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Fire, explosion and chemical toxicity hazards of gasification energy from waste

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ABSTRACT

In recent years there have been an increasing number of attempts to develop commercial-scale gasification of municipal solid waste. The results have been widely disappointing, with many high profile and often catastrophic failures. The causes and analyses of these process failures remain inadequately reported in peer-reviewed literature. This paper identifies and discusses these hazards in the context of modern preferences, using case studies and historic antecedents to explore the engineering challenges which underpin loss prevention in the gasification energy from waste sector. It shows that there are many hazards: flammable, toxic, and corrosive gas mixtures, the auto-ignition of stored feedstocks, multiple explosive atmospheres due to both overpressure and underpressure combined with many ignition sources, plus heightened risk at times of start-up, shut-down or during testing. It also identifies how risk is heightened by preferences for novelty, lack of stakeholder understanding, a desire to operate at high outputs, and a reluctance to learn from history.

1. Introduction

On 7th August 2017 a man died of serious burns after an explosion at a gasification Energy from Waste (EfW) plant in Oldbury, West Midlands, United Kingdom (Perchard, 2017). Six weeks later (on 25th September 2017) and approximately 100 km away, two men were seriously injured in a second gas explosion at another EfW plant, this time in Nottingham, UK (BBC, 2017). Both accidents come at a time when the UK's Waste sector has become one of the most dangerous in the country, with a fatality rate around 15 times greater than the rate across all industries over the five year period up to 2016, and over three times greater than the rate in the construction sector (HSE, 2017).

The UK Government currently describes gasification of Municipal Solid Waste (MSW) as an Advanced Conversion Technology (ACT). Like many countries faced with a chronic solid waste problem and the desire to maintain high throughflow of consumer goods for economic reasons, over the last five years it has pro-actively supported the implementation of commercial gasification ACT with various avenues of financial subsidy (House of Parliament, 2014; House of Parliament, 2015; Green Investment Bank, 2016). This has stimulated entrepreneurial investment such that currently the UK is in the midst of an unprecedented level of environmental and planning permit applications to build and operate gasification EfW plants (Dowen, 2017). This is despite a track record of almost ubiquitous failure both in the UK and elsewhere (Dowen, 2016; Quicker et al., 2015).

The modern EfW industry is reticent in its approach to the disclosure of accident or failure diagnostics about gasification, whether due to commercial concerns or proprietary restrictions. A handful of non-peer reviewed reports are available but these do not go into technical details about the causes (Dowen, 2016; Seltenrich, 2016). Yet, the reasons for these failures can be understood through perusal of academic literature which details why MSW-fed gasifiers have never been able to operate effectively outside of a research environment due to the physical and chemical heterogeneity of a mixed waste feedstock (Consonni and Viganò, 2012; Reed and Das, 1988; Rollinson and Williams, 2016). Such literature also reveals that there are multiple pathways for fire, explosion, toxic gas release, and environmental pollution (Bridgwater et al., 1999; Reed and Das, 1988).

For the purposes of loss prevention, the cornerstone of which should be the risk assessment, it is proven that safety appraisal should be based on learning the lessons of the past. This requires an examination of case studies and historic antecedents to facilitate the identification of the underlying causes of the risks associated with any technology or process. In the capacity of gasification engineer, this author has been party to the independent appraisal of many of the recent UK permit applications. Worryingly, most show little or no awareness of the risks and challenges associated with the concept. Many also deviate markedly from the specific design features that have permitted gasifiers to attain safe and stable operation in the past. This is of importance not just for loss prevention in the process industries, but for the general public who

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want to understand the risks associated with these seemingly “novel” technologies – particularly those who have greater concerns because they live in close proximity to the proposed site, legislators, and civil servants who have both the ultimate responsibility for granting permission to operate and the power to impose safety conditions. This paper therefore attempts to address this limitation by exploring the risks associated with gasification EfW using historic evidence and recent case studies along with providing a description of the underlying scientific reasons for why the losses occur.

2. History of thermochemical EfW technologies

The first large-scale machine to thermally decompose of municipal refuse and permit the simultaneous extraction of energy was built in the late 1870s by Alfred Fryer and Sons, ironically of Nottingham, UK (Clark, 2007). It is a little known fact that its patent included both gasification and incineration (Tucker, 1977). Whereas gasification of mixed refuse had no future (for technical reasons which will be outlined below), incineration did; and by 1912 there were 338 municipal waste incinerators operating in the United Kingdom, eighty of which were adapted for generating electricity (Tucker, 1977). From the 1920s onwards, waste incineration was phased out in the UK and landfilling became the preferred option (Clark, 2007; Cooper, 2010). This preference lasted for approximately forty years when, due to the high costs and finite availability of landfill space, incineration of waste re-appeared. It quickly acquired negative publicity due to dioxin emissions, fly ash, and other process challenges of aggressive acid corrosion and abrasion that are inherent when municipal waste is burned (Hulgaard and Vehlow, 2010). Despite this, incineration is still the most common technology choice for industrial EfW (Leckner, 2015).

Commercial-scale gasification of mixed waste never materialised because it has proven technical limitations which mean that it can only work effectively with homogeneous feedstocks (i.e. lignocellulosic biomass, coal, and coke) and in small-scale reactors specifically restricted to that feedstock type. For accounts of the history, theory and praxis see for example Goodrich, 1924; Rollinson, 2016a,b; Kaupp, 1984a. On this limited basis only, gasification systems that could power cars, boats, trucks, and small stationary applications developed and reached a technological peak in the 1930s and 1940s (Generator Gas, 1979; Horsfield, 1979; Kaupp, 1984b). After the Second World War, as oil became cheap and readily available again, gasification fell out of favour. But, during the 1970s and 1980s interest in lignocellulosic biomass gasification picked up, particularly in Northern Europe, Asia, and America, with researchers re-visiting the work done in the war years (Food and Agriculture Organization, 1986). This is because these small-scale biomass gasifiers offer greater sustainability benefits in comparison to large-scale biomass combustion, and can provide off-grid energy independence, particularly for rural communities where there is an abundance of forestry residue (Rollinson, 2016a,b).

In the early 1990s, despite no further technological advances, but because of the negative publicity associated with incineration, the waste industry began to target gasification as a possible alternative for MSW thermal treatment. Initially, many authors in peer reviewed literature embraced the concept (Malkow, 2004; Arena, 2012). Over the last few years however, the evidence from repeated failures combined with a greater understanding of the historical evidence of gasification's limitations, has led most to now accede that the concept is overtly challenging, to question the feasibility of positive efficiency, and to assert that gasification of mixed waste is only possible when operating in close-coupled combustion mode and/or stabilised using fossil-fuels (Consonni and Viganò, 2012; Dong et al., 2016; Quicker et al., 2015). Despite this, a few current publications still inadvertently and erroneously cite the old review articles (see for example: Inthararathirat and Salam, 2016; Shiota et al., 2017). As Leckner observes in a review of the subject (Leckner, 2015):

> “… ten years later, the enterprises promoting the conversion systems mentioned by Malkow do not exist or they have focussed attention on other equipment, such as grate furnaces”

One country, Japan, has persevered more than any other with commercial MSW gasification in the last two decades. But, to do so its operators have had to bolster the process with copious amounts of limestone, coal, oil, and/or natural gas, all of which undermine the sustainability credentials of the system. Technical reports reveal that in addition to the limestone, typical blends of ca. 100 tonnes of coal per every 1000 tonnes of MSW are necessary, along with operating using energy intensive oxygen-enriched air (Tanigaki et al., 2012, 2013, 2015; Quicker et al., 2015). A further aspect of the Japanese approach has been to have a regime of operating hours much lower than would be considered economically feasible in other countries, namely one of a maximum 250–280 days per year (Leckner, 2015; Suzuki and Nagayama, 2011). Even with these impositions, it is now reported that Japan is moving away from gasification and towards mass burn incinerators, along with a greater focus on waste prevention strategies (Leckner, 2015).

3. Process features and hazard identification

Incineration literally means “burn into ashes”. The process is designed so that there is complete mixing of the waste coincident with an abundant supply of oxygen. The combustion gases produced are almost exclusively gaseous water (H_2O) and carbon dioxide (CO_2) which means that they are neither flammable, toxic, nor explosive; however when MSW is incinerated, the gas is still highly attritional and corrosive due to fly ash and chlorinated molecules which are unavoidably formed. These waste gases then exchange their heat in an equally well understood boiler system and steam turbine. Overall the risk is minimised due to the relatively simple nature of the process, the chemically inert product gas species, and the mature understanding of the safety issues associated with all components (Elston and Pal, 2011).

Gasification is different. Literally meaning “gas production”, it is a development on the natural phenomenon of pyrolysis which occurs when organic matter is heated in less than stoichiometric oxygen, resulting in the evolution of a complex hydrocarbon-rich mixture of condensable species (ca. 70–80% by mass of the original feedstock), and leaving behind a fixed carbon framework (char) (Bridgwater, 1995). It is more akin to a chemical processing plant than an incinerator (Elsdon and Pal, 2011). To the uneducated, the differences seem trivial in the sense that gasification of waste requires less oxygen but must still obey the same reactor engineering principles of residence time and high temperature. But, this observation is incorrect, for gasifiers cannot aim for maximum temperature and surplus oxidation. They must attempt to split the feedstock into high calorific value gas that is rich in carbon monoxide (CO), and hydrogen (H_2), with lesser concentrations of methane (CH_4), at the same time as producing low by-product quantities of oil (tar) and char. The only way to achieve this is to exclude oxygen from the decomposing feedstock while maintaining high temperature inside a physio-chemically complex reaction vessel. This is illustrated by Fig. 1 which shows a schematic of two types of gasifier reactor, separated into chemically and thermodynamically distinct zones, each zone requiring the maintenance of specific conditions to facilitate its own preferred chemical reactions for steady-state, but with each (zone) influenced by heat and mass transfers across the whole system. The challenges are many, and with a mixed waste they are extreme; for without oxygen, and with the high sensitivity to solid, gas, and heat transfer variation, contaminant tar and thence system failure ensues (see Section 5). As noted by Dasappa et al. (2003):

> “The performance of the system, on occasions, was excellent with little tar content and on other occasions, for no apparent reason, produced reasonable amount of tar. This behaviour was traced to

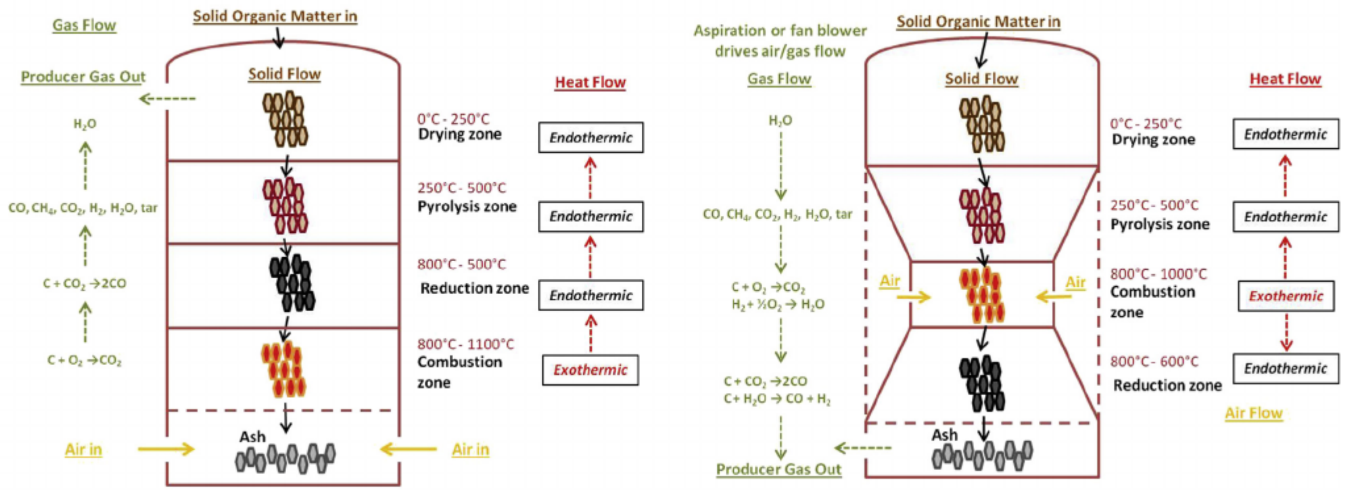

Fig. 1. Schematic of two gasifier designs showing different reaction zones along with heat, solids and gaseous flows. Complex thermodynamics dictate the chemical interactions within each zone. These are in turn a function of material packing, reaction kinetics, temperature, and air/gas throughflows, all of which are dependent on various post and pre-reactor components.

the structure of the bed with varying fuel chip sizes and moisture content."

This however is common knowledge to anyone who has operated a gasifier, but is apparently overlooked, discounted, or unknown by the current proponents of MSW gasification. Over one hundred years of research has shown that even slight changes in temperature and oxygen content can have a significant influence on operational status, process instability and the production of corrosive and toxic by-products (Kaupp, 1984a, b; Reed and Das, 1988, Consonni and Viganò, 2012).

The core of the gasification process is the reactor which is often called the "gasifier". But, because there is complete inter-dependency across all components the system as a whole is often also labelled as "gasifier". There have been many types of gasifier proposed, and the reader is advised to consult the following texts (Bridgwater, 2003; Kaupp, 1984a, b; Reed and Das, 1988). All however have the over-arching challenge of simultaneously managing internal reactor temperature and oxygen intake in order to control a delicate balance of chemical reactions on the one hand and the associated heat and material transfers on the other (Kaupp, 1984a, b; Reed and Das, 1988). Because of these challenging process requirements, gasifiers are reliant on a series of ancillary components to manage the complex multi-phase outputs. In many, the prime mover both accepts the gas to convert it into useful energy and also drives the process by aspirating the reactor, but there are also essential pre- and post-processing units for gas cleaning and gas cooling (invariably multiple sub-stages), feeding units, by-pass lines to a flare system and of equal importance is the operator (Rollinson, 2016b).

Table 1 shows a summary of the differences between gasification and incineration with respect to general process safety and hazard.

Table 1
Process variables for the two methods of thermochemical decomposition of waste (adapted from Elsdon and Pal, 2011). †Pressure is system specific with some gasifiers designed to operate at high pressure and some designed to operate at sub-atmospheric pressure.

Hazard	Gasification	Incineration
High temperature	Yes	Yes
High pressure	Varies†	No
Flammable gas generated	Yes	No
Toxic gas generated	Yes	No
Corrosive/Erosive gases	High	Medium/High
Tar (Condensable hydrocarbons)	Yes	No

Table 2 identifies the risks associated with varying stages in the gasification process.

All gasifiers produce tar – a complex cocktail of predominantly phenolic and poly-cyclic aromatic hydrocarbons – which is both an environmental toxin and a process-line contaminant. Yet, and despite this factor being the main cause of gasifier system abandonment, it is common for many current gasification EfW permit applications not to mention tar. Extensive research undertaken over the last thirty years has shown that without catalyst, temperatures of above 1100 °C are required for tar elimination (Vreugdenhil and Zwart, 2009; Parikh et al., 1988; Kiel et al., 2004). These temperatures are not attainable inside a gasifier (see Fig. 1). Tar reduction must then be addressed by ingeneous design. But, even with an optimised biomass gasifier operating with homogeneous feedstock, multiple, and importantly non-standard, post-processing stages are required (Zainal et al., 2001).

4. Gasification fire, explosion, and toxicity antecedents

Gasifier safety was pioneered during the years between 1939 and 1944, predominantly in Scandinavia, Germany and the USA. Rather than being considered a safe technology, it was identified as very high risk, with many failures and frequent fatalities. The problem was so great that the hazard was described as "garage death" as exemplified by the following extract (Salen and Lindmark, 1979):

> "It is necessary to take into account not only the danger of acute poisoning (which is easier to handle), but also the treacherous, insidious chronic poisoning, which in the case of large scale generator gas [gasifier] operation may become very dangerous for public health. The fire hazard is also serious".

For example, in Sweden during the years 1939 and 1945 there where 2865 gasifier fires reported to the Gas Generator section of National Swedish Fuel Bureau. At its most severe, in one quarter of the year 1942 there was equivalent of four gasifer fires per day (Salen and Lindmark, 1979).

Modern records of gasifier fire and explosions are less well reported. In a World Bank gasifier monitoring programme in the mid-1980s, a gasifier in Santa Lucia in Brazil reported a number of explosions (Stassen, 1995). More detailed accounts are provided by reports of the Indian experience of commercialising gasifiers during the 1980s (Dasappa et al., 2003):

> "Regarding the fire hazard and associated thermal explosion possibility, the issue is related to a mixture of gas and air in flammable

Table 2
Process component risk aspects associated with gasification (adapted from Bridgwater et al., 1999; Reed and Das, 1988).

Process Stage	Fire	Dust Explosion	Gas Explosion	Gas Poisoning	Tar	Skin Burns	Particulates
Fuel Preparation	X	X					
Feeding System	X	X	X	X			
Gasifier Reactor	X	X	X	X	X	X	
Gas Cleaning	X		X	X	X	X	X
Gas Utilisation	X	X	X	X	X	X	X

> proportions getting ignited in a burner at unwanted times. There have been four cases of such a nature leading to thermal explosion with effects such as bulging of the outer cover of a filter, lifting of the top cover of the gasifier, and blowing off of a safety diaphragm near the engine."

More recently, it was a fire which ultimately caused the permanent closure of the MSW gasification plant at Dumfries, Scotland in August 2013 (Holder, 2013). This plant was one of four commercial ACT EfW installations used as case studies in a document by the UK's DEFRA (2013). All the plants in this report are now closed, with the last of these, on the Isle of Wight, abandoning gasification in 2017 and converting the site to a wholly conventional mass-burn grate incinerator (Slow, 2017). The Dumfries fire followed initially sixteen months of problems when the site was shut-down because of 38 by-pass stack activations, over 200 reported emission limit breaches, two dioxin emission breaches, ca. 100 notifications of short term exceedances; and then after re-opening 12 months later, a further 50 bypass stack activations, 3 low temperature, 23 low O_2, 6 dioxin failures, 2 exceedances of the daily HCl limit, 1 exceedance of the daily NOx limit, 2 failures to meet the heavy metals limit, 1 complaint of flies, and 2 incidents of dark smoke emissions from the bypass stacks (McIntyre, 2013).

Due to numerous high profile failures, Germany has now abandoned the concept of commercial MSW gasification (Gleis, 2012; Quicker et al., 2015). From the aforementioned references, two systems are of note: In 1992 the Thermoselect technology was operated as a pilot plant in Fondotoce (Italy), followed in 1999 by two industrial size plants in Karlsruhe (Germany) and Chiba (Japan). The plants in Karlsruhe and Fondotoce shut down followed by stoppage in construction of a further plant in Ansbach (Germany) in 2002 and the cancellation of projects in Hanau and Herten (Germany) and Giubasco (Switzerland) (Quicker et al., 2015). It was reported that the Karlsruhe facility was forced to close temporarily in 2000 after releases of toxic gases were discovered, and operational problems included an explosion, cracks of the high temperature chamber's concrete due to corrosion and heat, and a leaking sediment basin that held cyanide-contaminated wastewater (Quicker et al., 2015). Other reports state that the regional government admitted that the walls of the chamber were so battered that pieces had fallen off and could have caused an explosion (GAIA, 2006). The second infamous failure was the RWE-ConTherm plant at Hamm which was a Rankine cycle system that operated under pyrolysis gas derived from MSW. The plant closed in 2009 due to a chimney collapse, which, after analysis was found to be due to corrosion (Gleis, 2012). It was identified as being caused by the feeding material not matching the process and creating internal temperatures beyond tolerable process limits (Chen et al., 2014).

Waste as a feedstock has its own safety antecedents. In August 2003, the spontaneous ignition of Refuse Derived Fuel (RDF) stored in a cylindrical silo at an EfW plant in Mie Prefecture, Japan resulted in two explosions (on 14th and 19th). In the first, four workers were injured, while the second was fatal as it blew the roof off the site and killed two fire fighters (Gao et al., 2004; Hirano, 2006). This was not an isolated occurrence: similar accidents involving spontaneous combustion of RDF have also occurred at power plants located in Ohmuta City in September 2003, followed by another accident in Ishikawa Prefecture in October 2003 (Matunga et al., 2008). The subsequent investigations found that the critical ignition temperature was predicted to be as low as 40 °C–80 °C for stacks of RDF in the 1 m–5 m height range (Gao and Hirano, 2006).

RDF is reconstituted MSW that has been created by pre-processing the raw MSW by one or more of screening, shredding, pelletising and drying. The same material also goes by the name of Solid Recovered Fuel (SRF) when it is split into five categories with respect to calorific value, chlorine and mercury content (European Committee for Standardization, 2011). Such shredded and reconstituted organic material is known to have a propensity for the release of toxic gases (Kuang et al., 2009), to self-heat and auto-ignite when stored (Larsson et al., 2012).

5. Risk assessment of gasification EfW hazards

As with any chemical plant risk assessment, the site should be divided into functional units to achieve the highest standards of process integrity (World Bank, 1988). But, the risk of fire, explosion, and toxic gas release from a gasifier EfW system requires far more depth, as the system depends not only on the design of the reactor, along with how it is operated, but also to a great extent on the consistency and heterogeneity of the feedstock. Due to this inter-dependency a holistic approach is essential.

5.1. *Producer gas*

It is the necessary function of a gasifier to create flammable and toxic gas, called "producer gas". This contains H_2 and CO both at concentrations of ca. 20 vol%. Producer gas also contains varying quantities of higher hydrocarbons (tars) and char particulates. These process-line contaminants adhere to or condense upon all post-reactor surfaces due to their complex nature and wide range of dew points, so in addition to being directly flammable, they add to the risk of fire, explosion and gas escape by impairing the integrity of downstream components.

The explosion limits for hydrogen and carbon monoxide are wide: 4 vol% 76, and 12.5 vol% 74 respectively (Bridgewater et al., 1999). To adjust internal reactor conditions so that the species are outside these limits would not be possible due to chemical thermodynamic equilibium limitations (Melgar et al., 2007; Zainal et al., 2001), but also because it would mean that the gas was rich in CO_2 and H_2O and therefore had no utility value. Indeed, it is one criticism of some claims of success with MSW gasification that to combat tar, proponents have had to adopt a more manageable "two-step oxidation" scheme (Consonni and Viganò, 2012), or as others have called it, they can only maintain stability while operating as: "incinerators in disguise" (GAIA, 2006).

In terms of toxicity, concentrations of CO above 0.16% in air cause death in 2 h, and with just 1.28% death can occur within 1–3 min. Consequently there is also more than enough CO in producer gas to cause fatality at extremely short levels of exposure should a leak occur (Food and Agriculture Organization, 1986).

Total system integrity with respect to gas tightness has to be a key safety feature. For this reason, historic antecedents of successful gasifier operation make this of paramount importance, and require that all valves and joints are checked with diligence at start up and during operation (Reed and Das, 1988). Although CO toxicity is now well understood as a result of these early experiences with gasifiers, the danger associated with fire, explosion and corrosion in MSW gasifiers is less well addressed.

5.2. Explosion and ignition

Many gasifiers are not pressure vessels, although some designs have been proposed to operate in this way, such as the failed German SVZ Schwarze Pumpe system (Quicker et al., 2015). Classic gasifiers function under either aspiration (creating moderate underpressure) or from fan blown (moderate overpressure) air throughflow. There is a risk of exposion caused by both overpressure and underpressure resulting in both internal or external explosions by both ingress of oxygen or egress of producer gas.

In fan-blown systems, outward egress of producer gas will occur if there is a leak at any point between reactor, gas clean up, and prime mover, whereupon the risk of explosion is created as it encounters air and ignition sources. With aspirated (negative pressure gasifiers) the risk of explosion is varied, as further reported by the Indian experience of gasifier systems (Dasappa et al., 2003):

> "The explosion problem arises when the pressure drops across the elements are so large that air ingestion occurs through the filter water seals. This leads to a gas-air mixture flowing into the engine or the burner … If it flows into the burner after a changeover from engine mode to burner mode and the gas gets lit, there is a possibility of flame travel back into the ducting, particularly when the flow rates are being reduced (like when blower is turned off). This leads to the flame reaching all the way into the large volume filter where the spontaneous combustion leads to large pressure rise and explosion."

The greatest risk of fire, explosion and toxic release comes when the system is starting up and shutting down, or operating intermittently (Generator Gas, 1979). When the reactor is not operating optimally the engine must shut down to protect it and other components against dirty choking gas. Thus it immediately creates back pressure in the hot reactor which results in the rapid release of toxic and flammable yellow smoke from an otherwise seemingly normal or gas-tight system (Salen and Lindmark, 1979). Because these components are not designed as pressure vessels, the pressure created at this shutdown period is so considerable that gas leaks out even from a tight gasifier which has been pre-tested and found to have no leak points (Salen and Lindmark, 1979). It is indeed commonplace, as this author can testify, and as there are many spark or heat sources nearby the fire and explosion risk is high (Food and Agriculture Organization, 1986):

> "During the start-up of an installation, the gases are as a rule not passed through the entire filter section, in order to avoid blocking the filters with the tars produced during start-up. The filter may thus still contain air, and after an inflammable gas is produced and led through the sometimes quite voluminous - filter section an explosive mixture can result. If the gas is now ignited at the fan outlet a backfire can occur, leading to a violent explosion in the filter section. It is for this reason that it is advisable to fit the fan outlet with a water lock".

The heightened risk, and the need for greater depth of risk assessment at start-up and shut-down has particular relevance for novel, untested MSW gasifier systems. These must require extended (often indefinite) periods operating between start-up and shut-down during their commissioning stage. Indeed, it is usual for many to never get beyond commissioning (Dowen, 2016).

Certain types of gasifier operate as "packed bed" systems (e.g. Fig. 1). These create additional explosion hazards when the bed does not remain packed and void spaces are created, due for example to a lack of feedstock or feedstock channelling. When this happens it can lead to oxygen breakthrough and dangerous explosion situations caused by structural collapse of the feeding hopper leading to oxygen ingress (Food and Agriculture Organization, 1986). The problems again concern the feedstock and its direct impact on gasifier instability, and hence why there are greater challenges with MSW. This is particularly problematic for process safety appraisal because there is currently no official standard for characterising gasification feedstock. Conventional proximate and ultimate analyses (used for coal, and biomass) are unsatisfactory, as Reed and Das (1988) observed, before recommending that any such standard should include a measurement of all the following: particle size and shape, particle size distribution, char durability, fixed-carbon content, ash content, ash fusion temperature, moisture content, calorific heating value, and friability.

Optimum temperatures inside the reactor are between 800 °C and 1000 °C. But because gasifier reactors should be insulated to reduce heat losses, the danger caused by the external casing is significantly reduced. Other process components cannot or should not be insulated however: the flare stack for example, a component which is active during start-up and shut-down or whenever the reactor is not operating effectively (of particular relevance for novel concept designs) will have, in addition to the naked flame, a hot outer casing. Likewise the cyclone dust separator, used as the first stage of post-reactor gas processing to extract larger particulates, and without which the later gas polishing stages cannot function satisfactorily. The outer casing of these cyclones may get to temperatures of ca. 350 °C at the inlet, but cyclones should not be insulated as it impairs the efficacy of tar and soot reduction leading to downstream deposition problems (Rollinson, 2016b).

An insulated cyclone is one of the many reasons why char particulates become entrained in the producer gas flow. These hot particles (along with condensed-phase organics) will clog downstream heat transfer surfaces leading to an escalation of gas temperature, but can also directly cause fires in post-processing components such as baghouse filters. Gasifiers must have some method of collecting char and soot particles. Classic packed bed downdraft gasifiers do this at the base of the reactor in an ash/char grate. Due to the high carbon content of this material, it can combust if it comes in contact with an ignition source.

5.3. Structural integrity aspects

Using refuse as an energy feedstock creates greater process challenges that are not present with fossil or biomass fuels. This is caused partly by the high chlorine content (from plastics and food adulterated with salt) creating dioxins and hydrochloric acid (HCl), and by the variability of moisture (due to its endothermic enthalpy demands reducing internal temperatures), along with a high proportion of metals and other inorganics generating fly ash. Subsequently, corrosion and erosion, attrition and downstream fouling are major problems. Fouling of the heat transfer system not only reduces efficiency but it subsequently results in a heightened exit temperature of the gas. As the gases do not release their heat to design specification, this increases the risk of fire and corrosion in post-combustion components. For systems which specify baghouse filters as a gas cleaning stage then the risk of fire in these units is increased.

With gasification, these corrosive and erosive challenges are accentuated by there being tar and soot in the gas stream from operating at sub-stoichiometric oxygen levels. Corrosion is likely to occur where there is condensate since gasifier water contains organic acids. Thus in sections of the gasifier, wet scrubbers, and chimneys or anywhere that the tarry water condenses there is a hazard of both corrosion and tar deposition. Stainless steel can corrode at heightened temperatures and mild steel more so, and aluminium components should be absolutely avoided (Reed and Das, 1988).

5.4. Tar, soot and char dust

Although they cannot capture all tar molecules (Kiel et al., 2004), many gasifier systems utilise water capture techniques, and these must then have wastewater emissions. In Sweden during World War Two the maximum permissible phenol content of water released to sewers was 10 g/m^3 (10 mg/L), yet the typical phenol content of gasifier condensate or gas cooler system condensate is 1500–3000 mg/L (Reed and Das, 1988). In recent years, during its period of operation in 2003, the Karlsruhe thermoselect plant allegedly disposed of 120,000 m^3 of wastewater into the Rhine; and with the Fenebrache plant, it is alleged that the Thermoselect officers contaminated a lake with polluted wastewater (GAIA, 2006).

6. Discussion: gasification risk in a modern process management context

In the early days of gasification, the large number of fires and fatalities were reduced by education and regulation (Generator Gas, 1979). As expertise developed it was identified that there were three overarching requirements to maintain both safety and process integrity. These were: the need for operational diligence, a comprehensive understanding of the process and its risks, and to keep the technology within its stable operational limits. This is summarised by a more recent study (Food and Agriculture Organization, 1986):

"Poisoning accidents, explosions and fires have been caused by unsafe designs or careless handling of the equipment."

In a more modern context, attempts to gasify mixed municipal refuse at the commercial scale have deviated from these historic precepts for two reasons: firstly, it is in order to try and make the technology cope with a heterogeneous feedstock, and secondly because novelty is encouraged by policy and to attract investment. Additional aggravating risk factors come from the lack of clarify about system performance and the poor understanding of the technology among stakeholders (Kasedde, 2009). Such a landscape is however not new to gasification as the following extract, written in 1909 following a survey of seventy gasifier plants in the U.S.A, illustrates (Kaupp, 1984a, b):

> “It can not be denied that many of the difficulties [with gasifiers] are due entirely to incompetent operators. Some plants have been put out of commission temporarily by the prejudices or the lack of ability and training of the operators or engineers in charge. But, many of them have undoubtedly been the result of a short sighted policy on the part of some manufacturers, who are not willing to give proper and necessary information about design, construction, and operation of the plants made by them. The possibility of a sale at the time is apparently the only interest they keep in mind, and the future is allowed to take care of itself”.

The current preferences in the waste and energy industry are for automated systems and/or minimal staffing levels, usually with SCADA control to provide remote warning and early detection of process instability. Alongside this, and to achieve higher economic returns, plants in Europe are invariably designed for 24/7 working and long operational periods of more than 333 days per year (Suzuki and Nagayama, 2011). These strategies do not suit gasification technology. For reasons already described, the gasifier systems have been found to succeed only when there is the presence of highly trained staff to oversee the site management and adequate time set aside for maintenance. This is identified as one reason why gasification on the large-scale in Japan has not had the levels of failure seen elsewhere in the world as in this country run time is limited to at maximum 250–280 days per year (Suzuki and Nagayama, 2011).

With regard to knowledge, commercial gasification EfW plants in Europe are operated by companies and staff from the energy/mechanical engineering sector. However experienced these professionals are in their own field, they will have limited experience with the unique features of gasification (Elsdon and Pal, 2011). The acknowledgement of these factors and the acceptance of the need for learning from historical antecedents should be paramount if the industry is to avoid catastrophic accidents that have occurred not just with gasification, but in the wider chemical processing industry, such as Hicksons (Patterson, 2017), and Buncefield (Herbert, 2010). These case studies show that a chemical process when operating outside of its operational norms, by staff not familiar with this type of engineering is a dangerous mixture of novelty and hazard which has led to devastating consequences. One of the many lessons from Buncefield was that reduced staffing on site reduce the potential of direct visual detection of leaks (Herbert, 2010).

With novel systems that have been untested prior to permit applications, the time at start up and shutdown will predominate, as must naturally occur with experimental operation. In this author's experience, such heightened risks are seldom stated in permit applications. Yet, as this study has shown, it is at these times when the gasification process is at its most dangerous. For this reason, extra focus should be placed on start-up, shut-down, and testing, with greater diligence given to mitigating harmful emissions and explosive atmospheres. This includes not just housekeeping and operational procedures, but higher level plant design.

With regard to minimising toxic exposure for on-site operatives or visitors, although carbon monoxide detectors are inexpensive and efficacious, due to the high toxicity and propensity for gas escape, it remains highly advisable for gasifiers not to be operated in enclosed spaces. This is unfortunate for many of the novel EfW proposals, in attempts to bypass public concerns about odour from putrefying organic waste, state that the system will be constantly enclosed behind automated doors that are only elevated for delivery purposes. This is folly, for it goes against all the historic antecedents of the early 20th Century for which the title “garage death” was applied. Modern proposals which suggest this are, by attempting to counter adverse planning objections for a lesser hazard, greatly increasing the risk of on-site fatalities from toxicity, fire and explosion.

RDF and SRF is more commonly proposed as a preferred gasification EfW feedstock in permit applications. The rationale given is that it is a better and hence more homogeneous feedstock. It is true that the calorific value of this material is likely better than raw, unprocessed waste, but it is still highly heterogeneous; and furthermore shredded feedstock is wholly unsuitable for many gasifiers due to its propensity for steamed disintegration inside the reactor, and its tendency to inhibit heat and material transfer thus causing internal pressure drop (Reed and Das, 1988; Rollinson and Williams, 2016). Due to the safety antecedents of self-heating during storage, the environment and duration of time stored must therefore be adequately appraised with a fire risk assessment to also cover stacking, avenues of moisture ingress, wrapping (if any) and monitoring of temperature and carbon monoxide, methane, and hydrogen levels.

21st Century plant management preferences also identify the complete enclosure of the gasification system as a means to mitigate noise. Although the gasifier “reactor” is silent in operation, it cannot function without fans, a flare stack, extraction systems, and multiple powered gas clean-up stages, along with an engine or turbine to accept the gas. All of these ancillary components make noise, with the magnitude directly related to the size of plant. Even a very small three-cylinder gas engine at 10 kW rating will have noise levels at 1–2 m range of slightly above 80 dB, the daily E.U. workplace exposure limit (Rollinson, 2016b). EfW plants have prime movers of 100 times larger than this, which necessarily require large process fans to aspirate the system or cool the gas, and in many cases also machinery to grind, crush and sift the waste. Noise must be abated by soundproofing, particularly as many plants seek 24/7 working regimes. This causes problems for systems that simultaneously must also have ventilation to mitigate gas toxicity, but invariably the permit applications again do not address this, leaving the ultimate decision, as with all aspects mentioned in this paper to the diligence and knowledge of the local responsible person assigned to assess the plant.

To this end, and to ensure future safety against loss prevention, greater awareness about both recent and historic gasification antecedents is necessary. Only in this way can the potential costs of catastrophic damage, the devastation to families of those injured or killed, environmental disaster, and loss of commercial reputation, be avoided. Loss of public confidence in incineration of waste already exists, but by learning from history the same can hopefully be avoided with gasification.

7. Conclusions

Due to the challenging nature of the process, most large-scale commercial gasification plants fail. Causes are seldom disclosed, but history provides detailed evidence of the reasons for these failures. It also reveals that the technology has high risks associated with multiple pathways for fire, explosion, and the release of environmental toxins.

A gasifier must inherently create a highly toxic and flammable gaseous product. The toxicity risk is due to carbon monoxide that is inherently produced in concentrations far above the fatal doseage. Toxic, acidic, and condensable hydrocarbons (tar) are also created as unavoidable by-products, and this occurs in greater quantities due to difficulties in stabilising the process, particularly when mixed waste is used as a feedstock or when the system is unconventionally designed. Due to the multi-component and dynamic nature of operating a gasifier, there are multiple pathways for the leakage of these toxins. The highly corrosive nature of the product gas also accentuates the risk of toxicity pathways due to its adverse impact on process integrity.

Fire and explosion hazard is created by the producer gas being ubiquitously within its explosive range combined with the high risk for contact with multiple ignition sources within the gasifier system. This is evidenced by historic antecedents which report 2865 gasifier fires over a six year period in Sweden. Explosive environments are also evidenced by historic antecedents. These are caused by both underpressure (oxygen ingress) and overpressure (flammable gas egress) in both the high temperature reactor and in ancillary components, again due to the multi-component and dynamic features of a gasifier system.

Start-up and shut-down are identified as times when there will be a significantly heightened risk for fire, explosion and toxicity hazard. This is particularly concerning for modern "concept" systems which must necessarily operate on a test-basis, and which try and obviate less hazardous aspects such as noise and odour without a proper appraisal of the risk antecedents.

Raw waste which is pre-processed by sifting out some of the inorganic content, shredding, compacting, and drying has a propensity to self heat and auto-ignite. There have been several recent accidents due to the spontaneous combustion of stored RDF.

If the waste industry is to avoid further process losses, it must learn from the lessons of gasification history and the lessons of risk assessment developed through major chemical process accidents of the past. At present however, risk is being aggravated by a reluctance to disclose or address these failures, preferences for novelty, a lack of stakeholder understanding, and a desire to operate beyond technological capabilities.

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