

LESSONS FOR SAFE DESIGN AND OPERATION OF ANAEROBIC DIGESTERS

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Anaerobic digestion (AD) has been in use since the 19th Century for disposal of domestic, industrial and municipal waste, in some cases the resulting biogas also being put to use as a fuel. Over the last decade this technology has grown rapidly, in particular seeing widespread application at large farm scale in continental Europe. More recently, growing interest in renewable energy has led to many new plants being built in the UK, the 75,000 t/a facility at Barkip in Ayrshire, capable of exporting around 2 MW of electricity, being one.

As part of the due diligence activity for this plant a study was undertaken to determine the frequency and causes of accidents on AD plants. A large number of incidents were identified, many resulting in serious injury and in some cases fatalities. The majority involved either biogas explosions or H_2S poisonings; neither of these hazards is new to science. The number of incidents appears to result from an industry previously lacking a formal safety culture handling materials for which a more rigorous chemical engineering approach and procedures are required. Lessons learned and put into effect apply to all stages of an industrial scale AD project, from design, documentation and process review through project management to commissioning, operation and maintenance procedures.

ANAEROBIC DIGESTION AS A SUSTAINABLE ENERGY TECHNOLOGY

Anaerobic Digestion (AD) takes place naturally in ruminants, peat bogs and in warm organic matter. In the form of the anaerobic septic tank, AD has been used for many years as a means of reducing organic waste. Small-scale use of AD derived biogas for lighting and pumping has also been practised since the 19th century or earlier. However, there has been a rapid expansion in the last 20 years with AD being applied at farm and then industrial scale with biogas fuelled electricity generated for export. Although AD plants can be fed with dedicated high carbon energy crops, from a sustainability perspective it is most attractive as a means of generating useful electricity from what would otherwise be waste materials. These may include farm manure and crop residues, food factory and catering wastes, abattoir wastes, supermarket out of date foodstuffs, bakery waste, glycerol by-product from biodiesel production, etc. Until recently almost all such wastes arising in the UK were processed as animal feed or put into landfill with consequent methane emissions to atmosphere. By controlling the methanogenesis in an anaerobic digester, a waste disposal and environmental nuisance is transformed into a quasi-renewable energy source achieving a significant reduction of greenhouse gas emissions. If the digestion process and feedstocks conform to relevant quality standards the feedstock waste is transformed into a quality organic fertiliser suitable for organic food production. The digestate quality standard (PAS110) also enables these products to be sold to the general public.

Although the digestion process is ideally operated at near steady-state conditions, on most AD plants a few hours of low pressure gas accumulation is provided for operability reasons. Within the installed capacity of the engines, AD can therefore contribute to load balancing on the grid to an extent matched by few renewables other than hydropower. With further investment and safe management of the additional gas inventory this load balancing capability would further enhance the ultimate value of the biogas.

Plant sizes have steadily increased over the past 40 years, from processing the manure from smallholdings into $10kW_{thermal}$ domestic hot water and heating systems to 20 $MW_{electrical}$ slurry–maize digestion energy parks that have the potential to develop across the great German plains and Russian Steppes to form a major long-term source of fuel gas for Europe.

The AD process converts organic materials into biogas by a series of microbiological stages. The percentage reduction in solids varies greatly depending on feedstock and the process is critically dependent on maintaining a healthy community of the right types of microorganism. Biogas is predominantly methane and carbon dioxide in varying proportions, 3:2 being typical, together with small quantities of other gases including potentially lethal concentrations of H_2S. The latest developments in the industry include cleaning the biogas to pipeline quality and injecting the gas directly into the national grid. Potentially up to approximately 50% of the national grid domestic gas consumption could be met by AD generated biomethane.[2]

THE BARKIP AD PLANT

The UK now has around 70 operating large-scale biogas plants with as many again in planning or under construction. One such recent plant is located at Barkip in Ayrshire which is owned by Scottish and Southern Energy plc and operated by Zebec Biogas Ltd.

Construction of Barkip Anaerobic Digestion plant began in May 2010 and commissioning in August 2011. Barkip was built to process a mixture of locally sourced food and farm wastes and to return materials in a form

Figure 1. AD plant incident[1]

suitable for use as a fertiliser in agriculture. The Anaerobic Digestion plant is a proven design from the main process contractor Xergi A/S. Xergi is an experienced contractor based in Denmark with 20 years experience and has built more than 50 similar plants. Barkip is a wet anaerobic digestion plant treating waste and biomass materials thermophilically (ie at a temperature between 45 and 55°C). The reception facilities are designed to accept multiple feedstocks including food, grass, grains, silage, manure and slurry. These are mixed according to a recipe in order to control various processing parameters, the most important of which being nitrogen and solids contents. The mixture is macerated and pasteurised at 70°C prior to digestion in two parallel digesters. The digestion process occurs in two digester streams sized to provide sufficient residence time to complete the digestion. Each stream comprises two large (3500 m^3) continuously stirred reactor tanks, the first operating at thermophilic temperature and the second mesophilic (37°C). The biogas produced is purified by a biological scrubber using bacteria (thiobacillus and sulfolobus) to remove hydrogen sulphide. The biogas is fired in reciprocating engines to produce approximately 2MW of electrical power and 2.2MW of heat output (in the form of 90°C hot water). Digestate is separated into solid and liquid fractions which are used for agricultural benefit, the liquid fraction being concentrated by evaporation using the heat output from the engines. This both increases nutrient concentrations and minimises transportation and storage volumes.

Figure 2. Barkip AD plant primary and secondary digesters

FREQUENCY AND CAUSES OF ACCIDENTS ON AD PLANTS

As part of the technical due diligence activity, a review was carried out to identify the frequency and causes of accidents on AD plants. Much of the best information from eyewitness accounts and official reports of investigations tends to be withheld following incidents in order not to compromise the legal process. This may take several years to complete which is especially unfortunate at a time when the industry is growing rapidly and engineers need to know what is going wrong in order to design out problems before they recur. Such information that is available is generally second-hand and has to be culled from newspaper and journal reports. The review therefore involved a search based on words related to AD accidents (e.g. biogas, accident, incident, explosion, fire, death, anaerobic digester). These were translated into the most relevant European languages (Danish, French, German, Spanish and Swedish) and used as internet search engine terms. This brought to light newspaper reports of AD plant accidents which were translated and analysed for clues as to their type, frequency and, most importantly, cause. The report highlights 13 deaths world-wide from 2003 to 2010:

- India, one explosion 4 deaths
- Germany, gas incident 4 deaths
- Philippines, gas incident 4 deaths
- UK, gas incident 1 death
- 11 Serious Injuries (including serious burns from explosions and near fatal gas-related injuries)
- 13 other noted Injuries (including 11 firemen – mainly gas related)

The population of digesters these accidents relate to was estimated as close to 10,000 in Europe and many more world-wide. Although the method of study limits it at best to a review of the perception of local reporters, none the less its findings gave the best indication to date of the type of actions required to make the AD industry safe.

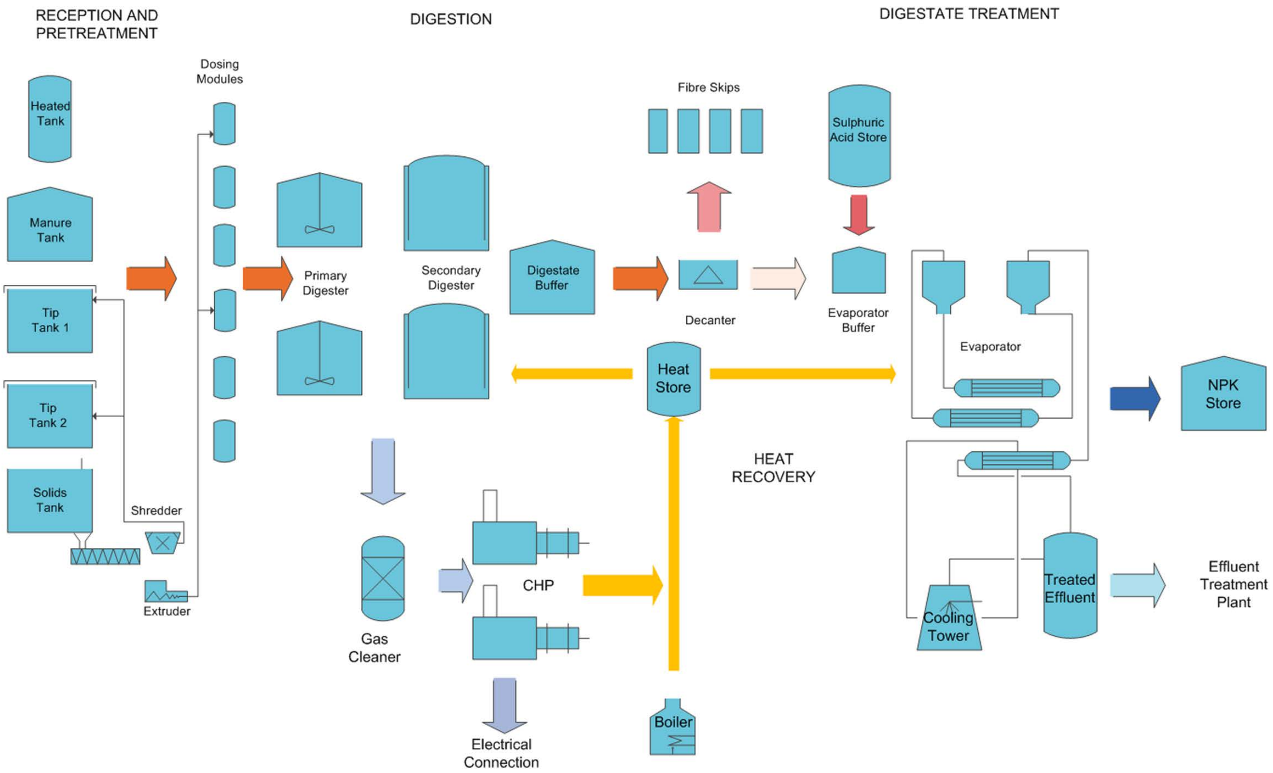

Figure 3. Block diagram Barkip AD plant

EXPLOSIONS, FIRES, CONFINED SPACES AND GASSING

The report identified 36 AD plant biogas explosions or serious fires since 2003 and suggests the true number may have been larger in the earlier years when reporting by local newspapers was less comprehensive than it is currently. In addition there were 39 pollution incidents through valve or tank failures, some of which involved large quantities of slurry. The greatest number of fatalities and serious injuries, including those to fire-fighters, were the result of H_2S poisoning; there were also some very serious explosion injuries including life-threatening burns and permanent deafening. Many of the newspaper reports show shocking photographs of devastated sites. Although, put into context, the total number of serious incidents represents about half of one per cent of plants, every one of these could have been avoided if best practice procedures as adopted by the UK chemical industry had been implemented. Whereas the scale of hazards in the AD industry is lower than for example in petrochemicals, AD plants do make and store toxic and flammable gas.

Explosions. Some digesters underwent deafeningly violent explosions, indicating that a mixture close to stoichiometric fuel air mixture was ignited. The flammability diagram indicates that dangerous conditions occur when a large amount of air is mixed with 5%-15% methane.

This risk can be minimised by general good practice. This includes integrity of design and construction, HAZOP review, DSEAR/ATEX procedures, gas meters and alarms, removal of ignition sources, permits to work backed up by risk assessment (RAMS) procedures and, in particular, appropriate purging and isolation procedures.

First commissioning. At least five plants are reported to have exploded when they were being commissioned for

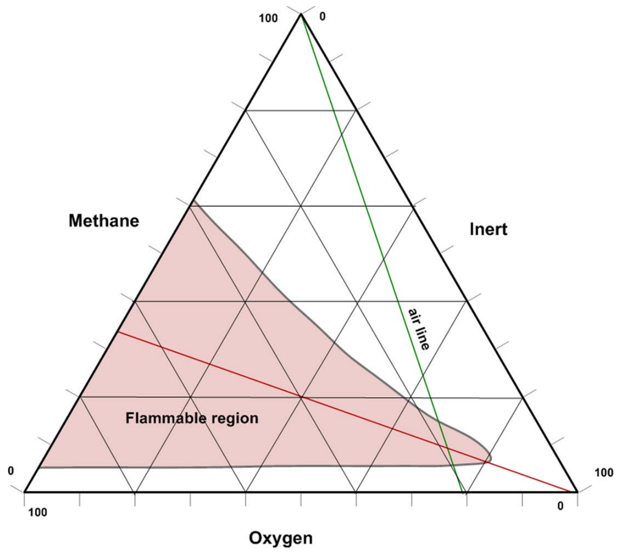

Figure 4. Methane/oxygen/inert flammability diagram[3]

the first time. There are industry standards for commissioning process plant which clearly had not been followed. These include pressure testing, inert gas purging and hot work permits; in particular welding prior to an explosion was implicated in a number of cases.

Materials certificates. One plant was reported as being built with sub-standard tank bolts that failed during commissioning, resulting in a large land pollution incident. Materials and building control failures need not occur; good project management should ensure that the appropriate procedures to avoid them are adhered to.

First maintenance of the digester tanks (after containing gas) is a common time for explosions and toxic gas incidents. Welding and entry into the confined space of a biogas tank both resulted in incidents. Repairing of rotating equipment fouled by the digester contents was also implicated. Confined space training and industry-standard procedures as for first commissioning still apply.

H_2S. An incident in 2005 involved a reception tank with its safety features manually disabled. This allowed H_2S to escape from the mixing organic wastes so rapidly that four men were killed instantly. Blending organic wastes from different sources that react to produce H_2S on contact is inherently dangerous. Functional design safety features and operator training are crucial for safe operation and further protection against gas poisoning can be provided by fixed gas alarms and personal gas alarms.

None of these techniques are new to science nor to the chemical engineering industry, but in many cases they clearly haven't been absorbed into the culture of AD. Nor is the problem limited to the developing world, many serious incidents having taken place in Europe. Non-functional or disabled safety equipment combined with poor understanding of the hazards presented by H_2S was another major issue.

EXPERIENCE FROM THE BARKIP PROJECT

The Anaerobic Digestion plant project implementation at Barkip from concept through construction to commissioning took place over a short timescale (April 2009 to August 2011). In common with many projects this led to a restricted timetable in which to complete the many important tasks required to ensure that all safety issues had been properly considered and addressed.

One consequence of the compressed timescale was that some of the design documentation was not available before construction began. This meant that the formal design and safety review process was conducted in parallel with construction rather than beforehand, by which time there was less opportunity for designs to be altered.

This timescale meant the importance of due diligence in the development phase of the project and in assessing experience of the contractor were paramount in ensuring that subsequent alterations to the design were minimised.

Scottish and Southern Energy have an embedded "safety first" culture which is encapsulated in a "stage and gate" process termed Process Safety Review. This is to ensure that design and operational methods are safe and compliant with applicable regulations as the project progresses to completion. This process has been designed for large capital projects which are the bread and butter of large multi-utility energy suppliers such as SSE. The rigour imposed by such a system was of considerable benefit at Barkip in ensuring that important safety controls were in place in time with the build of the plant.

From the outset of the project ZEBEC recognised that the hazards associated with AD needed to be properly managed. As soon as sufficient details of the plant were available, a DSEAR review was carried out and ATEX zones defined in the areas where escape of biogas was possible. Despite the successful track-record of the main AD contractor, it was agreed that a systematic process safety and operability design review was also necessary. It was apparent that a fully rigorous HAZOP review of the whole plant would have been economically unrealistic and unnecessarily detailed in the context of many of the plant operations. On the other hand there were a number of interfaces between areas designed and/or supplied by different parties which clearly merited scrutiny.

The review team decided that the best methodology was a property-word/guide-word prompted approach along the general lines of HAZOP. But it was agreed that a smaller review team than normal for a formal HAZOP and the grouping of more items together into each review node would be appropriate.

KEY FINDINGS FROM THE PROCESS DESIGN REVIEW

In practice the time commitment entailed by the review methodology proved to be fully justified. It identified a large number of operability issues which would otherwise have caused problems during commissioning and also eliminated a smaller but still significant number of potentially serious safety problems. As expected, many but by no means all of the issues identified related to interfaces between areas engineered or supplied by different sub-contractors.

Key findings from the design review process are listed below; most of them are applicable to many other AD plants. Whereas these findings generally reflect lessons learned from the due diligence study, the structured review methodology enabled the team to focus on the specifics of this plant:

- Ensuring ventilation systems are fit for purpose; especially at offloading tanks where large volumes of materials are deposited, toxic gases may be generated by mixing different materials and subsequently displaced. It is important to ensure that gases cannot be released and operators exposed to them during offloading of materials. Face velocities at tip tank opening were designed at >0.5m/s to reduce exposure risk.
- Understanding where hydrogen sulphide can be produced and where it can accumulate.

- Where pasteurising tanks are not completely sealed, pressure should be monitored and feeding valves interlocked to prevent them opening if the ventilation system fails or underperforms.
- Ensuring that detection systems are positioned in risk areas and operators are trained to evacuate the area immediately on sounding of alarms.
- Identification and zoning of ATEX areas should include taking account of potential gas accumulation in semi-confined spaces such as bunds and reception halls. It is important to appreciate that in some circumstances its CO_2 content results in biogas being denser than air.
- Ensuring that the process control systems in the biogas gas handling part of the plant are fit for purpose. In some cases additional operating procedures and other safeguards may need to be provided to reduce the risk of explosion and gas poisoning incidents to tolerable levels
- Ensuring safe vehicle movements are factored into building design and in training of operators and delivery drivers. HSE Guidance on Waste Processing Facilities is an invaluable guide.
- Recognising and managing the risks of legionella in process water and cooling systems.

BARRIERS TO PROCESS SAFETY AND OPTIMISATION

A number of issues were encountered which made the design review more difficult than it should have been. Many of these appear to be the consequence of a difference in culture between the AD industry in Europe and what is required to design, build and operate a process plant to UK safety standards. The vast majority of AD plants do perform satisfactorily. But the customer is often expected to take this on trust and it can be hard to obtain detailed documentation supporting safety-critical aspects of the process and control system. It is worth drawing attention to some of the key issues:

Flowsheets and P&I diagrams. The process and instrumentation diagram (P&ID) is arguably the single most important single document defining a continuous process and a certain minimum level of information is necessary for it to form an adequate basis for process review. At present there is a lot of variation between what different companies see fit to include in the drawings which they describe as P&IDs. The AD industry should adopt a clear definition of the information required. Examples of data which are necessary but hitherto often omitted or provided inconsistently include, inter alia:

- All process lines and connections to vessels, etc, to be shown.
- Line numbers and/or line codes to be shown in conjunction with a line schedule, so the size, material specification and other relevant data can readily be ascertained for every line.
- All process connections and instrumentation connected to process lines, vessels and other equipment to be shown.
- To the extent practicable, all process vessels to be shown on the P&ID in a manner which represents the physical configuration/layout of the vessel and associated pipework.
- All nozzles to be shown on tank and other process vessel drawings such that they can readily be reconciled with connections shown on the P&ID and their relevant positions be clearly understood.
- Interfaces to be shown explicitly and consistently between one P&ID and any other to/from which it connects. This should include unambiguous referencing of lines between each sheet and the next.
- Details of subcontracted items/design packages to be shown in a consistent and joined-up manner.

Process control. In the majority of cases the review team eventually established that the process control systems proposed were competent to perform the functions for which they were intended. But this was often difficult to confirm from the documentation provided. Thus it was difficult either to sign systems off as satisfactory or to be certain that they needed to be improved. Again, although some instances occurred elswehere, such issues were prevalent where controls interfaced between plant designed and/or supplied by different companies. Some of the worst cases were when the operation 'the other side' of the interface was new or unusual to the AD industry. An example in the case of Barkip was control of the hot water from the biogas engines which is used as a heat source for digestate evaporation.

As an aside, the presence of an evaporator plant changes a scenario of freely available waste heat for digester heating to one where every kW of thermal energy used elsewhere represents an opportunity cost in lost evaporation. As a result, optimising thermal integration, previously largely irrelevant, becomes economically significant.

Most of the process control issues identified related to process operability rather than safety, but a small number of them, in particular those regarding integration of the gas cleaner unit, have significant safety implications. As with P&IDs, the AD industry should determine suitable standards of documentation to ensure that control systems are fully defined and their function properly explained, for example:

- Clear written description of the purpose and function of all control systems.
- Control across interfaces between suppliers to be described in a fully 'joined up' manner.
- Documentation to be provided to the same standard for control across interfaces, with subcontracted packages as for items provided directly by a single supplier.
- Control philosophy to be fully described before commissioning.
- A consistent approach to back-up control systems with quantitative justification provided when safety or operationally critical operations depend on the integrity of a single system (irrespective of whether or not SIL rated).

- Clear explanation of the consequence of utility failures on control systems, including explicit description of behaviour of automatic valves on power or air failure.

Industry accident and safety database. As mentioned above, understanding of past incidents is important to minimising the probability of recurrences, but very little information is available regarding safety incidents in the AD industry. The industry should work together to develop a database of incidents and work towards publishing key findings as soon as possible after an incident has been identified. In view of legal issues this may be difficult to achieve in practice, but the benefits in terms of avoided deaths, injuries, economic loss and damage to the industry's reputation are irrefutable.

Quantitative assessment. The majority of hazards and operability issues identified can effectively be resolved by means of robust and comprehensive procedures, and in some cases small design changes. On the other hand, a small proportion of potentially serious problems, relating in particular to biogas generation and handling, rely more explicitly on safety instrumentation. For these, a layers-of-protection (LOPA) approach was applied to ensure an acceptably low residual level of risk. Generally, adequate protection could be achieved by relatively straightforward means and without resort to SIL rated equipment. However, in the absence of any meaningful body of data, estimating the frequency of initiating events was very much a matter of judgement. Developing a quantitative database of equipment failure, process upsets etc, would complement an industry accident database; this would help to ensure both that the required levels of safety are achieved and that this outcome is reached in an economical manner.

There's always a first time. The majority of the plant covered by the design review was found to be fit for purpose. But it's worth noting that, in the opinion of the review team, the existing safety case did not always give sufficient attention to pre-empting low probability high consequence hazards which were not known already to have resulted in an incident. The industry needs to guard against assuming that something which has not resulted in an incident in a few hundred operating years is necessarily so improbable that it can be disregarded.

In this context, the industry should continue to strive for intrinsically safer designs and operating practices, rather than complacently copying or, at best, adding bolt-on safety features to what has gone before.

SUMMARY OF LESSONS AND RECOMMENDATIONS

AD is becoming an established feature of the energy landscape, with a growing part to play both in sustainable energy generation and waste disposal. It shares some of the hazards of the chemical/petrochemical industry but with fewer dangerous materials and less extreme worst case scenarios. Nevertheless, unnecessary serious accidents will continue to occur unless the AD industry universally adopts an approach to safety closer to that applied in the chemical industry.

There are historical parallels between AD and the pulping industry as it was 20-30 years ago. Similar lessons being learned today are almost certainly also relevant to other processes being operated in what are not yet generally perceived as chemical engineering industries.

KEY RECOMMENDATIONS TO THE AD INDUSTRY

- Ensure a high level of safety is built into the process design, construction operation and maintenance of AD plants by adopting best practice as applied in mainline chemical engineering industries, including:
  - safety/risk assessment methodology
  - identification and zoning of ATEX areas
  - robust operating and maintenance procedures
  - higher and consistent standards for process documentation
  - continuous endeavour to develop intrinsically safer designs
- Ensure ventilation systems are fit for purpose, especially at offloading tanks.
  - monitor ventilation performance wherever the process is not completely sealed
- Take account of potential for biogas accumulation in bunds and other semi-confined spaces.
  - understand that owing to CO_2 content biogas can sometimes be denser than air
  - understand where H_2S can be produced and where it can accumulate
  - ensure detection systems are positioned in risk areas
  - ensure operators are trained to evacuate the area immediately on sounding of alarms
- Ensure process control systems in biogas gas handling areas are fit for purpose.
  - review need for additional layers of protection to reduce risk of explosion and gas poisoning incidents to tolerable levels
- Ensure that safe vehicle movements are factored into building design and training of operators and delivery drivers.
- Develop and disseminate a qualitative and quantitative AD industry incident database.
- Give more attention to integrating and optimising design and control systems at the interfaces between different parts of the plant and/or different suppliers.
- Manage the risks of legionella in process water and cooling systems.

REFERENCES

1. Photocredit: Thomas Warnack (Thomas.Warnack(at) T-Online.de).
2. National Grid 2009 http://www.nationalgrid.com/NR/rdonlyres/9122AEBA-5E50-43CA-81E5-8FD98C2CA4EC/32182/renewablegasWPfinal1.pdf
3. Redrawn from open source information.