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Review into RDF Fire and Explosive Hazards

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The use of Refuse Derived Fuel (RDF) has grown over the last 30 years due to its perception as a readily available Bio-fuel. This increased use of RDF, is closely shadowed by the growth of industrial fires and explosions, and these associated hazards require a rethink of fire and explosion protection/prevention processes at power plants. It is known that RDF fires are notoriously difficult to detect and extinguish when in enclosed storage spaces and can last for days, weeks or even months. Additionally, under conducive and aligned conditions, the effluent from RDF deep seated smouldering fires can lead to explosions. It is therefore necessary to review current practices within RDF pellet fuel handling & fuel storage, to prevent future accidents, and to make the industry as safe as possible.

1. Introduction

RDF technology evolved in the early 1970s in the USA (Cheremisinoff, 2014), and today, RDF is recognized in the Generation Industry, and deemed an established and needed, even sustainable technology. RDF pellets are the product of separated Municipal Solid Waste (MSW), classification of RDF product is outlined in BS EN ISO 21640: 2021 (BSI, 2021). RDF has increased its standing as an alternate fuel (Sapuay, 2016) owing to the recognition of the amount of non-recyclable burnable waste materials that can be redirected from landfill and be converted into a product that can be used instead of conventional fuels (Sever Akdağ, Atimtay and Sanin, 2016). Well-organized use of RDF, as an energy source can add to a recycling-based society (Sakka et al., 2005), RDF technology helps towards managing MSW and incineration reduces waste bulk. The recognised drawback is that it is still dependent on combustion technology, which adds to pollutants and noxious emissions. Strict regulations on emission levels of specific toxic materials, that are harmful to human health are required for this technology to continue as credible and sustainable renewable source of energy (Edo et al., 2016).
Until the recent introduction of BS EN ISO 21912:2021, there was no guidance on specific fire and explosion safety protection measures and systems. For that very reason, current protection measures within existing RDF fuel handling & storage facilities should be reviewed. Incidents spanning a 30 year period, indicate that the handling and storage of RDF, involves a palpable risk of fire that can lead to explosion. And because RDF can generate heat spontaneously, this heat build-up can be a major risk within large bulk storage when specific conditions align, and heat generation from within the pile leads to thermal runaway (Edo et al., 2016). RDF self-heating tendency varies considerably, due to; manufacturer/producer, batch, segregation process and time of the year, influencing the inconsistent nature of the MSW received at sorting hubs. Other factors such as; ageing and/or degradation (due to different material handling methods), storage type and localized environment, can also affect and influence the fuel characteristics (Vasconcelos, Silva and Martins-Dias, 2014) (Anuar Sharuddin et al., 2016). Past investigations, give an understanding into the behavior of RDF in fire situations, exposing the lack of recognized guidance standards for RDF, which meant that it was classified as waste and regulated as such.

2. RDF Manufacture

Standard RDF production comprises of the removal of non-flammable materials, then the MSW is typically shredded into small pieces. The shredded MSW is dried and compressed into approximate columns of 50 mm

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to 100 mm by anything from 6 - 20 mm diameter, at 100 °C compressed to form pellets, briquettes or slugs (Sakka *et al.*, 2005). Although producers target for uniformity of product, the unpredictability of MSW and its wide-ranging composition makes this almost impossible, additional difficulties arise if the pellets are paper or plastic rich. Badly manufactured or poorly stored RDF pellets are vulnerable to deterioration and can start unravelling (Edo *et al.*, 2016). Significant incidents documented in Japan, Europe and the USA, over a 30 year period, didn't foster any important initiatives to develop international guidance standards for processes related with production, handling and use of RDF.

3. RDF Hazards

Certain manufacturer's claim that RDF pellets can be stored for up to three years without significant biological or chemical degradation (Vasconcelos, Silva and Martins-Dias, 2014) (Anuar Sharuddin *et al.*, 2016), but operational knowledge shows that these declarations are presumed rather than substantiated, and that the problems associated with RDF pellets are down to poor quality of product and variability, influencing biological and chemical stability (Çepelioğullar *et al.*, 2016). Key factors to consider when evaluating suitability of storage and storage awareness, should follow the stages presented in the flowchart in Fig. 1.

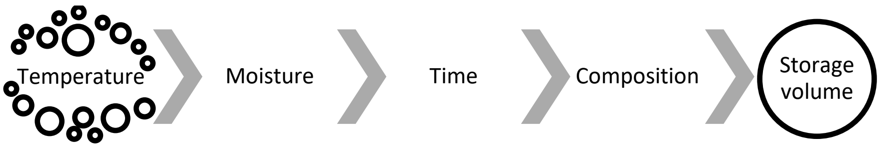

Figure 1. RDF storage awareness.

In the author's experience, RDF should not be stored for any prolonged periods of time, preplanning of storage systems, to ensure that they are emptied, cleaned and dried, will help prevent spontaneous ignition incidents. Existing shortcomings in manufacturer's safety data sheets, continue to show erroneous, inadequate and incomplete information, with inadequate safety warnings on the hazards connected with Fire-fighting, Handling & Storage, Stability & Reactivity and Ecological Knowledge. Pyrolytic Behavior of RDF and spontaneous ignition at ambient temperature through chemical oxidation, due to contact with air has consequent resultant reactions, especially when heat and microorganisms, metamorphose into a reactive peroxide, which is the process that is able to cause spontaneous ignition (Yasuhara, Amano and Shibamoto, 2010).

Bulk storage fires, can be defined as one (or more) of the following: Surface flaming, Surface smouldering, Subsurface smouldering or Deep seated (Ogle, Dillon and Fecke, 2014), the discovery of any one of these stages, does not mean that the fire is in its earliest stages. It is also possible that the fire can descend into the stockpile, where the energy dissipates into the surroundings until it becomes totally oxygen controlled, and festers, up until exposed again to air (and a new supply of oxygen) (Babrauskas, 2021).

Gao et al.(Gao *et al.*, 2004) established that the pyrolysis process of RDF, from diverse producers, are all comparable and that the principal "organic elements" of the pyrolysis process happen in a temperature range of 150°C - 550°C. They argued that the initiation energy at ignition temperature was 89.82 kJ / mol.

This critical ignition temperature was predicted by using the Frank-Kamenetskii theory (F-K theory), and the relation between Tc and the height of the RDF pile was calculated, disturbingly revealing that 40 °C, would be sufficient to ignite a 5 m high pile of RDF. In theory, the greater part of RDF should be: paper, card, wood, plastics and fabric textiles. This diversity in structure involves differing thermal degradation for every component within the RDF, this overlap during pyrolysis, means that the assessment of pyrolytic behaviors of the RDF mixed materials becomes more complex (Çepelioğullar *et al.*, 2016).

Cepeliogullar et al., states that Thermogravimetric Analysis (TGA) is usually needed to observe the thermal behaviors of RDF materials and they provided data on mass loss characteristics to explain the properties and behaviors at high temperatures, a summary of the altering heating rates influencing the mixed material's pyrolytic behaviors, were given in the 'Journal of Analytical and Applied Pyrolysis', along with TG (Thermogravimetric) and DTG (Derivative thermogravimetry) curves, they encapsulate the important peak temperatures and amount of residue after pyrolysis, what seems clear, is that the thermal decomposition of RDF can be broken down into four separate phases. Being: Moisture removal -> Decomposition of cellulose and hemicellulose -> Decomposition of plastics -> Char gas interactions at high temperatures. Even though the composition of RDF varies from area to area, researchers tend to agree, that RDF decomposition is mainly related to the degradation of cellulosic and plastic components, together in tandem with humidity/moisture (Çepelioğullar *et al.*, 2016).

Following a number of (assumed) spontaneous ignition incidents at RDF storage facilities in Japan, Yasuhara et al. (Yasuhara, Amano and Shibamoto, 2010), studied storage conditions that could repeat and induce spontaneous ignition in RDF samples to try and understand this phenomenon better.

Their interpretations showed that, when the initial temperature of different RDF samples were constant, the samples with the higher moisture content had shorter induction times. Other findings that influenced induction times were, not unexpectedly, the size of the RDF sample, and fascinatingly, they observed that there was no link between bacterial fermentation and spontaneous ignition (Sakka *et al.*, 2005). This though may have been down to the type of experiment. As temperatures rise, the energy required for ignition reduces to a point when the temperature is high enough to cause spontaneous ignition. Yasuhara et al. (Yasuhara, Amano and Shibamoto, 2010), established that spontaneous ignition of RDF occurs, subject to a number of unknown factors that could cause chemical oxidation reactions under certain storage conditions, they state that: initial temperature, moisture content and the size of the samples, are the important factors which must be known to ensure the safe use and storage of RDF.

Observations presented by Koseki et al. (Hiroshi Koseki, Yusaku Iwata, 2007), who experimented, as part of their assessment of hazardous fuels generated from waste, found that the measurement result (heat generation starting temperature and calorific value) of RDF samples generated more heat after water is added, and what's more, it is suspected that fermentation played a role in the heat generation of the RDF and wooden pellet (bark), this is important, because it demonstrates heat generation beginning at significantly lower temperatures than presently believed as hazardous within the Generation Industry. His results are presented in Table 1.

Table 1. Heat generation starting temperature and calorific value (Hiroshi Koseki, Yusaku Iwata, 2007).

Sample	Heat generation starting temp °C	Rising temp °C	Peak Temperature °C	Calorific Value J/g
RDF	51.3	70.1	97.7	19.5
RDF + Water 20%	29.5	36.1	65.0	14.4

On the base of the author's own experience and observations, waste fuel varies from other fuels, due to its diversity, and therefore it's more problematic. Spontaneous combustion being an exothermic process is reliant on combustible material and an increasing temperature along with sufficient oxygen to develop. It is also rational to deduce, that traces of metals may intensify the rate of self-heating. But, ignition and temperature development are also reliant on other factors, such as: Particle size, Amount of organic material, Moisture content, Size of the waste pile, Surface area of the waste fuel available to reaction and the Pressure over the pile.

The author's study of past occurrences, (Gao *et al.*, 2004) (Gao and Hirano, 2006) (Ogle, Dillon and Fecke, 2014)(Hiroshi Koseki, Yusaku Iwata, 2007)(Suzuki *et al.*, 2005) substantiates, that a number of those incidents have been ascribed to the short comings in the management of the risks involved with RDF. Further analysis of incidents typically suggests that large volumes of RDF fuel was present, which has commonly led to a recurring pattern of incidents, that in its plainest form can be summarized as shown in Fig. 2.

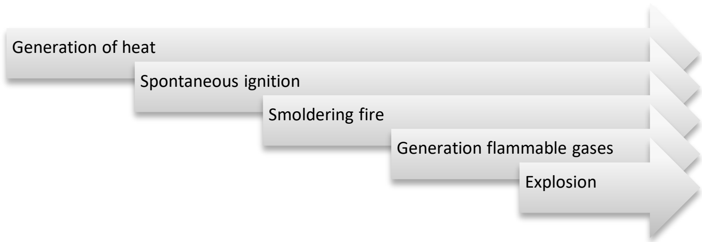

Figure 2. Steps from RDF heating to explosion.

It can rationally be presumed, that the addition of moisture quickens the trigger processes to fire, and once fire occurs, there is a real possibility that an explosion can follow if conditions align. Regardless, of the assertions of a safe & stable fuel, and prevaricated good storage ability claimed for RDF, explosions and subsequent fires have occurred on a regular basis and it appears, that the past lessons were not studied effectively enough nor taken into account especially in recent RDF projects.

Revising the variety of papers available on the comparison of pyrolysis behavior, differences are clearly evident at low and high temperatures due to the cellulosic material present (Edo *et al.*, 2016) (Anuar Sharuddin *et al.*, 2016). In fact, analysis shows that the burnt samples heated to temperatures of 350°C and beyond, generate volatile gases from the RDF pellets, together with a softening and clustering effect of the burning and heated pellets.

The RDF production processes involving MSW, especially in relation to composition inconsistency, clearly impacts more intensely on the traits and behavior of RDF pellets than with wood pellets. The degree of sterilization of RDF during the production process is usually unknown or unquantified (not declared); production data sheets normally state that the pellets are biologically inactive; nevertheless, pyrolysis inside the silo implies that this is not the case, as self-ignition of RDF within silos is clearly possible (Gao *et al.*, 2004).

Furthermore, ignition of explosions may be caused by the abrupt release of trapped low weight volatiles, producing the right gas stoichiometry for an explosion. Though, another possible theory is when temperatures within the pile reach beyond auto-ignition temperatures, smoldering for long enough to generate explosive/volatile gases from the produced smouldering fire effluent.

Reviewing the information on RDF production and storage hazards, an exploratory picture forms on the self-heating and thermal runaway, fire and explosion event process that possibly develops, through the evidential information analysed, a consequence of key-factors can be summarized, as shown in Table 2 below.

Table 2. Key stages in the fire and explosion development processes.

Phenomenon	Process	Consequence	Key Factors
Self-heating	Bio-chemical self-heating T < 70 °C	Formation: CH_4 & CO_2 Temperature increase	Presence of micro-organisms Composition Moisture content Storage volume Temperature – ambient Time – age
Thermal runaway	Low temperature oxidation T > 50 °C	Formation: CH_4, CO & CO_2 Temperature increase	Storage volume Temperature – ambient Time – age
Fire	Smouldering pyrolysis T > 250 °C	Formation: CH_4, CO & CO_2 Temperature increase	Oxygen level Storage volume Temperature
Explosion	Explosion	Pressure wave Secondary explosions Secondary fires	Level of effluent gases Ignition source Oxygen

Experience has shown that power station conversions, using the same ‘materials handling’ equipment, designed for the previous fuel, without a proper re-evaluation of plant suitability for the fuel being introduced is clearly not a safe option, and that the introduction of any, new or different fuel, requires a complete technical design re-evaluation.

In reality, the difficulties of RDF fire hazard mitigation begin with the challenging issue, of discovery and detection of a fire within the storage pile, and when a fire incident does occur, the difficulties then usually continue throughout the entire fire-fighting operations. Deep-seated silo fires are challenging to detect during the early stages (hours and days) of the fire, and before physical (visual/smell) signs appear. Deep-seated fires can smoulder for some time, and measuring (certain) gas concentrations (such as CO and CO_2) in combination with temperature monitoring, is presently, the most recognised method of detection used to determine the occurrence of fire within indoor fuel storage. There are also limitations on the claimed effectiveness of multi-gas detection commonly used in silo head spaces, an over reliance on this method limits detection to fires near the surface of the pile and excludes ignition deep within the pile until the fire is well developed.

Most storage facilities have detection systems designed to prevent the introduction of an ignition source through the fuel route, reasoning that this is the most likely cause of fire. But volatiles can build up unnoticed when the accelerating self-heating process begins and when it is totally oxygen controlled. At this point, there will usually be insufficient buoyancy within the fire effluent to clear the pile into the head space to actuate detection. Further complications to detection, exist in the form of hardened plastics fusing together, this bonding effect of RDF pellets, can form caps within the pile, due to prolonged repeated cycles of heating and cooling (during the oxygen controlled phase). The caps formed within the RDF pile in effect block the volatiles from rising with sufficient quantity and energy to activate detection in the silo head space.

Suzuki et al. (Suzuki *et al.*, 2005), led a study on the extinction of an RDF pile and examined traits of fire growth and extinction, they discovered that RDF pellets clustered when heated, due to the plastics contained within the pellets, melting and working as a fixing agent. When applying water to the fire, the bonded/clustered pellets were cooled and formed a coating which prevented water, intended for extinguishment, from penetrating the pile, the pellets underneath (within the pile) remained hot with continued oxidation, consequently when these were exposed to air again, flaring, flame, heat and smoke re-emanated from the pile (Suzuki *et al.*, 2005). When, fire-fighting an RDF pellet fire it is advised that water jets should not be used, water spray is more suitable for indoor RDF surface fires to prevent and only for short periods of time, due to the possibility of swelling (not as profusely as biomass) or unravelling of pellets and the hazard of extra stress/tension to the weight loading, attributed to the retention of water impacting on structural integrity.

Another reason for limiting water, Persson warns about adding water due to concerns, that in certain circumstances, this could contribute to the formation of explosive combustible gas and the possibility of a water-gas reaction, $C + H_2O \rightarrow H_2 + CO$ occurring, when fire-fighting water comes into contact with temperatures above 700°C resulting in the creation of hydrogen (Persson, 2013).

Hogland and Marques (Hogland and Marques, 2003) carried out a study on storage to initiate spontaneous combustion within an RDF storage pile, to evaluate long term storage. The RDF part of the research, revealed that spontaneous combustion was detected after approximately six months. They also noted that no flaming resulted unless an attempt was made to dig out the fire, any excavation resulted in a reenergizing of flaming. They also deduced, that the pyrolysis within the pile was oxygen-limited, additionally supported, by the explicit smell of gases linked with incomplete oxidation and partial combustion of hydrocarbon mixtures. Fire service attempts to extinguish the fire with water onto the pile were unsuccessful and the wetting yielded polluted fire water run-off. After three days the fire accelerated, and the original pile was broken down and spread out, this turned out to be the most effective and efficient way of extinguishing the fire. A readily easy way of emptying a storage facility would be very advantageous and possibly even crucial in dealing with a fire incident efficiently. This would assist in lessening the risks during fire-fighting operations, to personnel and property, and would help reduce potentially hazardous and costly long-drawn-out incidents. It should be emphasized that during any silo emptying operations (as the empty head space volume increases) this must be controlled to nullify the buildup of explosive gases. It is suggested that this could be done with Hi-expansion foam together with Nitrogen gas.

4. Conclusions

For RDF to have a sustained role in a challenging energy market, it must be perceived as easy, cheap and dependable. If financial losses due to business interruption happen often, then confidence will disappear. Results show that temperature, moisture content, time, composition and storage type (preferably dry), together with volume are important key factors in the self-heating process of RDF. Chemical oxidation is significant in the generation of internal heat reaching a state of self-ignition. High moisture content, has an influence on self-heating and self-ignition. 70°C seems to be the critical point indicator of self-heating. Fire-fighting jets should be avoided as they can cause collapse of gaseous caverns and dislodge gases. The best and most efficient method of extinguishing a pellet fire is to be able to spread it outdoors and hose it down. Fire safety design and systems evaluation should assess if a fire can be detected, controlled and suppressed early enough without unacceptable damage to plant.

This paper is based on the authors RDF investigatory experience and existing scientific studies, it focuses on smouldering RDF effluent that can lead to RDF explosions, to help the power generation industry in reviewing the design of new, or the conversion of existing power station projects. Small scale laboratory experiments are currently being carried out in association with Lodz University of Technology on RDF samples, using different techniques, to better understand the effluent process during smouldering, it is planned to use any conclusions to aid future planned larger 1:6 scale silo storage & fire experiments in the summer of 2022.

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