

Explosion safety in anaerobic digestion sites; where it can go wrong and guidance to avoid that happening

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As of 2022, the UK had over 650 operational anaerobic digestion (AD) facilities, found across various sectors, including agriculture, food and drink, waste treatment and municipal waste. This number is expected to grow as the government continues to drive policies for renewable energy generation. From a design point of view, the layout and operation of an AD plant is variable from one site to the next, influenced by factors such as the volume and type of feedstock, the complexity of the digestion process and whether gas and/or power to grid is planned. The process safety approaches at each site should be appropriate for that specific setup. For example, pressure relief devices should be rated for the expected biogas pressures generated by the microbiological process, and thus capable of maintaining containment within that digester. The specific hazards of each site should be considered by the operator and appropriate safe systems of work created as a result.

In recent years, several high-profile incidents in the AD industry have occurred, where serious injuries or deaths have resulted, including, explosions caused by ignition of the biogas. In response to these incidents HSE has undertaken a programme of inspections at AD sites to identify common process safety problems. As a complementary activity and to further aid understanding of activities at these sites, a review of documentation related to the AD industry was undertaken. The review activities included data retrieval from formal reporting schemes (e.g., under jurisdiction of HSE and EA, as available/appropriate), where relevant incidents in the sector from 2010-2020 were extracted and process safety information related to these incidents compiled. Additionally, relevant publicly available technical literature, both nationally and internationally was accessed, in order to gain an insight into the range of existing safety standards and guidance that relate to AD process safety and to understand if knowledge gaps exist that may be contributing to the incidents that have occurred.

This paper presents some of the findings from both the literature review activities and the anecdotal observations from site visits. The content has aimed to focus on process safety aspects relating to explosion safety specifically, rather than environmental impacts. It is hoped that the reader will find practical information that can be incorporated into their own safety considerations around AD, whether as an operator or an interested party. The information has been laid out in four sections; Part 1: Overview of UK incident records, Part 2: Findings from HSE programme of inspections, Part 3: Standards and guidance, Part 4: Ventilation system design. The format of the final section is more prescriptive than the preceding sections. It was noted during the site inspections that, in many cases, correct sizing of ventilation systems for the respective tank being ventilated, had not been considered, resulting in a very real risk that an explosive atmosphere was not being mitigated. Thus, part 4 has been included so as to provide the user with insight into the principles of scouring and some of the underlying theory that could be used to specify adequate ventilation flow rates to prevent the accumulation of biogas for the specific tanks of interest. A brief introductory section on the process of anaerobic digestion is included to provide context for the reader.

Keywords: Anaerobic digestion (AD), biogas, process safety, DSEAR, foaming, ventilation

Explosion safety in anaerobic digestion

Anaerobic digestion (AD) is a series of biological processes in which micro-organisms digest plant and/or animal material in sealed containers, producing biogas, which is a mixture of methane, carbon dioxide and other gases. The scale of the process is dependent on business need and may vary from small farm scale processes using livestock manures to large municipal plant initiatives processing industrial sewage. The organic material remaining after digestion, known as the digestate, is rich in organic matter and nutrients such as nitrogen, phosphate and potash and is regarded as a useful end product in itself. The generated biogas, containing methane, can be used as an energy source, whether by combustion locally e.g. intermediate-scale digesters used in generating electricity, usually via use of combined heat and power (CHP) engines or large-scale digesters with plant for upgrading the biogas to biomethane which may then be injected to the national grid at dedicated points. An overview of the typical process is shown in Figure 1 on the next page.

AD is a complex, living, biological process that is affected by numerous interdependent factors such as temperature, retention time and agitation. It is important, both for gas yield and for safety, that a stable digestion is maintained in the digester vessel. Variation in the feedstock composition, rates of organic loading and retaining feed, and incorrect commissioning can all contribute to "souring" of the digester. This results in reduced gas production rate, excessive production of unwanted by-products e.g. ammonia, or unreacted feedstock (which could cause foaming). Monitoring of these factors provides early warning if a digester is beginning to deviate slowly from optimal conditions. It should also be considered whether these deviations have occurred due to a process safety issue, rather than a change in microbial activity. For example, a reduction in gas production may be occurring due to crust formation preventing gas release into the headspace. It could also be as a result of a leak in the system due to membrane tearing or an equipment failure.

Methane, the main gas of interest in biogas, has an explosive range of between 5 % and 15 % vol. in air. Within biogas, methane accounts for between 50 % and 70 % of the overall gas mixture. Thus, the generated methane has the potential to be within its explosive range at various times during the process, not only during intentional gas generation activities such as the digestion process but also at times when presence of methane is not essential e.g., in the feedstock reception area/holding tanks, or when storage tanks are being accessed for maintenance purposes.

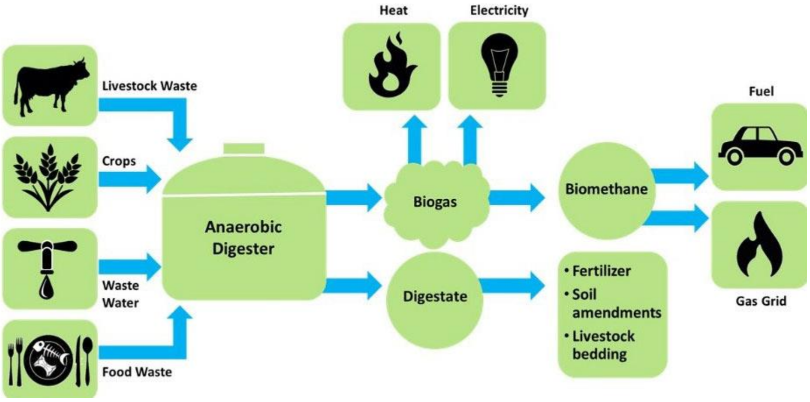

Figure 1: Anaerobic digestion process (Graphic by Sara Tanigawa, EESI. Reproduced with permission).

In the UK, explosion safety at AD installations is regulated according to the Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR). As part of the requirement for this regulation, it must be determined where within the process explosive atmospheres are expected. If an explosive atmosphere cannot be reduced/removed, such as installing forced ventilation systems, then these areas must be zoned and classified appropriately according to the frequency and duration of the explosive atmosphere. Appropriately rated equipment must be used in these areas, e.g. ATEX equipment, and signage must be at these zone entrances to warn users of an explosive area.

For hazard area classification (HAC), the zones are defined as follows:

Zone 0 – an explosive atmosphere is present continuously, or for long periods or frequently.

Zone 1 – an explosive atmosphere is expected to occur occasionally in normal operation.

Zone 2 – an explosive atmosphere does not normally occur, but if it does, does so rarely and only for a short time.

Zone 2 NE – the likelihood of an explosive atmosphere being present is extremely low, but if it does, does so rarely and only for a short time. ATEX equipment is not required for Zone 2 NE areas ,

The following sections provide more details on incidents relating to fire and explosion, potential corrective actions and observed process safety trends across the AD industry.

Part 1: Overview of UK incident reports

This section relates to anaerobic digester site incidents, the majority of which were recorded by either the Health and Safety Executive or the Environment Agency between 2010 and 2020. Data has been extracted from these reports and summarised under topics including, year/industry type, nature/category of incident and plant involved. In the first section some general statistics are given related to all incident types i.e. toxic, environmental and injury aspects as well as explosion risk. In the subsequent section, further analysis of the incidents relating to fire and explosion risk has been carried out, where anecdotal data has been extracted and summarised. Some recurring underlying causes have been noted and expanded upon e.g. foaming events causing tank rupture; in these cases the relevant corrective action, if it was logged has been extracted and detailed in a flow diagram format. In this way, as well as knowing the cause, the reader may gain increased understanding of process safety but also may find some useful corrective strategies that could be applied to their own setup. Note: this is not an exhaustive list of all incidents, and some events may not have been extracted due to keyword search criteria not representing a match e.g. if report did not log that the incident occurred at a biogas/anaerobic digestion site.

General statistics

Over the time period from 2010-2020, using search criteria that included biogas/anaerobic digestion as keywords, 68 incidents were recorded. In terms of incident occurrence by industry, 40 of these incidents occurred on industrial sites, 9 were logged as agricultural sites and 19 incidents did not specify industry. It is thought that this seemingly larger incident occurrence in industrial sites is more likely as a result of underreporting in the agricultural sector, rather than the industrial sector being inherently more incident prone. This supposition appears to be corroborated by anecdotal observation and material breaches identified as part of the inspection scheme, which is discussed further in the “Findings from HSE programme of inspections” section below.

Figure 2 shows the breakdown of incident type over the ten-year period; categorised as fire and explosion risk, asphyxiation/toxic gas release, physical injury, and environmental pollution due to biogas release to atmosphere or slurry (solids) release. From these reports, environmental pollution accounted for the most frequent occurrences. This is again possibly down to level of reporting (or underreporting) of human safety issues. Environmental permitting of most AD sites tends to be routinely inspected against the environmental criteria of the license rather than health and safety regulations. Where physical injuries resulted (7 incidents), reasons included equipment failure due to corrosion, use of incorrect tools/PPE or operative not anticipating the hazard and thus not implementing a safe system of work. In the case of asphyxiation/toxic gas releases (7 incidents), where operatives were in close proximity, this tended to be during maintenance activities, for example breaking of a crust in the digester. Where toxic gas releases occurred (not necessarily causing an asphyxiation risk), this tended to be due to failure/absence of an odour abatement system, such as an H_2S scrubbing. In terms of fire and explosion risks (15 incidents), these tended to occur as a result of a deviation from normal operating conditions, including foaming causing blockage of PRVs leading to over pressurisation, or power cuts causing safety critical equipment such as flares to stop. The most serious incidents involved hot works on storage tanks that contained accumulations of flammable gas that had not been properly identified during Hazardous Area Classification (HAC).

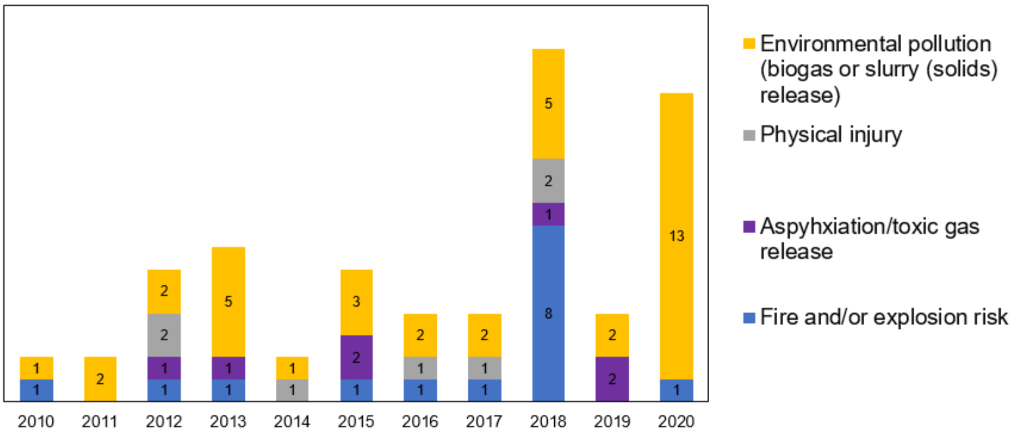

Figure 2: Breakdown of incident from 2010-2020 by nature of risk that occurred i.e. environmental pollution, physical injury, asphyxiation/toxic gas release and fire/explosion risk. The number of incidents for each incident type is overlayed on the relevant section of the bar.

Fire and explosion incidents – modes of failure, underlying cause

Though many reports are categorised in terms of their environmental impact, the anecdotal information within the report throws light on some process safety issues that commonly occur. This anecdotal information has been extracted for incident types categorised as fire and explosion risk and is listed in Table 1 below, segregated by the area of plant where the incident occurred, for example the digester tank, the storage tanks/areas pre or post digestion, or reported as a site wide issue. Where recurring trends have been noted, the related keyword is highlighted with an asterisk. The keywords that are highlighted in grey are discussed in more detail in the next "underlying cause and corrective action" subsection. A similar exercise has been completed for the other incident types however is outside the scope of this paper and so not included here.

Table 1: Anecdotal data relating to incidents where fire and explosion risk identified. Where recurring trends have been noted, the related keyword is highlighted with an asterisk. The keywords that are highlighted in grey are discussed in more detail in the next "underlying cause and corrective action" subsection.

Fire or explosion risk	
Location	**Cause of incident**
Site-wide	1. Poor site design – Lack of safety features i.e. no flare, vacuum relief, pressure relief venting close to buildings. Lack of ventilation in storage tanks 2. Inadequate/no hazardous area classification* - poor understanding of HAC 3. No safe systems of work* considered explosion/fire risk, in particular during maintenance activities and when visitors on site. 4. Dangerous electrical management i.e. exposed electrical connections, internal wiring in poor condition 5. Adjacent fire caused failure of biogas dome on nearby tanks, releasing biogas
Pre digester (reception/mixing)	1. Poor understanding of HAC
Digester	1. Floating layer of feedstock i.e. straw, disabled level indicator and PRVs, caused rupture of digester tank from pressure build-up – feedstock only partially chopped 2. Crust formation* due to agitator failing (needed manual restart), blocked PRVs resulting in hatch on roof failing instead to relieve pressure – onsite staff unaware of corrective procedure, leading to delayed response

	3. Excessive foaming* led to blockage of PRVs causing rupture of digester membrane – inadequate control measures meant excessive foaming went undetected. Operatives unaware of any operating procedures for dealing with foam. 4. Power failure* meant safety critical components not working i.e. flares, CHP so PRVs continuously activated – no operating procedure for failure scenario 5. Change of feeding process caused elevated gas emission which caused tank to buckle (didn't fail completely) – site acted appropriately to mitigate effects
Post digester (digestate storage/ containment)	1. Hot works on tank* wrongly assumed to not contain a flammable gas accumulation 2. Digestate storage tank caught fire due to lightning strike – consider lightning assessment 3. Gas storage tank collapsed, flare didn't work – inadequate preventative maintenance plan and safe systems of work 4. Poor ignition control in Hazardous areas.
CHP/Upgrader	1. Siloxanes crusted on engine causing fire – inadequate preventative maintenance plan and safe systems of work 2. Catalytic iron filters caught fire due to overheating, caused by exposure to air i.e. maintenance activities – poor risk and hazard understanding 3. Due to low quality gas i.e. high H_2S, flame continued to be quenched causing release of unburnt gas

Fire and explosion incidents – underlying cause and corrective action

Three of the underlying causes are discussed in this section; crust/floating layer formation, excessive foaming events, and catalytic iron filters for H_2S scrubbing going on fire. The data has been presented in Figure 3 showing how an operator could recognise the phenomenon based on the visual indicators, the contributing factors (based on incident reports) and potential corrective action that was and could be taken.

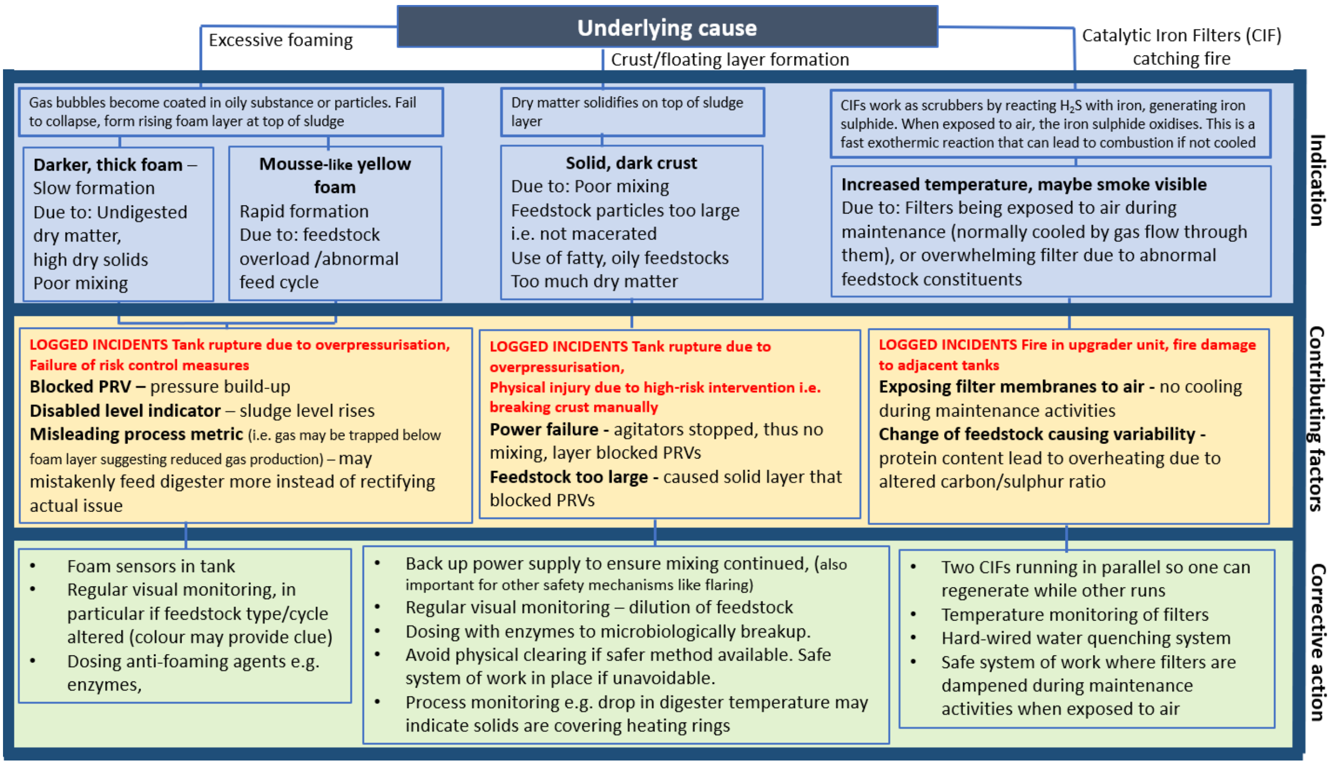

Figure 3: Diagram showing data related to three common underlying causes of fire and explosion incidents. The first row describes the visual indicators, the second details the contributing factors that led to the incident and the final row outlines some potential corrective action that was taken.

Part 2: Findings from HSE inspection programme

Summary of inspection campaign

Twenty-two inspections at AD sites were carried out by HSE's Field Operations Division in 2021/22. These were large sites dealing with sewage, food, and industrial wastes. In 2022/23, forty-nine inspections were carried out at agricultural sites. Note: these were routine inspections and not in response to an unsafe occurrence or concern being reported. The outcome of this campaign was that material breaches were found in 50% of cases for industrial sites and 40% of cases in agricultural sites. It was noted that the quality of competent advice i.e. safety reports generated by external consultants, has been poor at some sites with one external contractor receiving an improvement notice following the provision of inadequate advice/DSEAR report. In general there has been difficulty in demonstrating competency amongst duty holders due to the lack of industry specific competency benchmarks. That being said, the campaign overall produced positive outcomes; for example, one operator applied the advice given by the HSE process safety specialist around hazardous area zoning at one of their managed sites to all of their operated sites. The following sections provide more specific information about some of the issues and recurring trends that were encountered.

Hazardous Area Classification

Hazardous Area Classification (HAC) involves identifying locations on a site where flammable atmospheres can occur; it is the most fundamental part of a site's efforts to control explosion risks. The results of such assessments affect both the choice of equipment to be used in hazardous locations and site procedures and precautions. For example, the need for a permit–to-work system in an area is often determined by the results of HAC. There has been a recent history of catastrophic incidents in the UK in which the potential for flammable atmospheres in tanks, other than the digester, was overlooked, and where uncontrolled hot works caused explosions resulting in multiple deaths and serious injuries; one of the most severe of these included the explosion of a silo at Wessex Water, in December 2020, which resulted in four fatalities. Unfortunately, the results of the inspection programme support the suspicion that these incidents reflect more widespread weaknesses in the reliability of HAC at AD sites. The inspections noted problems with:

i. Reception tanks, mixing tanks, buffer tanks and other enclosed areas containing raw waste: The waste is often at close to ambient temperature and may not normally produce gas rapidly. However, AD plants can experience variations in feedstock, residence time and environmental conditions. Microbial populations respond in complex ways to such variations and occasional creation of flammable atmospheres is possible in some cases. At many sites, the completed HAC simply ignored such tanks without proper analysis of potential gas production and ventilation.

ii. Digestate storage tanks (after the digester): Since most digesters operate as well–stirred reactors the digestate includes a substantial quantity of undigested material which typically has a significant gas-production potential. Text in some of the European standards recognise this and recommend treating the ullage of such tanks as hazardous areas. The HSE inspections revealed that some sites simply ignored the potential for flammable atmospheres in digestate storage tanks during HAC.

iii. Assessment of pasteurised material: In some sites the waste is pasteurised before or after digestion. There appears to be a common misconception that such material is then sterile and thus are microbiologically inactive. However, heat treated material is often discharged into large un-sealed tanks where it may be kept for a significant period. The contents of such large tanks are not sterile, with pasteurisation only intended to reduce the level of some pathogens in the mixture, and new microbial activity means the gas production potential can be rapidly realised. Both the potential gas production rates and the ventilation rates needed to prevent flammable gas mixtures forming are often poorly understood.

iv. Adequacy of ventilation: Ventilation of potentially hazardous areas occurs in a number of ways e.g., using forced ventilation, natural ventilation (wind and or buoyancy driven) or gas exchange linked to filling and emptying of tanks. It was rare for sites to have reliable assessments of the adequacy of ventilation in vessels both before and after the main digester. This repeated observation motivated the production of the short discussion on ventilation design in part 4 of this paper.

Following the recommendations as suggested during HSE visits, changes to the visited sites included reclassification of zones. For example, where poor or unreliable ventilation was identified, these tanks were reclassified as Zone 2. This type of zoning was also introduced for tanks which could develop flammable atmospheres more quickly than appropriate emergency responses could be reliably deployed. On some sites with adequate forced ventilation for foreseeable gas production rates, the tanks were reclassified as Zone 2 NE. This zoning was contingent on a system for detecting any failure of the ventilation system and communicating this to operators and managers well within the time that it would take to develop a flammable atmosphere. There also must be a clearly documented and reliable system for provision of emergency ventilation. This type of zoning mirrors the classification of gas turbine enclosures protected by forced ventilation. A Zone 2 NE has the important advantage over a simple classification as non-hazardous, in that it recognises that flammable atmospheres *can* occur and are only prevented by a functioning ventilation system. Zone 2 NE classifications should be included in Hazardous Area Zone plans and in site procedures and precautions.

Understanding of risks associated with density variation in biogas

Depending primarily on the balance of CO_2 and methane, explosible biogas can be significantly lighter or heavier than air. In typical digester operations, biogas is usually slightly buoyant. However, it can be heavier than ambient air, especially if the gas is produced in psychrophilic (low temperature) conditions or where waste is exposed to the ambient air, for example during emptying of a digester. Similarly biogas in a poorly ventilated storage tank may accumulate at the top or low down near the surface of the waste. This issue is significant in the placement of detectors and sampling points and is also very important in designing ventilation systems that will control the development of flammable atmospheres.

The inspection programme revealed a generally low awareness of potential density variations in biogas, and that the effects of foreseeable density changes were very rarely examined in DSEAR assessments. Where biogas was incorrectly assumed to always be buoyant some important zones were missed – for example around the ground level opening in overflow pipes. The potential for heavy gas to accumulate in the lower parts of tanks with marginal ventilation was not recognised. The level of awareness of this issue is not helped by the mixed quality of guidance on the issue. The fact that biogas can be lighter or heavier than ambient air is recognised in a number of European guidance documents (Austrian, German, French). For this reason, it is recommended that biogas should be detected (via its methane content) with detectors at both high and low level.

Other standards do not always recognise the effect of density changes. For example, the BS ISO 24252:2021 "Standard on biogas production" (ISO, 2021) requires that light gases (such as methane) are detected at high level (only) whereas heavy gases such as hydrogen sulphide are detected at low level (only). In fact, biogas does not separate into individual gaseous components with different densities. For most leaks of normal biogas, hydrogen sulphide and all the other biogas components accumulate at high level. A low-level hydrogen sulphide detector may fail to provide an early warning of high concentrations within an enclosure. In non-standard conditions, accumulation of heavy biogas at floor level can occur. In this case the arrangement of detectors as recommended in BS ISO 24252:2021 would only provide an early warning if the biogas happened to contain sufficiently high concentrations of hydrogen sulphide. Even if an alarm was given, the fact hydrogen sulphide is being detected would only indicate a toxic risk, and not the flammable risk that also accompanies dense biogas. This may prompt the wrong kind of emergency response.

The risk of development of flammable atmospheres in tanks can be controlled by forced ventilation; the fact that biogas can be heavier than air must be recognised when considering ventilation strategies. If ventilation is provided by extraction with an inlet vent on the roof, scouring of flammable gases from the lower part of the tank occurs by entrainment into the downward jet of fresh air. The following factors will improve the efficiency of scouring:

i. A single inlet vent (rather than several distributed over the tank top),

ii. Vents in horizontal or near horizontal surfaces (i.e. in the roof rather than at the top of the walls),

iii. Round or square vents (rather than slots with an equivalent area),

iv. Smaller vents with higher speed inflow.

Maintaining safe conditions does not require particularly high airflows, it would not be surprising for the calculations in a typical situation to show that ventilation rates on the order of 1 air change per hour are adequate to control risk.

Poor quality or missing risk assessments/method statements

Many sites did not have written procedures for potentially hazardous operations such as de-gritting, start-up and emptying of the digester, which are an expected but infrequent part of plant operations. Instead, there was a reliance on the knowledge and experience of operatives who were involved in the work on each occasion. The fact that an operation has been undertaken without incident in such a manner does not mean that it is an appropriate system. The process conditions leading up to work are often variable, as are experience and level of engagement of operatives. Thus, safe systems for maintenance work should be documented as standard operating procedures and employees should receive appropriate training before they do any such work. Documentation for this kind of activity should include:

i. A risk assessment specific to the maintenance tasks being undertaken. For example, what hazards are there when opening the digester hatch to replace the agitator and can additional temporary risk control measures be put in place during that activity.

ii. Written work instructions (and a permit to work if carrying out hot works) that considers the specific hazards of that part of the plant, such as pressurised pipes, location of potentially explosive atmospheres, checklist to confirm that additional risk control measures have been put in place (active ventilation, clearance measurement with gas detector).

Some specific guidance documents are discussed in "Part 3: Standards and Guidance" section below, that may provide useful templates for operators wishing to create these safety documents. An example of one such template, namely a flow diagram for assessing the hazards for a maintenance activity is shown in Figure 4.

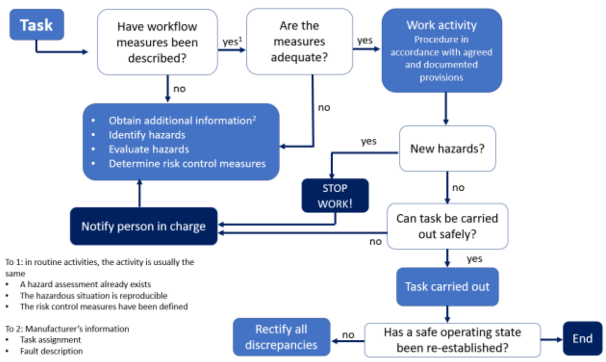

Figure 4: Example of thought process that could be applied when assessing hazards for a maintenance activity, based on templates from German guidance (German Biogas Association, 2016)

Foaming/crusting

Generation of excessive amounts of foam or an impermeable crust on the surface of liquid waste can lead to loss of containment or blockage of vents, gas off-takes or relief valves. The consequences could include:

i. Over-pressurisation and potentially a failure of the tank if gas escape is prevented.

ii. Scalding risk if foaming occurs in a pasteuriser (a situation that had occurred at one of the sites visited).

iii. Escape of materials associated with environmental or health risks.

iv. The potential for unplanned and/or high-risk intervention. A fatal H_2S poisoning incident occurred at a farm AD plant when operatives opened a digester to break up a crust on the waste surface.

Thus, continual monitoring, including visual observation, should be made of digester contents, in particular if a change of feedstock or feeding rate has occurred and preventative action should be taken that avoids the need for direct intervention e.g. maceration of feedstock prior to inputting into the digester, use of anti-foaming agents.

Part 3: Standards and guidance

Summary of standards and guidance documents

It was noted that many countries, including the UK, do not have biogas specific laws, regulations, or competencies. Rather the regulation of biogas plants tends to be covered by multiple existing areas of law such as agriculture, waste management, construction, health, and safety at work. The mechanism for construction and bringing biogas plants into operation is then managed (for the most part) via environmental permitting licences. As part of the standard permit regime in England, the Environmental Agency has produced a series of statutory guidance documents. These are prefixed "SR," and give criteria which the AD installation must adhere to for the particular AD activity covered by that SR. These SR guidance documents are prescriptive only in terms of environmental aspects and minimisation of pollution/impact on sensitive receptors. This is perhaps not unexpected at this early stage of the AD application process. It is stated in the SR documents that appropriate safety documentation should be present, e.g. risk assessment or DSEAR, but there is no guidance for the applicant, to assist with the preparation of this documentation. It is expected that an element of this responsibility for safety documentation will lie with the plant installer/designer and be shared with the operator as part of the handover and acceptance procedures. However it is not known if this is the case in practice.

Germany, the country with the largest proportion of biogas plants in Europe, has a more comprehensive inspection and approval process than most. In this case, adherence to the areas of law mentioned above i.e., agriculture, waste management etc. are specifically examined as part of the licensing approval for biogas plants. Thus, it was thought that it would be useful to collate learning from both national and international guidance documents, in particular if there are countries with more detailed practical guidance for risk assessing an AD site. Table 2 lists some national and international guideline documents relating to AD, and summarises the scope of the document. These guidance documents may provide useful reference material for the reader wishing to know more about how to protect and mitigate against the various hazards on an AD site. Note: some of the titles have been translated into English and so the reader may need to search for the document in the native language of that country. Three guidance documents, thought to be the most prescriptive in relation to fire and explosion risk are discussed in more detail below Table 2.

Table 2: Summary of some standards and guideline documents from national and international sources, providing an overview of the scope of the document.

Title	Scope
The practical guide to AD (UK) - Anaerobic digestion and bioresources association (ADBA, 2017)	Reflects current industry practice and changes to regulations and government policy and schemes – developed by AD industry.
BS ISO 24252:2022 Biogas systems — Non-household and non-gasification (ISO, 2022)	Outlines systems for biogas production by anaerobic digestion, conditioning, upgrading and utilisation from a safety, environmental, performance and functionality perspective, during all phases from design to operation.
ISO/DIS 19388:2021 Sludge recovery, recycling, treatment, and disposal — Guidelines for the operation of anaerobic digestion facilities (ISO/DIS, 2021)	To standardise good practices of operation of sludge anaerobic in order to support safe and sufficient operation of anaerobic digestion facilities, to produce sufficient energy recovery thanks to a sufficient biogas production in proportion to volatiles solids ratio and to control by-products qualities.
Technical basis for the assessment of biogas plants (Austria) (Federal Ministry of Education, Science and Research, 2017)	Provides a summary of the information required to assess biogas plants; the basic fundamental knowledge, overview of the occurring dangers, emissions and shows some possible remedial actions.

Title	Scope
Safety Rules for Biogas Systems, Technical Information (German Agricultural Occupational Health and Safety Agency, 2008)	Explains and substantiates the requirements for the construction and operation of biogas systems. Summarises the most important German regulations; also provides information about rules to be followed in terms of the operation.
Guidelines for the safe use of biogas technology (German biogas association, 2016)	Provides a comprehensive description of the issue of safety in biogas plants and points to various forms of practical assistance.
Safety rules for agricultural methanisation facilities (Ministry of Agriculture and Fisheries France, 2009)	Sets the minimum safety requirements to be adopted during the design, construction, and operation of an agricultural methanisation facility.
Guidelines for anaerobic digestion in Ireland (Composting and Anaerobic Digestion Association of Ireland (CRE), 2018)	Gives an overview of key regulations effecting the commissioning of an anaerobic digestion (AD) plant.
Common safety practices for on-farm Anaerobic Digestion Systems, (US Environmental Protection Agency, 2011)	Identifies the major hazards associated with an AD/biogas system and outlines basic practices to maintain a safe and successful working environment.
Guidance document on Anaerobic digester foaming prevention and control methods (Water Environment Research Foundation, 2014)	Provides a guidance manual for AD foam management. Identify steps to manage or mitigate AD foam incidents in full scale water resource recovery facilities (WRRF) (2014)

Guidance related to explosion safety specifically.

Information has been extracted from three of the guidance documents listed in Table 2, namely from the French, Austrian and German documents, where quantitative information related to explosion hazard and zoning has been given. Risk assessing an AD site in terms of explosion hazard is not a straightforward process as the concentration of flammable gases is variable depending on the current stage of the AD process. Risk assessments must consider anticipated gas concentrations during normal operation but also deviation from normal expected concentrations due to variation in biological activity.

It is also possible to have an explosive atmosphere in an area where it is not typically expected. For example, a digester tank would be classified as a Zone 1 during normal operation as it is expected that there is a methane concentration there continuously. However, if a maintenance activity is to be carried out on that tank, the gas composition within the tank may be deliberately altered to create a breathable atmosphere that will allow a person to enter the tank. Thus, a DSEAR risk assessment should also consider this kind of activity for this tank and zone appropriately for this change of activity, namely a procedure for safely purging the tank should be available, with appropriate risk control measures during this activity. Examples of zoned areas as listed in the German, Austrian, and French guidance documents have been summarised in

Table 3 to provide the reader with an appreciation of areas in which an explosive atmosphere may be expected.

Table 3: HAC zone areas and extents as suggested in Austrian (Aus), French (Fr) and German (Ger) AD Guidance documents.

Location	**Zone**	**Possible failure**
Front pits, reception area, pumping shaft for digested sludge		
Enclosed space/shaft **Open shaft**	Zone 1, if natural ventilation, Zone 2, 1 m radius around edges, if air changes of at least 0.5 per hour (Aus) Zone 2 (Aus)	Introduction of air with sludge movement
System parts, equipment parts, sight-glasses, connections		
Pipework, gas tanks	Zone 1, 1 m radius at outlet, Zone 2, 3 m radius from openings (Ger)	Seals not tight enough, air ingress due to degraded parts
Digester and gas storage tank (above digester area)		
Indoor (in gas space)	Zone 2 (Fr), Zone 1 (Aus)	Introduction of air e.g., due to vacuum production

Desulfurisation (air injection) **Outdoor**	Zone 0, 3 m radius (Aus) Exterior (if flexible membrane) Zone 2, 3 m radius, 2 m downwards at 45° radius (Fr and Ger), Zone 1, 1 m from membrane, Zone 2, 3 m (Aus) Exterior (if hardcover case) Zone 2, 3 m radius around the openings (agitator passage, porthole, manhole etc.) (Fr) Zone 1 for 1 m radius from opening, then zone 2 for 3 m radius from openings (Aus) Double membrane (support air). No zone between outer membrane and intermediate space is ventilated and monitored (Ger)	Leak to outside
Discharge lines (ventilation openings, pressure valves)	Zone 1, 1 m radius, Zone 2, 3 m radius (Aus) Zone1, 1 m radius, Zone 2, 3 m radius (Ger)	Release of gas as part or pressure relief
Fermentation residue storage i.e. digestate		
	As for digester (Aus)	
Condensate separator		
Inside of shaft **Mouth of vent line**	Zone 1, natural ventilation, Zone 2 if mechanically ventilated (Aus), Zone 1 (Ger) Zone 2, 1 m (Aus and Ger)	Air drawn in during separation process
Combustion unit		
Interior of room	Not classified, as ventilation and monitoring expected (Fr)	
Technically sealed components		
	No releases expected	

As seen in

Table 3, the guidance for zoning is similar across the three regions. The Austrian guidance appears to take the most conservative approach, for example, suggesting a Zone 1 areas around pipework connections and access openings in tanks (as opposed to the German guidance suggesting a Zone 2). The German and Austrian guidance documents both account for mechanical vs. natural ventilation, with higher hazardous zone classifications assigned where regular air changes cannot be guaranteed (effectiveness of ventilation is confirmed through measured ventilation flow rate and gas concentration monitoring). The French guidance suggests that forced ventilation should be applied in the combustion unit area, with methane detection also present, whereas natural ventilation is adequate in pre-mixing pits and technical rooms.

From a UK regulation point of view, DSEAR risk assessment documentation should refer to the ventilation considerations. In most cases, and typical in the UK, relief vents and air injection points tend to be classified with a 1 m radius zone 1, surrounded by a wider Zone 2 of 3 m radius as suggested in

Table 3. Some areas can be classified as a Zone 2 of negligible extent (NE) if ventilation has been shown to remove the potential flammable atmosphere. Where the zoning (including zone 2 NE) depends on mechanical ventilation, it is expected that the site will have an alternative mitigation/emergency strategy should the ventilation fail. This strategy should also be captured as part of the DSEAR risk assessment. Standard mitigation steps for fire and explosion hazard include use of pressure relief valves (PRVs), gas flaring, and inerting. PRVs prevent gas build-up to dangerous pressures in enclosed areas. Gas flaring involves deliberate burning of the gas at a designated point of egress, which creates an emergency route for gas build-up to be mitigated. Inerting involves displacing the air/oxygen in an enclosed area using a non-reactive (inert) gas such as nitrogen, such that an explosive atmosphere cannot be generated.

Within the Austrian guidance, it is explicitly stated that any container in which biogas is generated, processed, or stored e.g., digester, post-digester, gas storage, fermentation residue store must be equipped with at least one overpressure and one under-pressure safety device. Storage containers may not need under-pressure safety if the manufacturer guarantees this situation cannot occur. There are various types of pressure/vacuum relief valves. PRVs allow a tank to vent during filling, emptying and when thermal effects require. The relief valves can be present as a single unit or in combination with a flame arrester.

These are designed to protect the tank from damage created by over-pressure or excessive vacuum and provide protection from the effects of external sources of heat and ignition. Most AD facilities also contain an emergency flare, which allows burning off any surplus gas. The emergency flare should have a flame arrester in the pipework. Containers and pipelines must achieve technical tightness (i.e. be designed, operated, and maintained so as to prevent leakage). The Austrian guidance refers to specific regulations that must be adhered to in terms of gas tightness. Monitoring of methane gas levels is recommended, especially at locations with the highest probability for leakage to occur, such as the biogas inlet pipe near the CHP engine. With monitors on AD plant, it should be noted that hydrogen sulphide can damage catalytic type sensors (which are often used for CH_4 detection).

The French guidance mentions the importance of considering firefighting water supply for any intervention required due to a fire. Other comments include avoidance of combustible material in premises and as part of constituent materials of digesters, combustion unit etc. Regarding the CHP combustion unit, recommended fire prevention measures include a flame arrester upstream of the generator motor, a manual gas supply shut-off valve outside the building, a process stop device outside the building that allows the motor to be stopped, a biogas supply shut off valve that is triggered by excess gas flow rates, and flexible, anti-vibration connections.

In addition to the strategies mentioned in the French and Austrian guidance, the German guidance provides additional design considerations for minimising potential escape of flammable materials, including the use of a complete single hose system (rather than jointed sections) for gas transfer, routing of the ventilation and relief lines into the gas delivery system, having sluice gates on the drains with mutually locking shutoff valves, and potential for low-pressure operation mode.

These sections are just summaries of some of the safety strategies that are used; the reader may find additional useful information throughout the rest of the documents.

Part 4: Ventilation system design for storage tanks (pre and post digester)

This section has been included so as to provide the user with insight into the principles of scouring and some of the underlying theory that could be used to specify adequate ventilation flow rates to prevent the accumulation of biogas for the specific tanks of interest.

Density of flammable biogas mixtures

During normal anaerobic production of biogas in a digester the CO_2 fraction should be less than about 45% but during process deviations such as emptying of the digester the CO_2 fraction may rise. Biogas with higher levels of CO_2 is also likely in the ullage of input/output buffer, mixing or storage tanks. The flammability limits of different mixtures of carbon dioxide and methane is shown in Figure 5 . The data indicates that CO_2/methane mixtures with up to about 77% CO_2 are potentially flammable. Those with a fraction of CO_2 less than about 70% have a significant flammable range. The presence of CO_2 in mixtures has been shown to cause narrowing of the flammability range due to a variety of mechanisms such as changes in specific heat capacity causing lower flame temperatures or radiative heat loss effects induced by the CO_2 (Kangyeop, 2013, Pizzuti, 2016), however, despite these effects the flammable range of biogas mixture can be significant. The average molecular weight of CO_2/methane mixtures exceeds that of air (29 g mol^{-1}) for concentrations of CO_2 over about 50%. This means that, even in conditions where the biogas temperature is significantly warmer than typical ambient temperatures, there is a wide range of biogas compositions (where CO_2 concentrations are roughly over 50% and under 70%) that are within a flammable range, but heavier than air.

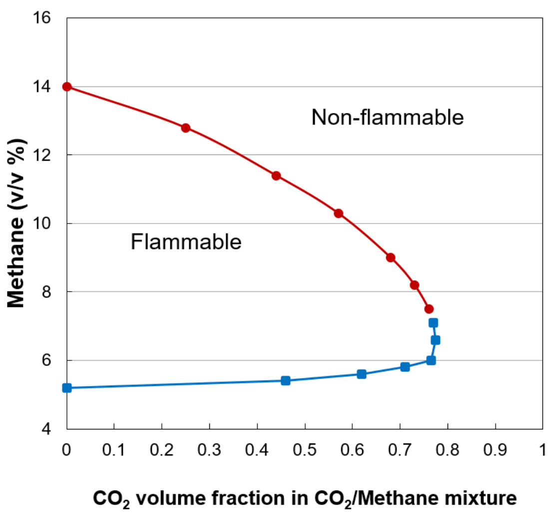

Figure 5: Flammability limits for mixtures of CO_2 and methane. Lower line LFL (blue), Upper line UFL (red). Data taken from Coward and Jones (1952)

Controlling the accumulation of light biogas

If the biogas is lighter than ambient air, the jets of air entering the tank through inlets at the top will progress right down towards the surface of the liquid. The result is good mixing between the inlet air and biogas produced, with a fairly constant gas concentration through the depth of the tank or possibly a slight excess gas concentration in the upper parts of the tank. In well mixed light biogas systems, and where the volume of methane production is relatively small, the concentration (volume fraction) of flammable gas in the ullage can be approximated by dividing the methane production rate by the ventilation rate. When this value is below the Lower Flammable Limit (LFL) volume fraction then the concentration of gas everywhere in the tank will be less than the LFL. A safety margin should be applied by increasing the volume flow of air, for example, increasing by a factor of four would reduce the gas concentration to 25% of the LFL everywhere in the tank.

Note: this does not mean that small vents at the top of a tank and natural (buoyancy or wind driven) ventilation are necessarily suitable for controlling flammable risks in tanks. Wind pressures can be effective at driving gas exchange but are weather dependent. Buoyancy forces depend on the degree of buoyancy and are susceptible to process variations. If the waste can produce gas, a minimum level of forced ventilation will typically still be required. But the level of extraction needed for light biogas is straightforward to determine from the ratio of the gas production rate, the LFL and an appropriate safety margin. Additionally, the gas in the extract is close in composition to that of everywhere else in the tank, so a measurement in the exhaust reveals the extent of toxic or flammable risk throughout the tank.

Controlling the accumulation of heavy biogas

If the biogas is heavier than ambient air, the problem of controlling the flammable atmospheres is more complex. Jets of air entering the tank through the inlets may not progress right down to the surface of the liquid. Whether this happens or not depends on the diameter of the jet, the depth of the tank ullage, the inlet flow speed and the reduced gravity (g’). g’ is a buoyancy parameter that relates the density of biogas to ambient air – it indicates the biogas flow e.g. upwards or downwards. If the speed of the inlet flow is not high enough relative to g’ then the jet of lighter inlet air will only penetrate a certain distance into the tank before turning upwards, as shown in Figure 6. Below this level, the biogas will be undiluted or partially diluted. There will be some local dilution due to entrainment of biogas around the turning zone of the jet however a lower heavy layer will stabilise at a certain depth, namely where biogas production from the liquid surface is balanced by removal in the ventilation flow. In this case, even if the ventilation rate is sized adequately to achieve an average concentration in the vessel that is below LFL, the fact that the ventilation jet does not penetrate to the liquid surface may results in regions where the concentration is above the LFL, and thus pose a risk. Thus, concentrations of toxic and flammable gases in the lower part of the tank may greatly exceed those in the extracted gas stream – which is normally the most convenient place for monitoring. The accumulation of high concentrations of biogas in the tank may pose a risk if, for example, hot work is carried out on the tank or manways are opened at low level.

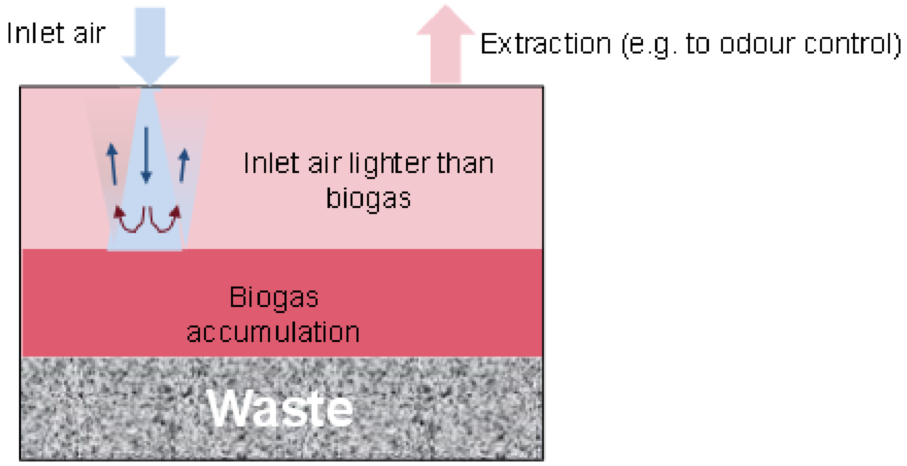

Figure 6: Illustration of top extraction of heavy biogas. Undiluted biogas may accumulate low down in the tank.

Ventilation design – assuming heavy biogas

One approach to designing a ventilation system and an appropriate ventilation rate is to apply fluid mechanics theory which mathematically describes how turbulent jets interact with and entrain fluids within their environment. For example the notable work of List (List, 1982) describes the penetration depth for a light downward jet penetrating a homogeneous heavier layer. Within the derived formula, parameters such as airflow and vent diameter (both of which would be known/specified by the manufacturer of the ventilation system) are used to calculate the expected jet velocity that the setup would provide. The gas concentration in the heavy layer is then calculated by relating the gas production rate (a typically monitored metric in an AD process) to the tank volume. These values are combined with other factors such as the buoyancy effects to derive a penetration depth that would result for a given airflow/jet design penetrating that particular concentration of gas. If the resultant value gives a depth that would exceed the depth of the ullage, then the assumed inflow rate is sufficient to eliminate a heavy layer. If not, then a different airflow value can be used e.g. a larger ventilation system, and the process repeated. By adjusting the airflow value and tank volume, this approach could be applied for various tank sizes.

In psychrophilic conditions lower foreseeable gas production rates lead to somewhat reduced ventilation requirements. Even with sizing for the expected conditions, a check, through gas monitoring, should be made to confirm that the well mixed concentration in the upper layer is in fact outside the flammable region. Ensuring adequate ventilation rates may be challenging for very large diameter tanks.

Conclusions

Incidents relating to fire and explosion tended to occur during times when deviation from normal operation occurred, such as an unnoticed change in the microbial activity, leading to scenarios such as crust formation or excessive foaming. Greater understanding of the process indicators is needed so that deviations from normal operation can be rectified before they become a process safety issue. e.g. awareness of the potential for foaming events or crust formation and how to take appropriate action to mitigate for them.

A good understanding of where and why flammable atmospheres can be generated is required amongst operators, and appropriate engineering and procedural steps should be taken to mitigate these flammable risks. This consideration process should be reflected in a detailed DSEAR assessment and zoning plan, and fire/explosion risks communicated to relevant staff. This may lead to the inclusion of other potentially hazardous areas that often appear to be overlooked in current practice, such as storage tanks. The DSEAR risk assessment should also consider those activities outside normal operation i.e. maintenance activities, foreseeable deviations; this should be accompanied by production of documentation and safe systems of work that mitigate for the (possibly different from normal operation) hazards.

Equipment, including ventilation systems, should be sized and adequate for the particular process for that specific AD site, appreciating the variations in pressure, gas production, gas density as a result of varying microbiological activity. The size of the tank needs to be considered in order to ensure adequate ventilation rates are achieved.

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