WASTE-TO-ENERGY PLANT PROCESS SAFETY CHALLENGES

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This paper presents an overview of process safety issues relating to waste-to-energy gasification/pyrolysis plants. Well publicised incidents such as Texas City, Buncefield and Deepwater Horizon act as reminders of the importance of a commitment to process safety management. This paper considers the relevance and application of established process safety practices from the process industries to waste-to-energy plants. It is proposed that these energy plants have hazards more akin to the process industries than the traditional energy industry.

Waste-to-energy plants are becoming increasingly complex, employing sophisticated technology; this means that rigorous hazard assessment processes and techniques are required to ensure plant safety. Examples of risk reduction measures and good practice are given.

The paper covers:

- Hazards of the feed material, including self-heating potential and dust hazards (e.g. biomass in the form of wood chips).
- Features relevant to process safety which are common to waste to energy plants which convert carbon-based materials into a product gas.
  - This includes gasification of biomass and municipal solid waste, and also pyrolysis.
  - An overview of the typical main unit operations within these plants is given, with relevance to process safety.
- Critical process safety issues are highlighted, focussing on gasification type waste-to-energy plants
  - There is fire and explosion risk potential, due to the presence of highly flammable gases (hydrogen and carbon monoxide).
  - Toxic gas release has potentially serious consequences due to the presence of large quantities of carbon monoxide.
- Distinctive features of gasification plants and related technical safety challenges in the development of a basis of safety.
  - Emergency venting is discussed, including pressure relief philosophy and explosion venting.
  - Flare system function and features.
  - Start-up and shutdown aspects, including emergency shutdown.

Relevant guidance and standards are considered, and examples of their practical application given. An approach to package system hazards is also discussed. Applying learning from the major hazards industries to waste to energy plants is key to preventing serious incidents within the power generation industries, now and in the future. The skills and experience of today's process safety specialists, including practitioners experienced in protection against risks from fire and explosions, are relevant here. They can play a vital role in the development of safe waste-to-energy technologies and the design of robust, high integrity plants across the world.

INTRODUCTION

The growing recognition of the effect of carbon dioxide emissions on global warming has sparked development of a number of technologies for reducing the impact of energy production. One of the technologies emerging is that of waste being used to generate energy, and specifically the use of gasification to create a syngas for use in generation of electricity and potentially usable heat.

The Energy Industry has a well defined specific set of safety issues relating to combustion, steam pressure, turbines, generators and power distribution, which are well understood and well controlled with techniques and standards in place. However, the introduction of Gasification Waste to Energy introduces a whole new series of safety issues more akin to chemical process plants. The aim of this paper is to show how, by applying the methods established for hazardous process plant design, the safe design of new waste to energy plants can be ensured.

BACKGROUND

THERMAL WASTE TREATMENT METHODS

The main types of thermal waste treatment are pyrolysis, gasification and incineration. Pyrolysis involves the thermal degradation of organic material in the absence of air/oxygen, and production of a flammable "syngas" (synthesis gas). Gasification involves partial oxidation in which solid organic matter is transferred to the gaseous phase to produce a flammable "syngas". Incineration involves full oxidative combustion, and no "syngas" is generated for downstream combustion.

TECHNICAL SAFETY DISCUSSION

HAZARDS OF THE FEED MATERIAL

Feed material to a waste-to-energy plant could include biomass, MSW (municipal solid waste) or RDF (refuse derived fuel). Potential hazards associated with the feed materials themselves include fire, dust explosion and toxic gas formation.

For example, where feed materials such as biomass wood are stored in large piles, there is potential for self-heating. Wood fuel is a source of nutrients for microbial activity, which, in the presence of moisture, over extended time periods in storage can lead to the generation of heat, and in the worst case self-ignition. A problem called dry matter loss can result from heat generation, which in turn is related to moisture content. Safeguards include maintaining dry storage conditions and minimisation of inventory levels to give relatively short storage times. A storage fire risk assessment should consider factors such as size/area of storage, occupancy and escape routes. As well as active fire systems, detection of hot spots and monitoring of carbon monoxide levels may also be employed.

Other feed hazards include hazards associated with dust, such as explosion hazards requiring protection by, for example, hot particle detection and explosion venting. There are also possible health hazards from dusts in the form of micro-biological spores. Potential toxic gas hazards should be considered, such as carbon monoxide formation in relation to self-heating, particularly in confined spaces.

WASTE-TO-ENERGY PLANT FEATURES RELEVANT TO PROCESS SAFETY

This refers to features relevant to process safety which are common to waste to energy plants which convert carbon-based materials into a product gas. This includes gasification of biomass and municipal solid waste, and also pyrolysis (e.g. tyres).

Considering the main types of thermal waste treatment, a comparison of process characteristics relevant to process safety is given in Table 1. The flammable "syngas" (synthetic/synthesis gas) produced during pyrolysis and gasification is made up of (mainly) hydrogen and carbon monoxide.

BREF 0806, "Reference Document on the Best Available Techniques for Waste Incineration", differentiates between the three types of thermal waste treatment in terms of reaction conditions. Typical corresponding reaction temperature and pressure ranges are given in Table 2.

Gasification process temperatures are typically higher than pyrolysis processes, and comparable to conventional incineration – in some cases higher. Whilst pyrolysis and incineration processes typically operate at around atmospheric pressure, gasification process pressure can range from slightly sub-atmospheric to relatively high pressure.

Pyrolysis processes operate in the absence of air/oxygen, and in an inert atmosphere such as nitrogen. In gasification, air/oxygen addition is controlled to give a stoichiometric ratio of less than one in order to achieve partial oxidation. In conventional incineration, an excess of air is used for complete combustion.

A typical gasification waste-to-energy plant process is shown in the flow diagram in Figure 1.

Raw waste requires pre-processing, involving drying and compacting for example, to produce a material in a suitable form for gasification. The resulting fuel is commonly referred to as refuse-derived fuel (RDF) or solid recovered fuel (SRF).

Alternative schemes would involve the use of a gas turbine generator or a gas engine in place of the fired boilers and steam turbine generator.

CHALLENGES IN THE DEVELOPMENT OF A BASIS OF SAFETY

The use of Process Industry safety techniques has identified a number of key issues relating to gasification plant design. It is important that the necessary features have been incorporated into the design at an early stage to ensure that the plant is safe, and meets the standards which are applicable to the hazards present. This will ensure that the facility meets the requirements of ALARP (As Low As Reasonably Practicable) and is able to handle a variable feed stock.

The most critical process safety issues applicable to waste-to-energy plants are explosion hazards, fire hazards and toxic gas – these are discussed below. Start-up and shutdown also require special attention.

Table 1. Comparison of features relevant to process safety

		Thermal waste treatment method		
		Pyrolysis	Gasification	Incineration
Process characteristic	High temperature	Yes	Yes	Yes
	High pressure	No	Yes	No
	Flammable gas generated	Yes	Yes	No
	Flammable mixture potential	Medium	High	Low

Table 2. Summary of reaction conditions

		Thermal waste treatment method		
		Pyrolysis	Gasification	Incineration
Reaction condition	Reaction temperature (°C)	250–700	500–1600	800–1450
	Operating pressure	Atmospheric	Sub-atmospheric to 45 bar	Atmospheric

Explosion Hazards

Overpressure, internal explosion and external explosion are relevant here. Overpressure could arise due to a range of scenarios – "standard" pressure relief scenarios corresponding to typical process plant systems, as covered in e.g. API 521, are likely to apply. The likelihood of either external or internal explosion is dependent on whether the gasifier operates at overpressure or underpressure respectively.

At underpressure there is a risk of air ingress and an explosion may occur inside a particular plant section. As there are likely to be sources of ignition within equipment, for example the gasifier, a key explosion prevention measure is avoidance of an explosive atmosphere. In order for an explosion to occur, oxygen is required in addition to the syngas level being in the flammable range. A gasifier plant routinely passes through the flammable range, hence the need for purging to remove oxygen. For hydrogen and carbon monoxide at room temperature and atmospheric pressure pressure, the limiting oxygen concentration is about 4%. A dangerous situation may occur during plant start-up, at shutdown or in the case of uncontrolled air intake, for instance due to leakages.

Gas tightness is an important prevention measure, to avoid air intake, which may lead to the formation of an explosive mixture inside equipment. Appropriate protection measures are design for containment and explosion venting. A single vessel operating at atmospheric pressure would need to be able to withstand an explosion/deflagration pressure of at least 7 bar (i.e. the maximum for hydrogen).

In plant sections where a positive pressure exists (e.g. after a blower), there is a risk of gas escape to the atmosphere, which may lead to an external explosion. Gas tightness is therefore important to avoid gas escape, as well as hazardous area zoning to avoid external ignition sources.

To achieve gas tightness, the use of welded connections is preferred (minimum flanges), in particular for hot pipes. An important area for attention is solids addition/removal which needs to be carried out whilst maintaining a seal.

Fire Hazards

Potential fire hazards arise due to the formation of flammable mixtures inside and outside equipment.

The nature of the gasification process means that ignition sources, and controlled, localised "combustion zones" are typically present within the equipment (e.g. gasifier). At underpressure there is a risk of air ingress and a fire may occur inside a particular plant section.

In plant sections where pressure build up exists, there is a risk of gas escape to atmosphere, which may lead to an external fire. Syngas from gasification can auto-ignite at temperatures above about 600–650°C.

Toxic Gas

The gasification process produces a highly flammable cocktail of gaseous components, including hydrogen, and which also contains a very toxic gas, carbon monoxide.

In plant sections where pressure build up exists, there is a risk of gas escape to atmosphere, which may lead to a toxic atmosphere. Gas tightness is therefore important to ensure containment and avoid release of toxic gas.

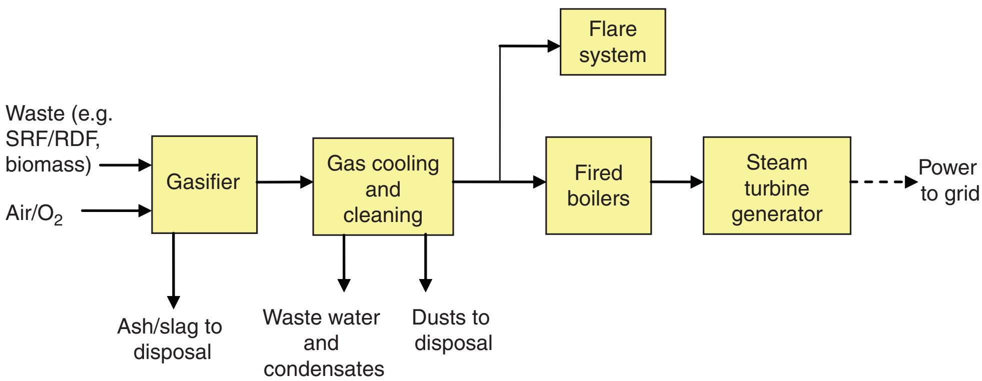

Figure 1. Gasification plant process flow diagram

The areas outside the equipment must be adequately ventilated to prevent build up of an explosive atmosphere, but also to ensure that there is no toxic atmosphere build up to cause carbon monoxide poisoning of employees. Carbon monoxide detection equipment should be provided to detect possible leaks.

Although the main risk is due to toxic gas, toxic liquids and solids are also relevant.

FEATURES OF GASIFICATION PLANTS AND RELATED TECHNICAL SAFETY CHALLENGES

Gasification is a partial oxidation process in which a carbon source such as coal or biomass is broken down into carbon monoxide and hydrogen, plus carbon dioxide and possibly hydrocarbons. A gasification waste-to-energy plant can therefore be viewed as a form of waste processing plant with petrochemical plant features, a relevant comparison being with ammonia production. A gasification plant can be considered to be analogous to an ammonia plant with steam and oxygen-fired reforming sections, both involving the generation of highly flammable mixtures of hydrogen and carbon monoxide, and the controlled addition of oxygen/air, at high temperatures. Ammonia plants employing gasification of coal are an alternative to ammonia plants fed by natural gas. In fact, gasification of biomass technology has been developed for deployment in an ammonia plant. Learning from the petrochemical industry is therefore relevant, for example with regard to equipment design and integrity for a high temperature duty and handling of a highly flammable synthesis gas ("syngas"). As shown in Table 2, gasification process pressure can vary, and may be high, as in an ammonia plant, or possibly marginally below atmospheric pressure, which presents its own challenges.

In addition to the "critical" process safety issues discussed earlier, key technical safety challenges include emergency venting/flaring and start-up and shutdown. These are discussed below.

Flare System Function and Features

The combination of boiler gas feed and upstream syngas generation leads to control issues in balancing syngas usage versus the generation rate and also syngas quality. In the case of an unplanned boiler shutdown (e.g. boiler "lock-out"), an alternative venting route is required, due to the time lag between shutting off Gasifier feeds and the generation of syngas stopping. To allow safe venting of the syngas generated in these circumstances a flare system, or equivalent, is required. Routing the vent by-pass to a flare system provides a means of avoiding pressure build-up in the upstream gasification section, whilst ensuring that the flammable gas is burned to minimise any environmental impact.

As well as handling/venting gas when the boilers are shut down, the flare system forms the final section of the pressure relief system in the event of a plant emergency shutdown (ESD). The flare system should incorporate a water seal vessel, automatic ignition system and flame monitoring with alarm.

Start-up and Shutdown Aspects

At start-up following an extended shutdown, oxygen needs to be removed from the plant by purging (e.g. by nitrogen). Following shutdown, the gasification section of the plant will typically be above the auto-ignition temperature. Unless a "hot restart" can be carried out in a short period of time, purging will be required to ensure the plant is held in a safe shutdown state.

During start-up and shutdown of the gasification reactor, syngas quality may not be adequate for combustion in the downstream boiler (alternatively, gas turbine or gas engine), in which case flaring will be required. Typical automated plant emergency shutdown (ESD) measures, for example in the event of high pressure or temperature in the gasification section, would be shutdown of the gasifier itself, including stopping waste feed and shutting off the air supply.

PACKAGE SYSTEM HAZARDS

The "core" process section of a gasification plant – including the gasification reactor itself, gas cooling and cleaning – is likely to be fairly unique, or at least variable, for different applications (projects and plants). This means that relatively detailed hazard studies will be required, particularly for larger, complex plants. When organising and carrying out hazard studies for the rest of the plant, there may be benefits in considering specific plant sections and packages separately (e.g. "standard package" HAZOP). For example, this could apply to steam/gas turbines, fired boilers/HP steam systems and storage systems.

Regardless of the approach adopted in carrying out hazard studies, it is important to address interactions between systems, for example syngas rate and composition (i.e. gasification reactor output) and control of boilers, gas turbines and gas engines.

CHALLENGES FOR THE ENERGY INDUSTRY

There is currently a strong emphasis on reducing the carbon footprint and one of the technologies being introduced is the use of gasification waste to energy plants. The energy industry has many years of experience of combustion, but has limited experience of the hazards of producing synthesis gas. These hazards are well understood in the chemical process industries, where safety techniques have evolved to ensure safe design of plants. Utilising this experience will help to ensure that the emerging waste to energy industry is not devastated by the type of major incident that has happened many times in the chemical industry.

The use of gasification in waste to energy production can be perceived as simple, and little different from combustion processes. However, in the gasification process, oxygen, often in the form of air, is deliberately introduced into equipment which contains a flammable gas. Any leak can either admit air to the flammable gas, or allow flammable/toxic gas to escape. These hazards are much less significant in conventional combustion plants where fuel is completely burnt in a clearly defined manner to produce a non flammable exhaust stream. There is no inherent reason why the skilled, competent engineers employed in the power sector cannot take on board these issues and develop a safe technology, but this journey can, and should, be made easier by sharing the experience of the chemical process sector.

There is now an opportunity to incorporate the skills applied in the process industry to ensure, as far as possible, that the emerging waste to energy industry evolves safely. Cross industry co-operation will result in a quicker, safer implementation of the new technology, greatly reducing the risk of a catastrophic incident, and subsequent devastating impact on those directly affected, but which could also have a disastrous effect on a whole emerging industry sector.

The application of technical know-how and sound engineering judgment based on experience is required in order to produce practical solutions to design and technical safety problems in these plants. For example, the emergency venting and purging philosophy has to address a number of challenges. We believe that the successful resolution of these types of technical problem is key to the safe operation of this type of plant, aiding achievement of world class environmental performance and will ultimately be key contributors to the commercial success of these plants.

Using the techniques of HAZOP, LOPA and SIL at an early stage in the design process, will ensure that the plant has been designed to operate in a safe manner and avoid a major incident. As an example, fault tree analysis may be considered appropriate, for example in the case of a large-scale, complex gasifier system. This would need to be preceded by a hazard identification (HAZID) study, or equivalent, by a project technical team.

The additional cost of these techniques both in the engineering and the provision of additional controls are insignificant when compared to the potential cost of damage to the facility, the devastation to families of those injured or killed, the reputation of the plant owners and other stakeholders, and the potential ramifications for the whole industry sector at this critical time in the evolution of emerging low carbon technologies. Loss of public confidence in this technology could result in a slowing of the world's adoption of alternative energy sources, with an ongoing use of fossil fuels, and the release of further non-renewable carbon dioxide.

CONCLUSIONS

A key technical safety aspect is that the design of the plant has to incorporate the necessary controls to ensure that the atmosphere within the plant remains outside the flammable region, and that appropriate venting and pressure relief systems (or containment) are provided in the design. Careful attention to start-up and shutdown aspects is vital.

A major challenge is changing the established practice of the power sector and supply chain. The additional hazards require controls which can be regarded as restrictive or over engineered. There are limited "standard/generic" design solutions available, unlike conventional energy plants where many plants of each type have been built and a "standardised" design basis is available. The technology is new and still undergoing development and as a result there are few examples of directly comparable incidents to learn from. It is vital that the lessons learned from the chemical process industry, including its numerous incidents, are successfully transferred to this growing, and potentially hazardous, industry sector, to ensure we do not repeat the errors of the past.

The transfer of knowledge between industry segments is vital to the effective safe implementation of new green technologies, to avoid both local incidents and potential loss of life, but also the impact of loss of public support. The process industry sector has a wealth of experience of the tools and techniques required to ensure, as far as is reasonably practicable, this does not happen. Whilst guidance is becoming available, recommended practice is often not directly applicable, due to the multitude of gasification technologies and corresponding reactor configurations available. Applying these techniques in the power sector is innovative, and will result in a safe and green future. The failure to apply the lessons of the chemical industry risks a major incident, or series of major incidents, which would be devastating for those directly affected, but which could have far reaching effects on the emerging technology and the efforts to reduce our dependence on fossil fuels. The process industry has learned many painful lessons and can, and should, transfer its knowledge, techniques and skills to the wider community.

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