled is the failure of the roof and as discussed under barrier 14, this would disperse the hot layer. (See also section 4.2.3 in the main text of the	1	0 – 0.1

Barrier Number	Barrier	Discussion	Range of probability of failure on demand (PFD)	
			(b) External fire	(c) Internal fire
		report). It is therefore proposed that a range of failure of there being enough oxygen of 0 to 0.1 is reasonable if the fire is internal. If the fire is external then there would be no consumption of oxygen within the warehouse so the probability of failure of this barrier is 1.		

Table 10: Estimated frequency of VCE due to external fire as a function of which barriers are present

Barrier (defined by barrier number from Figure 1) present? (Note: those shaded yellow are applicable barriers from Table 4)											Frequency per warehouse per year	
			5	**7**	**9**	**10**	**11**	**12**	**13**	**14**	**Min**	**Max**
			N	Y	N	Y	Y	N	Y	Y	2.0×10^{-10}	3.2×10^{-5}
			N	N	N	Y	Y	N	Y	Y	2.0×10^{-9}	6.3×10^{-5}
			N	Y	N	N	Y	N	Y	Y	9.9×10^{-10}	6.3×10^{-5}
			N	Y	N	Y	N	N	Y	Y	2.0×10^{-9}	6.3×10^{-5}
			N	Y	N	Y	Y	N	N	Y	2.2×10^{-10}	3.5×10^{-5}
			N	Y	N	Y	Y	N	Y	N	2.0×10^{-9}	6.3×10^{-5}
			N	Y	N	Y	Y	N	Y	Y	2.0×10^{-11}	3.2×10^{-6}

* 5-50 tonnes of LPG stored in aerosols

Table 11: Estimated frequency of VCE due to internal fire of another material as a function of which barriers are present

					9	10	11		13	14	Min	Max
					N	Y	Y		N	Y	0	3.5×10^{-6}
					N	N	Y		N	Y	0	1.4×10^{-5}
					N	Y	N		N	Y	0	7.0×10^{-6}
					N	Y	Y		N	N	0	7.0×10^{-6}
Y*					N	Y	Y		N	Y	0	3.5×10^{-5}

* 5-50 tonnes of LPG stored in aerosols

9.3.3 Frequency for individual warehouses

The barriers identified in Figure 1 can be used together with Table 9 to estimate the frequency of VCE for any individual warehouse. If a particular barrier does not exist for the warehouse, the probability of it failing should be set to 1. If it does exist, the range of values in Table 9 can be used, or a more accurate value specific to the particular warehouse, if known.

9.3.4 Comparison with risk criteria

Both individual and societal risk criteria can be considered. The HSE publication 'Reducing Risks Protecting People' (R2P2) (HSE, 2001) defines appropriate criteria.

Individual risk is the frequency of death of the person most exposed. Two groups of people could be considered:

- Workers in the warehouse. Due to working patterns and holidays, any individual person will only be present for about 25% of the time, but will be exposed to other hazards within the warehouse.
- Members of the public. In the worst case a member of public whose home was close to the warehouse could be exposed 100% of the time.

The criterion for a 'broadly acceptable' individual risk (which cannot be distinguished from the background risk) is 10^{-6} per year. An intolerable individual risk is 10^{-3} per year for workers and 10^{-4} per year for members of the public.

It is not clear that a warehouse VCE would necessarily cause fatality. The VCE scenario requires time to burst aerosol cans and emergency response may have evacuated people from the vicinity in this time. However, the range of effects of a VCE (see Figure 2 for 300 mbar overpressure) may extend for several hundred metres and evacuation may not take place unless a VCE is envisaged. In comparing with risk criteria, it is conservatively assumed that a VCE would cause fatality.

Table 8 shows that even the maximum value of the average risk for all warehouses is less than the broadly acceptable level. Tables 10 and 11 show that unless sufficient barriers are provided for a particular warehouse, the risk would be in the 'tolerable' region, such that additional barriers would need to be considered to reduce the risk ALARP.

Societal risk is to do with events that could cause multiple fatalities. R2P2 (HSE, 2001) suggests that an intolerable level of societal risk would be an event which killed 50 people at a frequency of once in 5000 years (2×10^{-4} per year). The number of potential fatalities would depend on the size of the VCE, the proximity of populations and the emergency response (evacuation) arrangements. Tables 8, 10 and 11 show frequencies below 2×10^{-4} per year even for warehouses with few barriers in place. HSE (SPC/PERM/39) has suggested that in a COMAH context a broadly acceptable level of societal risk might be two orders of magnitude lower than the R2P2 criterion. Tables 8, 10 and 11 therefore suggest that the societal risk from the VCE scenario for many warehouses may be in the 'tolerable' region for which the risks need to be reduced ALARP.

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Risk assessment for VCE scenario in an aerosol warehouse

In 2006, Dr Graham Atkinson of HSL was asked by HSE to review the risks from fires in large aerosol stores (Atkinson, 2007). Atkinson reviewed incident statistics and reports and concluded that the greatest risk to people from such fires was from explosions, not from the fire itself. He postulated a vapour cloud explosion (VCE) mechanism, whereby a fire of material elsewhere in the warehouse from the aerosols could give rise to a hot air layer close to the ceiling. Aerosols stored close to the ceiling could then fail and release their flammable contents, but not be immediately ignited by the fire. A large flammable vapour cloud could then form, which would give rise to a VCE when ignited. The report led to considerable discussion between HSE and the British Aerosol Manufacturers' Association (BAMA) about whether the proposed VCE scenario is realistic. Critiques of the Atkinson report were produced by Phoenix Loss Prevention Ltd (2007) and the BRE Centre for Fire Engineering at the University of Edinburgh (BRE, 2009). No other studies have been identified which address this issue.

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