

A CONSISTENT APPROACH TO THE ASSESSMENT AND MANAGEMENT OF ASPHYXIATION HAZARDS

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Asphyxiation by inert gases is a hazard throughout the chemical process industries and beyond. Best practice management of hazards associated with access to inerted vessels and confined spaces is well understood and well documented; the hazards associated with service supply lines and other process systems running through occupied buildings are not so well understood. This paper was inspired by the need to find simple, practical approaches to meet industry aspirations for best practice.

This paper presents the use of a zoning type methodology to:

- achieve a consistent approach to assessment and risk reduction;
- focus design such that the hazards are eliminated or minimized;
- assist operators in defining provisions & procedures to manage the hazard.

Risk assessment approaches, analogous to those used for flammability hazards, are proposed to assign zones that consistently identify the level of risk and enable appropriate management methods to be selected and deployed.

This is an application of existing data on leakage rates and dispersion models derived for flammable gases applied in the alternative scenario of oxygen deficient atmospheres. It is an approach that can be applied to any asphyxiation hazards from service and process systems pipework both inside and outside buildings although the focus is for inside buildings.

KEYWORDS: Asphyxiation, Hazards, Area Classification

INTRODUCTION

Asphyxia, the word is from the Greek *a* – meaning “without” and *σφυγμός* (*sphygmos*) meaning, “pulse or heartbeat”. Asphyxiation is a condition in which the body becomes deficient in oxygen due to an inability to breathe normally. Oxygen deficiency without remedial action can progress rapidly from diminished mental and physical capacity, to unconsciousness, to brain damage and ultimately to death.

Asphyxiation is a hazard encountered on many sites and many industries. Anyone using or generating gases or vapours that can displace oxygen has the potential hazard. When working with asphyxiant materials in confined spaces there are regulations and working practices to manage the situation. (SI 1713 1997) However, there are times when the work place is not apparently confined and the asphyxiation hazard is not immediately apparent. Such was the case when working on the planned review of the safety case for a plant at Sellafield. The plant used nitrogen to manage a flammability hazard within the process. Access to the inerted vessels and the precautions required were, apparently, well

understood. However, the problem stemmed from nitrogen supply lines running through rooms within the building. These rooms were ventilated by a cascaded induced draught system designed for radiological containment and not intended to manage asphyxiation hazards. This raised questions about the identification, assessment and management of asphyxiation hazards both inside buildings and in outside locations across the whole site.

This paper reports progress on ongoing work to develop a consistent approach to the identification, assessment and management of asphyxiation hazards initiated by that safety review.

THE NATURE OF THE HAZARD

The key to a successful and elegant hazard management strategy is to understand the nature of the hazard and how it arises. In the case of asphyxiation hazards, this requires:

- An appreciation of the physiology of asphyxiation;
and
- An understanding of how oxygen deficient atmospheres can arise.

PHYSIOLOGY

Humans need oxygen to survive; too little and humans suffer diminishing physical and psychological abilities with reducing oxygen ultimately leading to death; too much oxygen and humans can die from the accumulation of fluid in the lungs (oedema). A summary of these effects is provided in Table 1. (This is a compilation of data from a number of sources.) The life supporting oxygen range at sea level is 19% to 23%. The transport of oxygen into the blood is a combination of mass transfer and absorption chemistry; the mass transfer element means that partial pressure is the true driving force. This to the chemical engineer explains why people experience problems at altitude but can breathe pure oxygen at reduced pressure.

Curiously, the desire to breathe is triggered by rising carbon dioxide levels in the body detected in the carotid sinus rather than by reduced oxygen. This creates the sensation known as air hunger, which is the urge and desire to breathe. When there is not enough carbon dioxide to cause air hunger and trigger the breathing reflex victims suffer the symptoms of lack of oxygen without knowing it. Effective remedial action is needed otherwise the condition can very rapidly lead to unconsciousness, brain damage and death.

A typical human breathes between 12 and 20 times per minute at a rate primarily influenced by carbon dioxide concentration and thus pH in the blood. This obviously increases if the individual is carrying out heavy physical work, such as an operation or maintenance activities. With each normal breath, a volume of about 0.6 litres is changed from an active lung volume (tidal volume + functional residual capacity) of about 3 litres; breathing heavily from exertion can considerably increase the 0.6 litre figure.

Table 1. Effects of reduced oxygen atmospheres

Oxygen (vol%)	Effects and symptoms
23.5	Maximum “safe level” (23% is often the high level alarm set point for most oxygen detectors).
21	Typical O ₂ concentration in air.
19.5	Minimum “safe level” (19% is often the low level alarm set point for most O ₂ detectors).
15–19	First sign of hypoxia. Decreased ability to work strenuously. May induce early symptoms in persons with coronary, pulmonary or circulatory problems.
12–14	Respiration increases with exertion, pulse up, impaired muscular coordination, perception and judgement.
10–12	Respiration further increases in rate and depth, poor judgement, blue lips.
8–10	Mental failure, fainting, unconsciousness, ashen face, blueness of lips, nausea, vomiting, inability to move freely.
6–8	6 minutes – 50% probability of death 8 minutes – 100% probability of death.
4–6	Coma in 40 seconds, convulsions, respiration ceases, death.

When a person enters an oxygen deprived atmosphere, the oxygen level in the arterial blood drops to a low level within 5 to 7 seconds. Loss of consciousness follows in 10 to 12 seconds and if the person does not receive any oxygen within 2 to 4 minutes, heart failure and death follow.

Moving affected and unconscious persons from a nitrogen atmosphere into fresh air is not enough to promote recovery. The patient has to be physically resuscitated in order to restore the oxygen supply to the brain.

(Data compiled from: IGC Doc 44/00/E and US Chemical Safety Board Safety Bulletin 2003)

Unconsciousness in cases of accidental asphyxia can occur very rapidly, typically within one minute. Loss of consciousness results from critical hypoxia, when arterial oxygen saturation is less than 60%.

“At oxygen concentrations [in air] of 4 to 6%, there is loss of consciousness in 40 seconds and death within a few minutes”. (DiMaio 2001) If the atmosphere were to be completely devoid of oxygen, the sequence of effects should be expected to occur even more quickly.

At an altitude greater than 43,000 ft (13,000 m), where the ambient oxygen concentration is equivalent to 3.6% at sea level, an average individual is able to perform flying duties efficiently for only 9 to 12 seconds without oxygen supplementation. (DiMaio 2001) The US Air Force trains aircrews to recognise their own and other individual’s subjective signs of approaching hypoxia. No two people react the same; some individuals experience

headache, dizziness, fatigue, nausea, or euphoria, but some become unconscious without warning. (DiMaio 2001)

Loss of consciousness may be accompanied by convulsions and is followed by cyanosis and cardiac arrest. (DiMaio 2001) The onset of irreversible brain damage occurs at about 4 minutes and about 7 minutes of oxygen deprivation causes death of the cerebral cortex and presumably the medulla oblongata, which controls breathing and heart action. Only two breaths of an oxygen deficient atmosphere can induce unconsciousness and death! (IGC Doc 44/00/E)

HOW DOES THE HAZARD ARISE?

Asphyxiant gases are used for a variety of purposes across many industries; general examples include the exclusion of oxygen for fire safety or reasons of chemistry, as a transport medium in ejectors of Reverse Flow Diverters (RFDs) and welding operations. Hence, we can think of the hazard as present:

- through deliberate action either continuously or for significant periods of time;
or
- accidentally through leakage.

Identifying the need for a hazard management strategy for the former is relatively straightforward and one might argue covered by Confined Spaces Regulations. (SI 1713 1997)

The latter is more problematic. Service pipes run through occupied areas in both outdoor and indoor locations can leak through fixtures and fittings and can even break. This is the hidden hazard exposed by the periodic safety review of an operational facility. What is intriguing is that unlike flammable gases there is apparently little or no guidance on the management of this hazard. The guidance that exists examines bulk far field effects rather than near field effects. A large body of analysis and standards exists for managing the near field effects of releases of flammable gases these include: IP15, BSEN 600979-10:2003, IGE SR25 etc. This paper examines ways of evolving the approach used for managing flammable materials so that it can be used for managing asphyxiant materials.

HAZARD ASSESSMENT AND MANAGEMENT

There are two concepts that need addressing when managing and assessing a potential asphyxiation hazard:

1. The Far Field.
This represents the general areas of the space surrounding the source;
2. The Near Field.
This is the hazard close to the source of release where localised effects are significant.

THE FAR FIELD

The far field is the general area of a room; it represents the area first moved into upon entry into a room or location. The guidance to be found on managing asphyxiation hazards concentrates on this macro scale field often assuming perfect mixing.

The atmosphere in the far field area is normally monitored by static oxygen depletion monitors. The ventilation system should be designed to ensure that any leakage is diluted and well mixed so that the air movement presents the oxygen depletion instrument with a representative sample of the room environment. Thus, in the far field the safety of personnel is based upon a good ventilation system diluting any leakage, and promoting mixing in the room and a good monitoring regime (well placed instruments) checking for oxygen depletion. This is what the vast majority of people understand as the hazard of asphyxiation. Examining the far field in this way neglects the local effects in the near field and overlooks any 'dead zones' in the ventilation. Dead zones being areas of very little or no air movement.

The ventilation systems of most plants on nuclear sites are designed as radiological protection systems providing containment as opposed to an asphyxiation hazard protection system. Good mixing is not a success criterion. This also applies to systems designed to provide human comfort in occupied areas. These use only 5 to 6 air changes per hour, which is the level required for normal human occupancy. In such systems 'dead zones' probably exist. For normal containment ventilation or comfort ventilation, this is not a problem, but when the hazard is asphyxiation, the danger within these 'dead zones' is that nitrogen or any other asphyxiant gas can accumulate and develop localised oxygen depletion volumes.

Gases that are lighter than air will have some mixing through buoyant flow. Heavier than air gases do tend to accumulate at floor level. However, there is a myth that neutrally buoyant gases, like nitrogen, (having a similar density to air) mix readily with air. Having a similar density to air means there is no great driver for mixing and localised variations in oxygen content of air can and do exist. The 'dead zones' have to be identified and if possible eliminated.

THE NEAR FIELD

The near field represents the effects local to any gas release and the mixing zone around the release. It is a hazard that is not readily addressed by bulk ventilation. As the potential source of release is approached there is a possibility of a gas jet or a localised volume of inert atmosphere from a 'seep'. If the jet, or the localised oxygen depleted atmosphere is inhaled, there can be effects. If the amount of gas inhaled is enough to negate the detection of carbon dioxide by the body then the next breath will not follow and the individual will be in serious difficulties.

If the gas or vapour released is flammable, there is a considerable body of information on the assessment of the extent of the mixing zone. This is readily applied to any gas. Therefore, this body of information was used to try to define the nature of the problem.

There is a current trend to turn immediately to CFD (Computational Fluid Dynamics) modelling for such situations but we were looking for simple desktop approaches that could be applied. Source terms can be derived by looking at standard hole sizes, which can

be found for various types of fixtures and fittings in a number of sources notably Cox and Lees 1990 and IP15. The latter even contains some limited information on mixing extents for nitrogen. The strength of IP15 is that it is based on CFD modelling for the flammable materials. However, simple desk top jet mixing models are also used such as the modified Froude approach described by Burgoyne 1984, Brennan 1984 and Marshall 1977.

Where overall Jet Length J is given by:

$$J = 2.4Fr^{0.5}d \quad (1)$$

The Froude Number Fr is defined here as: $Fr = \frac{\rho_g^{1.5}u^2}{\rho_a^{0.5}(\rho_a - \rho_g)dg}$ (2)

Where u jet velocity given by: $u = \frac{G}{\rho_g A}$ (3)

and $A = \frac{\pi d_{ps}^2}{4}$ (4)

When the release is sonic the maximum pseudo diameter of the jet is used rather than the actual diameter of the release orifice used for subsonic emissions:

$$d_{ps} = d_o \sqrt{C_d \frac{P_1}{P_2} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{2(\gamma - 1)}}} \quad (5)$$

- d_o diameter of orifice
- C_d discharge coefficient
- P_1 line pressure
- P_2 final pressure
- γ ratio of specific heats

Now and the distance X to a given concentration E is given by

$$X = \frac{2050}{E} \left(\frac{G}{M^{1.5}T^{0.5}} \right)^{0.5} \quad (6)$$

where X distance to dilute to concentration E

- G mass flow rate
- M molecular mass
- T absolute temperature

If the calculated distance to the required concentration E is less than the Jet Length J then the Equation (6) applies. If however the distance X exceeds the Jet Length J then the

distance to the specified concentration lies outside the jet length, the momentum jet becomes wind controlled. The distance to the concentration (downwind) is calculated from:

$$X = 2.4Fr^{0.5}d + \left(\frac{920Q}{E}\right)^{0.55} - \left(\frac{920Q}{C}\right) \quad (7)$$

where

$$C = \frac{2050}{2.4Fr^{0.5}d} \left(\frac{G}{M^{1.5}T^{0.5}}\right)^{0.5} \quad (8)$$

Or a low momentum dispersion model such as

$$X = \frac{86.75}{E^{0.6}} \left(\frac{Q^2 \rho_g}{(\rho_g - \rho_a)g}\right)^{0.2} \quad (\text{Burgoyne 1984}) \quad (9)$$

These are sufficient to define the extent of the hazard. Future extensions to this work are to look at further CFD validation of these methods and what refinements to these desktop models exist.

The jet mixing model has to be used with caution as it is appropriate for a sonic flow and significant sub sonic releases, however there are three weaknesses using this approach:

1. The model assumes that the jet flows axially to a 0.5 ms⁻¹ wind, which will not be present in indoor locations;
2. The model assumes dilution by air; if the far field oxygen concentration in a room is reduced this will have the effect of increasing the dilution distance;
3. If the jet impinges on anything it can lose its velocity and the dispersion becomes a low momentum plume type dispersion.

As a pragmatic consequence, the recommendation is to use the low momentum plume type model, which is the more pessimistic approach. However, refining the risk based approach (The Institute of Petroleum 1998) to area classification used for flammable systems that establishes outer boundaries for Zone 2 hazardous areas whilst taking account of the risks associated with contributory factors would be advantageous. This is a future area of work.

This work led to a practical rule of thumb to allow for a near field of about a 1 metre radius around a release source for a jet release, unless it is a line breach.

Localised ventilation systems can be used to reduce the size of the near field, but they cannot eradicate it altogether – there is always a near field. The issues within the near field are:

- Identification of hazard potential;
- Awareness of the hazard by personnel on the facility;
- The use of procedures as part of the hazard management strategy.

The following safety rules are proposed for near fields that may pose asphyxiation risks:

1. There should be no lone working where near fields may exist.
2. There needs to be a good understanding of the emergency response and actions to be taken if there is an incident.
3. There needs to be close monitoring of any individual working within a near field, by someone trained in what to look for.
4. PPE (breathing air hoods, etc.) can also be used but only as a last resort.
5. The logical alternative would be to identify 'dead zones' highlighting their extent (possibly using markings on the floor) and the provision of additional oxygen depletion monitoring in that area.

ZONING PROPOSAL

Having used the concepts and principles used in defining the extent of flammable gas zones it is a logical extension to consider a Zoning system for asphyxiant gases. The benefits of doing this are:

- achieving a consistent approach to risk assessment and risk reduction;
- focusing designs such that the hazards are eliminated or minimized;
- assisting operators in defining provisions and procedures to manage the hazard.

Risk assessment approaches, analogous to those used for flammability hazards, can be used to assign zones that consistently identify the level of risk and enable appropriate management methods to be selected and deployed.

This is an application of existing data on leakage rates and dispersion models derived for flammable gases applied in the alternative scenario of oxygen deficient atmospheres. It is an approach that can be applied to any asphyxiation hazards from service and process systems pipework both inside and outside buildings although the focus is for inside buildings. This approach concentrates on line fittings and joints, one way to minimize the hazard potential is to use all welded pipe lines.

The proposal is to implement a three zone system:

- **Zone 30** where, during normal operations, an oxygen deficient atmosphere is present continuously or for long periods of time.
These are most likely to be the conditions inside process equipment;
- **Zone 31** where, an oxygen deficient atmosphere is likely to occur in normal operation occasionally.
These are likely to be around engineered access points into equipment;
- **Zone 32** where an oxygen deficient atmosphere is not likely to occur in normal operation but, if it does occur, will persist for a short period only.
This is most likely to surround process and service pipework and equipment, especially when located inside buildings.

As a simple example derived from actual plant experience of how this can be applied: consider the room illustrated in Figure 1, it contains equipment supplied with nitrogen and is accessed through an antechamber. The ventilation inflow is induced through door louvres and extracted at high level through a duct that is part of the engineered building extract system. Figure 1 also illustrates a means of recording the information representing it as a map of the specific problem. The nitrogen supply lines with fixtures and fittings, which are the potential leak points, can be recorded on the map. A ventilation survey highlights vent

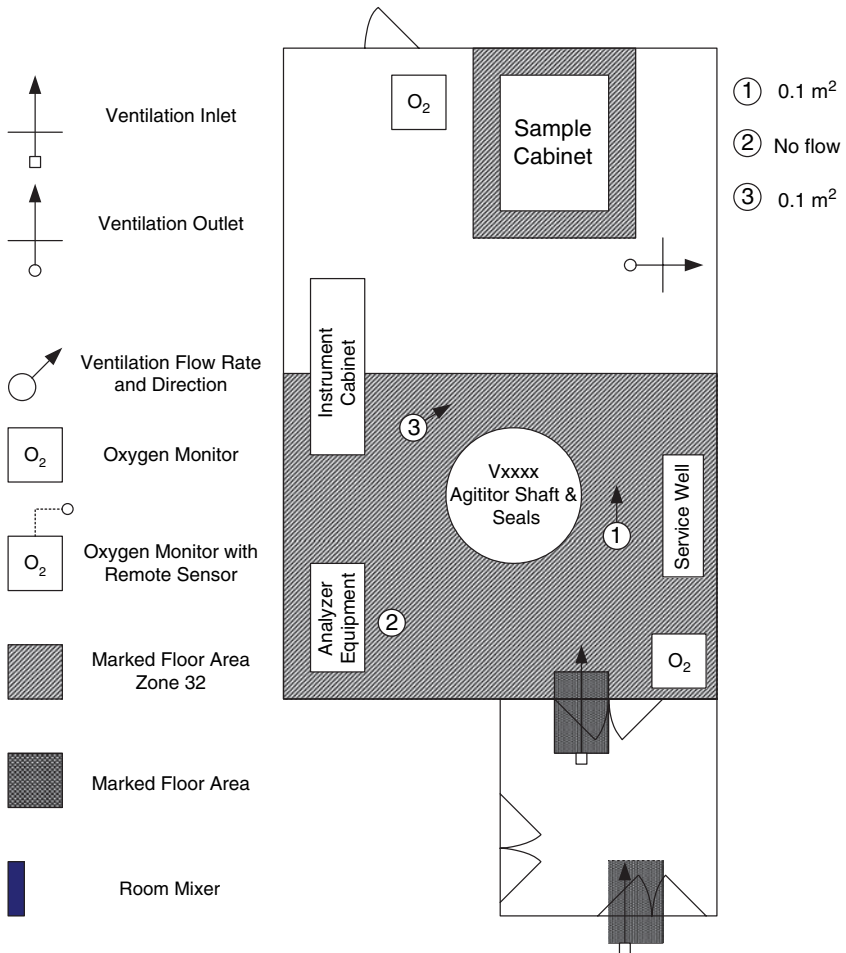


Figure 1. Example mapping of asphyxiation zones, vent flows and measures adopted.

flows and directions. In this case, it also highlights that any obstruction in front of the louvred doors has a major impact on vent flows and dead zones. This survey information is also recorded on the map. Marking out the boundaries of the near field around the potential leak points and the 'dead zones' shows the overlaps between sources leading to the identified Zone 32 area. Now the most frequent operation in the room is undertaken at the Sample Cabinet at the back of the room. Access to this requires an operator to pass through the Zone 32 area. In this way the deficiencies are highlighted and the measures to assist in the management and awareness of the hazard are recorded. The possible measures to manage the situation include:

- the use of additional oxygen monitors to monitor the atmosphere on the pathway to the sample cabinet. This demonstrates that the route is inhabitable before the room is entered;
- marking the floor to indicate to any operator that this is a potential hazard area and not to loiter;
- managing access to and occupancy of the room through Permit to Work procedures. This could include no lone working. The role of the 'buddy' would be to observe from the antechamber and be trained to recognise the behaviours that could indicate the onset of asphyxia and initiate a prepared recovery plan.
- Other measures to consider could be installed room mixers to reduce the dead zones or re-engineering the inlets to sweep stagnant areas and to remove the obstruction issue.

This example is for an existing facility but the mapping concept can also be applied as a design is developed, but its use at the design stage can help show how to demonstrate how the potential hazard has been minimised.

CONCLUSIONS

Zoning itself is not a protection system but highlights problems to both designer and operator; it draws attention to managing the near field effects and 'dead zones' often overlooked by existing guides. A set of guidelines is to be developed for each zone that establishes the minimum standards and best practices in various situations. Key to these are the ventilation capability for purging and mixing. One simple provision effectively used as part of a suite of measures for Zone 32 is to mark the zoning around potential leak sources on the floor. This provides a powerful visual indication of an invisible potential hazard, which can be used in a number of ways to assist in the protection of people.

This project is ongoing and future work is planned to refine the approach. This will focus on:

- Preparing detailed codes of practice and guidelines for use within the company;
- Developing and demonstrating risk reduction measures in practical applications;
- Using CFD to validate the simple desk top source term models.
- Evaluating and extending risk based approaches to hazardous area classification to asphyxiation hazard management.

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