



**FLUIDIZED BED COMBUSTION AS A RISK-RELATED TECHNOLOGY
A SCOPE OF SOME POTENTIAL PROBLEMS**

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ABSTRACT

This paper addresses the risk-related problems of fluidised bed combustion (FBC). The scope concerns the following areas:

- Fluidised bed combustion (incineration) as a risk-minimization technology for toxic and hazardous materials as well as for industrial and municipal wastes
- Hazard and relevant problems with various bulk materials during the preliminary treatment and storage in different handling facilities for fluidised bed combustion
- Operational problems of the process itself, such as sintering, fouling, erosion, corrosion, effects of fuel blend constituents on the emission, etc. and their effect on the equipment.
- Operational hazards and common start-up failures in fluidised bed combustion
- Fluidised bed emissions, both air-pollutions and ashes and the process performance effects on them mainly concerning the trace metal vitalisation and risk with the ash re-use.

Keywords

Fluidised bed, combustion, wastes, risk, hazards, inspectional analysis, process approach

INTRODUCTION

The paper tries to define the known and potential risk-related aspects of fluidised bed combustion technology from the positions of the modern Safety-Related Engineering Approach in process design. The analysis is based on published materials from both the government legislation authorities and scientific research papers. The analysis of the fluidised bed combustion technologies from the point of view concerning the potential hazard and consequential risks is usually done in the restricted area of the operational problem of the fluidised bed combustion facilities (Ehrlich, 1995).

The analysis could spread through the entire chain of combustion technology: fuel, fuel storage, fuel incineration, operational problems of the combustion device, gas and heavy metal emissions, ash disposal. This chain has three main elements:

- Fuel potential hazard in its natural existence.
- Fluidised bed combustion operational hazards
 - Hazards related to the fuel storage and preparation.
 - Hazards inherent to the combustion process and furnace design.
- Hazards related to the residues of the combustion process: ash properties, disposals and emissions (gases and heavy metal).

The paper will comment on these potential hazards and the risk related in accordance with the combustion consequence (the process chain) formulated above.

HAZARDS EVALUATION BY INSPECTION OF THE PROCESS CHAIN

Fuel Potential Hazards in its Natural Existence

The fluidised bed combustion technologies have advantages with respect to other combustion technologies as incineration opportunities allowing co-firings of coal and various fuels most of them having a biological nature. The hazard attributed to various biological fuels considered here is illustrated on Figure 1. Generally, the principal fuel is the coal that is not dangerous in its natural disposal. Thus, the ability of the fluidised bed to burn fuels in the form of large particles (3mm - 5 cm) offers an opportunity of co-firing of mixtures of coal and various wastes. From a formal point of view, the co-fired substances could be separated in two major groups:

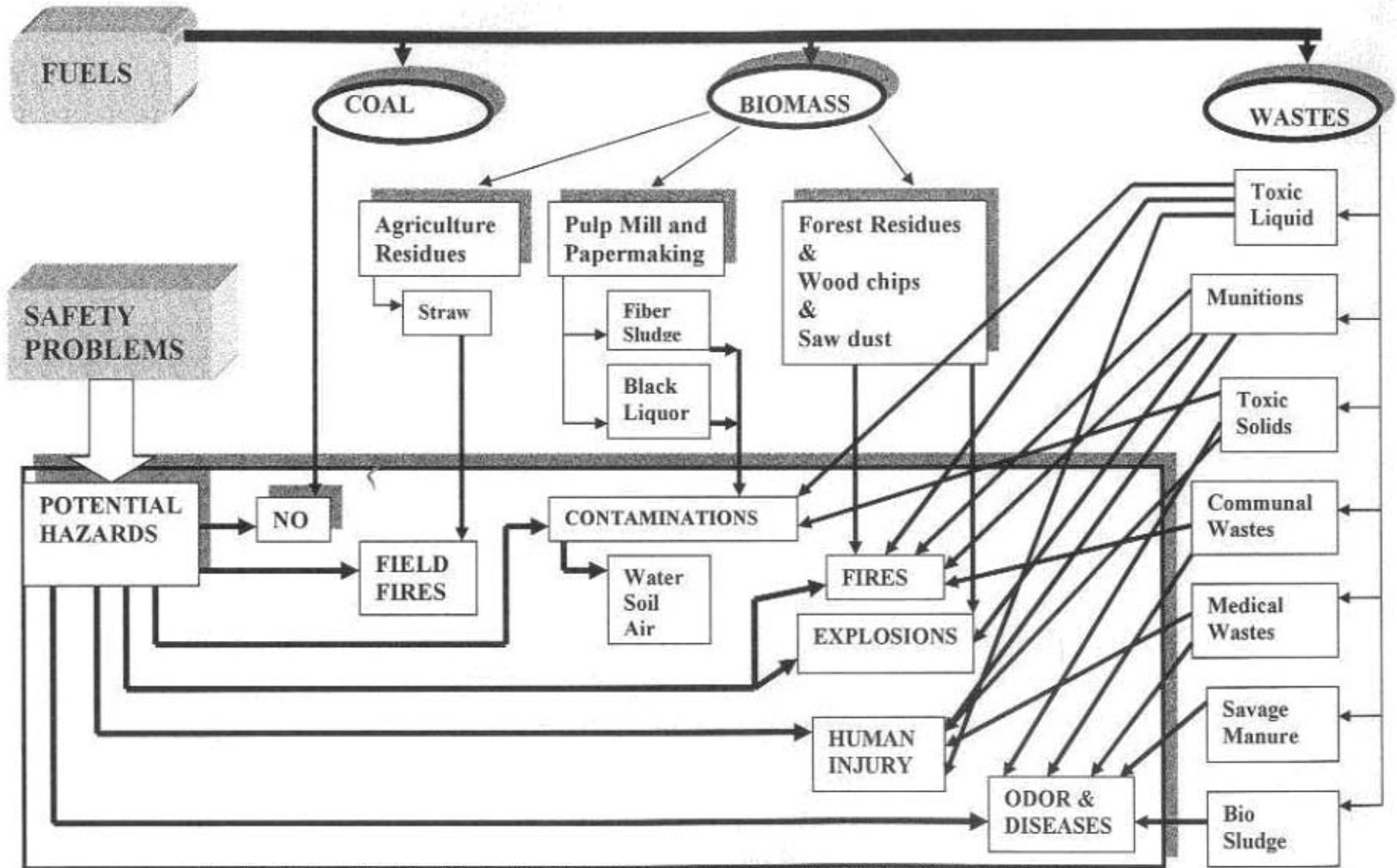


Fig.1. Fuels for FBC and their Potential Hazards before the Combustion Process

Renewable fuels. This type of fuel is based mainly on the agriculture residues and those based on the treatment of the wood. All of them could cause a danger upon certain conditions. Most important of them are the field fires and the wood dust explosions. The residues of the pulp mills and paper making industry mainly in the form of a black liqueur and fibre sludge are in the focus of the fluidised bed combustion as fuels containing large amount of biomass and organic matter. Their disposal in the field or in the water could cause environmental contaminations and problems.

Wastes. This common term concerns by-products of many process industries, communal, medical, military, agricultural fertilizers and sludge of different origin and shredded wastes. The schematic presentation of Figure1 tries to address the attention on the potential hazards of these waste materials that could occur if a certain waste material could be out a control.

The common feature of all these fuels employed in a co-firing combustion is the ability to burn in a fluidised bed. Thus, the **risk-oriented position** of the fluidised bed combustion among the other existing technologies is the ability to incinerate a wide range of materials, which are dangerous in uncontrolled disposal (Buron, 2000). In other words the fluidised bed combustion, despite the technical solutions and designs, has a great potential as a **risk-minimizing technology**. Some examples of procedures in fluidised bed combustion reducing the risks of the co-fired fuels are summarized in Table1.

FLUIDISED BED COMBUSTION PROCESS -POTENTIAL OPERATIONAL HAZARDS

The Fluidised Bed Combustors have specific hazards that could be taken into account in the initial stage of the plant design as well as during the exploitation. Ehrlich (1995, 1997) has discussed the major problem addressed to the safety design of fluidised bed combustion and the experience accumulated by US fluidised bed combustion plants has been incorporated in a series of developing NFPA's standards (NFPA, 1989, 1993). The present scope is stressed on three major steps of fluidised bed combustion technology:

- i.) Fuel pre-treatment and fuel storage in the power plant
- ii.) Fuel supply into the furnace and the combustion process itself considered as an interaction between the hot solids and the entire auxiliarities of the fluidised bed device.

Table 1: Examples - Fuel and their potential hazards both in a natural state and in the preliminary treatment

| WASTE | Natural Hazard | Preliminary treatment | | | Combustion | | Reference(s) |
|---|---|--|--|---|---|---------------------|--|
| | | Operation | Hazard | Safety Measures | Co-firing fuel & Inert bed | FB type | |
| Paper Mill Sludge | | Drying | Fire [*] | Sanitary measures [*] | Coal & Sand (limestone) | AFB & BB | Kraft and Orender (1993) |
| Primary Clarifier Sludge | | Drying | Infections [*] | Sanitary measures [*] | | Forced CFB | Kekki (1981) |
| Sewage sludge | Odor & Heavy metals | Drying | High Nitrogen content and low volatile trace metals release | Sanitary measures [*] | Wood/Coal blends (1) Silica sand and PVC particles (2) | CFB (1) BB(2) | Amand and Leckner (2001) (1) Amand et al.(2001) (1) Corella and Toledo (2000) (2) |
| Wood barks | Fire | Drying | Fire [*] | Fire protection measures [*] | Coal & Sand (limestone) | AFB & BB | Kraft and Orender (1993) |
| Paper Mill Sludge | | Drying | Fire [*] | Fire protection measures [*] | Silica sand No limestone | | Amand and Leckner |
| Toxic liquids (TNT) | Explosion | Drying [*] | Explosion [*] | Not conceived, but some Inertization could be developed [*] | No coal & Hematite | AFB | Grubor et al. (1999) |
| Municipal wastes as sanitary landfills | - Odor [*] - CO ₂ (1) - Toxic gases etc. - Leachate drainage and the ground water pollution (3) - Fire due to methane release (3) - Biological hazard(3) | -Hand-picking treatment (2,3) [*] -Shredder& metal separator& glass recovery (2,3) [*] - Storage | Damage of the equipment | -Moisture should be maintained (3) -Leachate collection - Controlled methane recovery for energy production (3,4) | Co-firing with coal (2,3) | BB (3,4) CFB (2) | Gupta (1996) (1) Xiaodong et al. (1999) (2) Kumar (2000) (3) Murphy (1999) (4) |
| Biomass | Self-ignition & Fire | Drying | Dust explosion & Increased Flammability | Total Inertization by Nitrogen | Coal & Sand (limestone) | PFBC | Wilen & Rautalin (1999) |
| Medical waste | Decease | Red bags (1) | Infection | Safety rules for waste collection (1) | Coal & Sand (limestone) | CFB (1) | Smith-Berntson & Stuart (1996) (1) |
| Tire | Fire, Smoke, Toxic products release | Large field storage | Spontaneous fire with heavy toxic releases | Elimination trough pyrolysis (1) Liquefaction (3) | Coal-tire blends (2) | AFB (1) | Williams & Besler (1995) (1) Mastral et al. (2000) (2) Mastral et al. (1996) (1) Harrison and Ross (1996) (3) |
| Bleach effluents from bleach-kraft mill | Chlorine release Sodium release | Treatment in clarifiers | Chlorine release [*] Sodium release [*] | Gasification or Combustion | Co-firing or gasification in the presence of solids (such as TiO ₂) (1) | AFB or CFB | Zeng and von Heiningen (2000) (1) |

^{*}Exists as a potential operation

^{*}Intrinsic feature of the fuel

^{*}Present author's opinion

(!)- Corresponding information and references

- iii.) Emissions of the fluidised bed - both gases and ashes as well as fluidised bed wastes are disposed.

Fuel Pre-Treatment

The fuel pre-treatment includes steps as drying (usually for sludges) (Linderoth, 1989; Kraft and Orender, 1993), size-reducing procedures, storage and mixing with adsorbent for SO₂ capture. Each of these steps may be related to special hazards such as:

- Spontaneous combustion during drying of low-rank coals (Sondreal and Ellman, 1974; Li and Skinner, 1985). The drying to a low moisture level removes inherent moisture from the coal structure in addition to the surface adsorbed water. This greatly increase the surface area available for low temperature oxidation (Kaji et al., 1985)
- Fire hazard in preliminary dryers of wood fuel (Bryers and Kramer, 1977)
- All types of dryers for preliminary dewatering of sludges produce vapour that can create an odour nuisance as well as to be pathogen for humans and animals.
- Obviously, the greater the temperature of the sludge dryers the more chance is of the dried sludge. In powder form, the sludge will ignite at ~ 380-400°C, but a weak exothermic reaction could occur at temperature less 100°C where the air content is between 25 to 125 g/m³. Therefore, fire preventative measures must be implemented: low oxygen concentration (<9-12% v/v) or temperature wells < 100°C (Frost at al., 1990; Kiely, 1997).
- Other potentially hazardous substances of the sludges that *are not affected* by the preliminary thermal dewatering are plastics and dioxins (Kiely, 1997).

Fuel Storage in the Power Plant

- Explosions and self-ignition of large piles of treated and stored wood by-products.
- Explosions and self-ignition of large dried storage piles of low-rank coal due to low-temperature oxidations (Carras and Young, 1994) or heat of wetting (Walker, 1967)
- Explosions under high pressure in supply devices of Pfluidised bed combustion (Wilen et al., 1999; Wilen and Rautalin, 1999)
- Fire and explosion of coal in thermal plant (Aparicio and Torrent, 1996).

Operational hazard - Combustion Process Itself

The coal combustion usually is carried out in a narrow temperature range of 815-899°C. The bed is cooled by various techniques and immersed surfaces (Oka, 1994) keeping the bed temperature in that range thus reducing the slagging, sintering and fouling if the hot particle bed. Moreover, the optimal temperature range allows lower emissions of NO_x. The moderate combustion temperature and turbulence also provide an ideal environment for the combustion of various low-grade fuels and wood wastes, waste materials and high-grade coal. There are many diverse fluidised bed combustion designs for large and smaller units (Oka, 1994; Valk and Bijvoet, 1995; Verhoeff and Holtzer, 1995). Most of fluidised bed combustion hazards are similar to those of suspension-fired boilers (Ehrlich, 1995, 1997). The following comments of some of the specific hazards of fluidised bed technology are according to Ehrlich (1995, 1997)

Hot spills of solids: The large fluidised bed combustion contains a large amount of hot solids fluidized in the furnace. The potential hazards are related to the furnace wall rupture or bottom ash-removal device failures. This requires the avoiding of the placement of critical components during the boiler design. Ehrlich (1995) mentioned of an accident, which resulted in two killed maintenance workers, when the hot solids of the dip leg suddenly flew into an empty but advanced furnace.

Lime burns: The removal of the fuel's sulphur requires limestone feed rate that exceed the stoichiometric ratio of calcium-to-sulphur (18kg/15kg=1:1) (Ehrlich, 1997). Higher ratios of 2:1 or more are not usual, since that causes ash rich of CaO, i.e. quicklime. The potential hazard of high temperatures generated when the quicklime rich ash contacts water in an ash conditioner or during in-furnace maintaining operations.

Steam generation after trip: The fluidised mass of hot particles can provide a sufficient sensible heat allowing a steam generation at near full capacity for a several minutes after the heat source loss if the fluidizing airflow continues. Thus, the loss of feedwater should lead to a fan trip as well as fuel trip (Ehrlich, 1997).

Operation at very high fuel-air ratios: Since the fluidised bed combustion contain a large amount of hot solids its inherent combustion stability is undoubted. This permits operation as much as four times the normal fuel-to-air ratio. Ehrlich (1997) commented that in several cases the fuel accumulation in the bed led to a rapid increase of the bed temperature. This

may lead to sintering and slagging of particle and bed defluidization. Furnace explosion may also occur in fuel excess in the bed.

Particle sintering and agglomeration: If any softening takes place on the surface of the mineral matter or the sorbent, then *there is a risk of agglomeration and fouling* (Grubor et al., 1999; Frost et al., 1990). Agglomeration increases with increases in the quantity of volatile alkali in the fuel. Biomass fuels contain varying amounts of these elements that may reduce the melting point of the ash, for example potassium, sodium, sulphur and chlorine (Ohman and Nordin, 1998).

In the case of coal as a fuel component, the iron content of the ash has significant effect on the complex ash behaviour. When iron is present in a completely oxidized form the fusion temperature of the ash rises, while the less oxidized form reduces the ash fusion temperature, (Srivastava et al., 1997), thus enhancing or avoiding the melting of the alkalis. The iron content of the coal and its degree of oxidation affect strongly the ash viscosity, which increases with ferrite content. The liquid slags with viscosity less than 25 PaS are not a problem (Srivastava et al., 1997).

The factors that enhance agglomerate formation include: *local reducing conditions in the bed, high temperature* (Frost et al., 1990), *increased pressure* and the presence of a *fluxing agent*. At present there are no reliable methods to determine bed agglomeration tendencies of fuels in their pure form or in fuel blends and combinations (Ohman and Nordin, 1998). The standard ash fusion test (ASTM, 1987) is commonly used, but insufficient results were presented (Gerald et al., 1981, Coin et al. 1995). Recently, new realistic methods employing the controlled fluidised bed agglomeration process have been reported by Ohman and Nordin (1998). Skrifvars et al. (1999) compared it with two more popular methods (ASTM fusion test and the compression strength based sintering test) testing alkali rich biofuels (Danish straw, olive flesh, bagasse, forest residues such as barks, branches and needles). The good predictions of the controlled fluidized bed (comparable to the best performance of the sintered strength test) need confirmation with large-scale experiments (Skrifvars et al. 1999).

A possible measure for increasing the melting temperature is the use of various minerals for effective alkali sorption (Luthra and Leblank, 1984; Wilen et al, 1987; Ohman and Nordin, 2000) such as kaolin, kaolinite, bauxite and elamthite. In the case of Kraft Black Liquor (KBL) gasification in fluidised bed the presence of TiO_2 leads to a reaction of the sodium

carbonate in KBL to form sodium titanates with high smelting temperature ($T_m > 960^\circ\text{C}$) (Zeng and van Heiningen, 2000).

The ratio of ash and bed material is connected to the defluidization can cause severe damages of the fluidised bed unit (see the examples of Ehrlich below). For example, the wood combustion in bubbling fluidised bed (bench-scale) at concentrations less than 0.1% of the bed material reduces the fluidization properties at 850°C (Davies and Dawson, 1989). Latva-Sompi (1998) suggests that pulp and paper mill sludges are not prone to defluidize the bed at typical combustion temperature. According to that study the bed agglomeration occurs only in the industrial plants (those commented in the thesis of Latva-Sompi) and mainly during the start-up periods and are related to technical problems of the fuel feed.

On the other hand, the combustions of high-volatile biofuels (Robina Pseudoacacia for example), bituminous coal or tyre lead to extremely high temperature when the finer particles burn in a very short time (Chirone et al. 1999), especially at higher oxygen concentration. This poses the problem of maintenance of the bed temperature since burning temperatures are beyond the melting points of alkalis and silica. For example, Grubor et al. (1977) reported a melting temperature of 764°C for potassium oxide and silica mixtures. Controlling the particle size is possible to decrease the burning temperature, since the largest particles of biofuels burn at relatively low temperature below the melting points of the relevant ashes (Chirone et al., 1999). The analysis of (Chirone et al. 1999) shows that about 95 % of the heat release of bituminous coals takes place in the bed, while only 43 % of the heat of the biomass is released in that zone. The remainder heat being released in the splashing zone above the bed due to extensively postcombustion of the volatile matters.

Operational Hazards – Process Effects on the Equipment Maintenance

Tube and membrane erosion and abrasion (Maude, 1992; Leckner et al., 1985; Rademakers, 1995) in both ABB's and AFB's and recently developed CFBC's. During the early development of AFBC and PFBC concern was expressed over the ability of evaporators, superheaters/reheaters, air heaters and uncooled components where the metal temperatures are around (or in excess) of 600°C corrosion was experienced with austenitic alloys with nickel contents. For higher temperatures, up to 900°C , high chromium ferritic alloys are most suitable. The thermodynamic approach (Rademakers, 1995) to identify the potential corrosion problems and resistant materials is limited, due the fact that in the different zones of the combustor, reactions occur and there is no equilibrium. At lower temperatures, depending on

many conditions at intermediate temperatures protective oxides can be formed. Under such conditions, there is a competition between the oxidation and erosion (Rademakers, 1995), which can result in either erosion of the oxides or in wear of the tube metal.

In the recently developed CFBC's the possibility of wear is greater due to the relatively high fluidizing velocity and the large particle size in the feedstock (Rademakers, 1995). In most CFBC's the heat exchangers are placed in the convective gas passages. High gas velocities entraining particles can cause erosion of the first heat exchanger in the line (superheater) and the tube temperatures are sufficiently high to form protective oxides (Rademakers, 1995). The recent studies have identified that the following components as being most at risk (Rademakers, 1995; EPRI/ANL, 1990).

Extensive studies on erosion-corrosion in coal-fired boilers have been reported by Levy et al. (Levy, 1986; Levi and Slamovich, 1986; Levy and Man, 1986). According to these studies, the impact of small solids on steel erosion-corrosion, increase the scale formation (by a diffusion mechanism and generally consisted of magnetite) temperature (Srivastava et al, 1997). Wright (1987) presented a comprehensive review on high temperature erosion in coal combustion.

Particle fouling due to enhanced ash adhesion at surfaces. The tendency of fouling the heat exchange surfaces increases with increases in quantity of volatile alkali in the fuel (Bryers and Kramer, 1977; Grubor et al., 1999). The fouling and the particle agglomeration have the same inherent origin, i.e. the low melting temperature of the ash formed. The fouling tendency of fuels does not depend on the ash content only. (Peltola et al., 1999), but most important factors are *the composition of the ash* formed during the combustion and the *ash mineral reactions* (see the next sub-section).

Obviously, the composition and the characteristics of the ash formed vary in accordance with the type of the fuel utilized. The growing use of biofuels supplied mainly as residues offers new problems. As a fact, the ash content is low, but the ash behaviour and reactions could be unfavourable that could hinder the wide use of the new potential sources of biofuels such as wood, wood wastes and agrobiofuel, as well as recycled fuels and demolition wood (Peltola et al., 1999). The Swedish experiments with various biomasses are indicative for ash behaviours and fouling tendencies when low-grade biofuels are used (Peltola et al., 1999). They were characterized as low-alkaline and low-chlorine fuels. These tests showed that the some important factors (and facts) and mechanisms are:

- ❑ **Fuels moisture** (if the residues are harvested during the winter)
- ❑ **The chipboard** (from the furniture manufacturing) increases the chlorine content and the molar ratio with the sulphur is close to one. During the combustion of chipboard/peat blends the relative ratio of alkalis (with respect to Cl and S) decrease, but the extend part of the chlorine escapes as gaseous HCl.
- ❑ **Chipboard combustion** increases the fouling, while the forest residues exhibit the opposite behaviour. On the other hand, the peat co-combustion increases the total amount of the ash, but the fouling rate decreases.
- ❑ **High share of simple salts and organically bound elements in the fuel.** The wood fuels give finer ash than the coal. The simple salts and the organically associated metals vaporize during the combustion when are fed into a hot fluidized bed. The alkali salts cause mainly deposits on heat exchangers right after the cyclones even the fuel contains low amounts chlorine and sulphur (Skrifvars et al., 1997b)
- ❑ **The inorganic mixtures formed in the bed** *do not melt at a certain temperature*, but have a wide temperature range where both solid and liquid phases exist. However, the alkali silicates could have a *low melting point* and can cause *sintering of the bed*. For example, the potassium silicate starts to melt at 742 °C within the range of K/Si ratio between 0.25 and 0.5 (Skrifvars et al., 1997a, and 1997b). It is absorbed mainly in the bed (experiments with fast growing willow *Salix*) that is a potential for agglomeration due to formation of a molten potassium silicate phase (Skrifvars et al., 1997b).
- ❑ **Particle deposition on the heat exchangers surfaces** through several mechanisms concerning *inertial impaction, thermophoresis (and electrophoresis deposition too), condensation and chemisorption*. Thermophoresis is more important fore very fine particles (less than few microns). According to Valmari (2000) up to 40% of the ash-forming constituents (experiments with wood-based fuels) remain in the bed that results in enrichment of bottom ash with K (due a reaction of K with the quartz sand bed). The remainder 60-70 % of the particles entering the convective ducts stick on the heat exchanger surfaces. The alkali silicates, mainly as large particles, rest more effectively, while the finer particle (mainly in the form of alkali chlorides and sulphides) form less than about 25 % of the fouling deposits.

- **Gas-phase condensation** or *gas-phase reactions* of SO_2 and HCl directly with the deposits (Jokiniemi et al., 1994) are the potential mechanisms of KCl and K_2SO_4 deposition. A majority of the condensed phase S is presented by K_2SO_4 (combustion of willow- Valmari, 2000) that results in deposition efficiency less than 20%. On the other hand, the combustion of forest residues results in 80% condensed S presented mainly by coarse CaSO_4 particles. When coal is the principle fuel both the low-temperature corrosion caused by SO_3 condensing to sulphuric acid and high temperature corrosion due to complex sulphates, take places (Srivastava et al., 1997). The vapour condensation and small particles diffusion has been detected as major mechanism of thin deposit formation when municipal wastes have been burnt (Steenari et al., 1999).

The agro-biofuel, grasses and straws may contain very high level of alkalis and chlorine compared to wood. Large amount of alkalis released by the flu gases result in increased fouling slugging potential. These deposits are relevant to operation problems (see *Particle sintering and agglomeration*) and ash provoked corrosion (see the next sub-section). Similar problems exist with the combustion of straw and pulp sludges that have Cl content close to 0.5 wt % (Coda et al.2001).

Second important sources of elements provoking surface fouling are the household wastes due the sodium chloride, or phosphates, in food (Steenari et al., 1999). The beverage package derived household waste may contain up to 1 wt % Cl, while the plastics could have Cl up to 5 wt % and PVC is the component with the highest chlorine level of these mixture wastes. However, referring the plethora of papers on combustion for this paper one idea should be conceived. It concerns the formation of fuel blends that during the combustion release components, which are compensating each other. It is a matter of argument, but the experiments of Corella and Toledo, (2000) concerning the increase of the chlorine content in order to capture the heavy metal emissions (see further *Heavy metal volatilisation*) give grounds for such an approach minimizing the risky elements emitted from the combustion zone.

Fuel ash provoked corrosion of boilers and superheater tubes. The problem is if great concern since it affects the performance of power stations by lowering their efficiencies. An extensive review on the problem has been reported by Srivastava et el. (1997). The reasons of the ash-provoked corrosion could be defined as:

- **Moisture**, concerned as an impurity of the fuel with a combination of some mineral impurities (concerning mainly coal as a fuel). This can be driven off, by the heating of the fuel to a temperature of 378-383 K (Srivastava et al., 1997). The moisture also remains in the air supplied to the bed. The nitrogen present in the bed could be concerned as a diluent reducing the combustion temperature and increasing the amount of the heat carried out by the waste flue gases.
- **Ash composition** is a complex depending on chemical reactions of the minerals at high temperature and is influenced by other substances under combustion. According to Srivastava et al. (1997), the behaviour in combustion of inorganic materials in coal depends not only on the nature and the amount of the natural constituents, but also on the rate of heating and the maximum temperature reached. The *layered minerals* such as shales and kaolins (used as alkali adsorbing component) break down at about 1273 K and melt completely at higher temperature (Watt, 1982, Srivastava et al., 1997). On the other hand the *sulphides* begin to decompose at 573 K (Powel, 1920; Srivastava et al., 1997) and under oxidizing condition the evolved sulphur is ultimately burnt to SO₂ that can be captured easy in the ash by the lime for example. Other part of the sulphur can escape as H₂S (at a temperature of 1273 K, which is not typical of fluidised bed combustion) and a small part is retained as sulphides in the ash. The chlorides represented generally by sodium chlorides such as potassium, calcium and magnesium chlorides of the coal and other components of the fuel blends. The chloride ions appear to be released to a greater extend than the sodium ions under hot conditions. Steenari et al. (1999) have tested the presence of chlorides on alloyed steel upon combustion of municipal wastes in CFB boiler. According to these experiments NaCl, KCl and CaSO₄ are the significant constituents of the ash deposits at superheater surfaces when municipal wastes are burned. Upon conditions in the superheater regions (temperature of about 750°C) fly ash particles could be partially melted (the melting points of NaCl, KCl and CaSO₄ are 800, 776 and 780 °C) and when impinged to the surface they are likely to adhere to it. Steenari et al., (1999) reported deposit thicknesses from 10 to 50 mm at the superheater surfaces.

Other reasons for damages can be summarized as:

- **Fire-side corrosion and metal wastage** of in-bed tubes and surfaces (Leckner and Hogberg, 1983; Johnson and Leckner, 1986; Rademakers, 1995; Verhoeff and

Holtzer, 1995). The situation is further complicated because of the fact that the metal and gas temperature and the composition of the flue gases is difficult to determine accurately. In addition, these conditions cannot be kept constant because of normal variations of the fuel characteristics such that the environment is constantly changing through the area where corrosions occur. Metal wastage of the superheater surface depends on the fabrication characteristics of the alloy chosen. For example, the sulphates on the surface of ferritic steels have little effect on the oxidation rate of the metal in air at $T < 977$ K. On the other hand, the alkalis provoke chromium losses from the austenitic steel surfaces as chromium chloride, thus increasing the oxidation rate (at $T > 672$ K) and replacing the normal chromic oxide film.

The recent results of Bautista-Margulis et al. (2002), addressed to in-bed tube corrosion show that for shallow beds (laboratory experiments with 20 cm I.D. combustor and Clipston and Calverton coals). At $T < 840$ °C and an excess of air $< 20\%$, over 25 % of the volatile matter may escape and burnt in the freeboard. Upon such conditions, an important portion of vaporized alkali chlorides accompanies the volatiles released. Thus, an increase in the gas temperature (due to volatiles combustion) would affect corrosion of the hotter ash deposit that later migrates toward the metal surfaces. On the other hand at bed temperatures $T > 890$ °C (and excess air $> 30\%$) the accelerated oxidation of in-bed tubes may be induced since the greater portion of the alkalis (as sulphates) might be predominantly as condensed phase. Bautista-Margulis et al. (2002) suggested that for low-volatile alkali content of the coals austenitic stainless steels (347H for example) are suitable for in-bed tube materials.

- **Low oxygen activity of fluidised bed combustion fuels can** lead to problems of heat exchange tube banks (Reid, 1981) due to the absence of sufficient protective oxide films on the metal surfaces and alternating reduction of the oxidizing conditions.
- **The liquid film in the air heaters.** These devices operate at low temperatures (relatively low with respect to the superheater) and no excessive corrosion and plugging occur. However, the metal temperature is low and the dew point is easy reached, thus accelerating the corrosion due to sulphuric acid condenses and corrosion accelerates. The oxidation of the metal component is insignificant, but the presence of a liquid film can cause catastrophic failure (Srivastava et al, 1997).

- ❑ **Erosion of the coal feed system** (rotary valves) due to the high-pressure difference between the mill and bunker outlet causing significant airflow (Verhoeff and Holtzer, 1995).
- ❑ **Poor combustion** of paper mill sludges due to high moisture content that results in reduced boiler efficiency and increasing emissions (Linderoth, 1989).
- ❑ **Emission of unburnt volatile matter** from the bed and its combustion at undesirable high temperature (up to 200-300 °C) in excess to the bed temperature) (Kukurbayrak et al., 1988; Oka et al., 1988) can cause serious problems in prototypes and commercial installations (Bautista-Margulis et al., 2002), such as: i) damage of materials as a result of hot spots; ii) fouling and corrosion; iii) high CO and NOx emissions, etc.
- ❑ **Hot gases backflow** through the feed system due to high pressure in the combustion chamber and ineffective feeding design.
- ❑ **Incomplete combustion and odour formation** in the case of sludge incineration (Frost et al., 1990) at low bed temperature.

Operational Hazards -Combustion process maintenance

The combustion maintenance problems addressed to the potential risks are mainly related to the start-up procedures. The earlier lessons from the development of fluidised bed combustion technology are those of the ***bed initial temperature before the start-up*** of fuel supply into the furnace. Ehrlich (1997) gave an example of the initial bed heating with a charcoal ignited at ~330°C and kept the bed at ~500°C. However, when the operators were almost that the coal tested would ignite it would only devolatilize and cause problems. The accumulated volatiles would cause a "puff" or a shake of the unit when would be ignited.

The **hot start-up restarts** provoked by equipment breakdowns cause problems (Ehrlich, 1995, 1997):

- ❑ A critical experiment with a small amount of coal fed on the top of a slumped bed followed by a quick re-fluidization may lead to: 1) a smooth furnace restarts if the combination of conditions such as bed temperature, bed mass and coal quantity are exactly right. 2) A unit "puff" and a six-meter flame shooting the access ports through which the coal is added.

- Unexpected events may occur if the control system fails. Two examples commented by Ehrlich (1995) are related to the CO accumulation in the furnace plenum (windbox) when the forced draft (FD) fan suddenly tripped, but the ID and secondary air fans continued to run for many minutes. The restart of the FD caused *explosion in the windbox and the upstream ducts*. **The first accident** occurred after a sudden defluidization of the hot bed, while in **the second** a large coal accumulation was discovered. In both cases the secondary fans causes an overpressure that put the gases generated inside the slumped bed toward the windbox and the air supply ducts. Ehrlich (1997) commented two possible explanations: *The gases* from the slumped bed contain CO which pushed into the windbox can explode if a CO/Air mixture of >12% CO is reached. *Second*, gas causing potential explosion is hydrogen as a coal gasification product. A H₂/Air mixture at > 4% explodes. In a stationary bed containing ~ 1% coal there are enough carbon and hydrogen to produce an explosive mixture. The **ignition sources** of both accidents are hot particles accumulated in the stationary bed. When the fan is turned on the re-fluidization starts in some parts of the bed that are thinnest. This cause fluidization instability dues the bubble appearance and particle back flow toward the air distributor. Thus, downward pulse of a hot mass could drive hot particle into the adjaced windbox. The effect is known as "sifting". The hot particles having some carbon present are adequate ignition source to start the explosion of the combustible gaseous mixture.

The **hot restart problems** provoked the acceptance of new start-up sequence for fluidised bed combustion plants. NFPA of USA has established a rigorous procedure including two step starting process considered by the NFPA's 8504 Committee appeared as a standard in August 1993 (NFPA, 1993). The start-up procedure (Ehrlich, 1995, 1997) concerns a purge procedure, like in the case of suspension-fired boilers, due to the existence of hot ignition sources in the unfluidized bed in the form of red-hot limestone particle and carbon. The **purge procedures** must avoid the accumulation of an explosive fuel/air mixture above the bed that can contact with the ignition sources. It is consequence of two steps including the purging of the furnace space above the slumped bed without any disturbance fluidization. The second step concerns a re-fluidization. If the average bed temperature is sufficiently high to ignite the fuel the main fuel flow may be supplied into the furnace directly, after a short outage. If the bed temperature is not enough to start the combustion, the purge should

continue to clean the air supply ducts of any explosive mixture and then the bed re-heating by the warm-up burners must start.

FLUIDISED BED COMBUSTION GASEOUS PRODUCTS

Emissions of Gases from Coal Combustion

Emissions of gases are attributes of all the combustion processes. Four main parameters affect the completeness of the combustion process and therefore the destruction of the waste (Buron, 2000): the temperature, the residence time in the furnace, the turbulence (air/waste) and the size of the waste particles. Despite the technical problems commented above, controversy surrounds the combustion of hazardous wastes burned in fluidised bed combustion units often contain toxic organic chemicals, heavy metals and chlorine, trace amounts of which may be released into the atmosphere in the form of emissions.

Process maintenance impact on the gaseous emissions: The *limitation of emissions of SO₂ and NO_x* has been intensively investigated during the earlier years of research on fluidised bed combustion (Bramer, 1995) by adding limestone to the bed. In later years, the efforts are focussed to reduce NO_x in accordance with the acid rain problematic. The emission of SO₂ and NO_x are influenced of many parameters of the combustion process (Bramer, 1995):

- Unstaged combustion (USC) of coal:
 - *Bed temperature in unstaged combustion.* Optimal sulphur capture temperature is about 850 °C.
 - *Freeboard temperature.* The experience of Twente University indicate that the NO_x profiles in the freeboard zone are influenced of gas temperature and the type of cooling
 - *Limestone addition and limestone type.* The incomplete conversion of the limestone to CaSO₄ increases the limestone combustion but the Ca/S ratio > 2 leads to practically constant sulphur retention (~ 90 %)
 - *Sorbent particle size.* The finer particles have approximately 10 % better sulphur retention compared to coarse limestone (data of TNO with Twente combustor and Carmeuse Engis limestone).

- Coal type. The calcium content in coal is very effective in reducing SO₂ emissions. For example a combustion of German brown coal with Ca_N/S = 2 reaches 90 % retention without adding limestone (Bramer, 1995).
- Fly ash recycling. This is relatively simple measure increasing the combustion efficiency of less reactive coals (Valk and Bijvoet, 1995).
- Fast fuel feed at the bed bottom (not at the bed surface). The sludge really enters into the hottest part of the bed (Corella et al, 1988, Corrella and Toledo, 2000). This is relatively successful measure for reduction of VOCs emission during sewage sludge combustion. The time for the pyrolysis/gasification of the sludge, as first step of the overall incineration mechanism is low and the yield as VOCs is lower that when feeding is performed at the bed surface.
- Staged combustion (SC) of coal: As the standards established after the middle of 1980's with respect the NO_x emissions became more severe: NO_x < 200 mg/nm³ (Bramer, 1995) the fluidised bed combustion's under oxidizing conditions are not capable to meet the requirements. The lower levels in fluidised bed combustion can be achieved by staged combustion. The experience of Twente University in the 4 MW combustor of TNO on staged combustion impact on SO₂ and NO_x emissions focuses to the main process parameters:
 - Effect of the primary air ratio (PAR). The lowering of the primary air ratio (Bramer, 1995) is an effective way to reduce NO_x emissions (by 30 to 50 % when PAR decreased from 1.1 to 0.6). The freeboard temperature has relatively large effect on NO_x emissions.
 - Effect of the bed temperature. In contrast to USC the increase of the bed temperature and related to it freeboard temperature reduces the reactions forming NO_x.
 - Bed material particle size. The finer coal particles lower NO_x emissions (Twente experiments at Ca/S = 1.5, total air ratio = 1.2 and T_B=850 °C)
- Urea Injection. The injection of reagents is the so-called secondary measure for reducing emission. Twente University experience (Bramer, 1995) shows that the emissions values of 200 mg/m³ is reached at molar ratio urea/NO_x = 2. The

freeboard of AFBC has appropriate reaction conditions for reduction of NO_x by urea injection. The urea is as effective as ammonia used for the same purpose.

- Periodically changing the oxidizing and the reduction conditions in PFBC. Zevenhoven et al. (1999) tested how stable CaSO₄ is in the gas atmosphere that periodically was changed from oxidizing to reducing conditions and *vice versa* in a temperature range from 850 up to 950°C. The results indicate that at 1 bar, CO₂ + H₂ give a higher reduction of CaSO₄ than CO at the same total concentrations. At 15 bars, the decomposition and the sulphation rates are lower, with CO and small amount of H₂ as the reducing species. The study sets up new questions concerning the sulphur capture with limestone in PFBC. According to Zevenhoven et al. (1999), it could suggest that a temperature optimum for sulphur capture exist for PFBC as well as for AFBC.
- Limestone effect on the gaseous emissions. The desulphurization effect of the limestone particles depends mainly on the pore size distribution rather than the specific surface area (Naruse et al., 1999). Its desulphurization efficiency is about 38 %. The common practice in both the bubbling and the circulating fluidised bed combustors are operations within the temperature range from 1073 to 1173 K defined mainly by the sintering properties of the fuel and the fact that upon these conditions the limestone can be calcined and sulphurized optimally. Really, the limestone particles are fed to the combustor extensively (Naruse et al., 1999). The reason is the plugging of the pores of CaCO₃ due to CaSO₄ formation and low utilization efficiency of CO (Hartman et al., 1974). As a result the amount of the ash formed increase enormously that leads to consequent effect of hot lime burn injuries (see further comments on solids emissions). Moreover, the CO₂ concentration in the atmosphere increases. Looking for more effective desulphurization agent Naruse et al. (1999) found out that wasted sea-shell had desulphurization efficiency of about 70% and attained during of about 30 h after the desulphurization operation. This gives an opportunity for replacing the limestone, since many kinds of shells are clarified as industrial wastes with amounts of CaCO₃. However, this is a solution for when such shells can be derived as a non-expensive industrial by-product. This is a fruitful idea for looking alternatives of the limestone as a desulphurization agent.

Emissions of Gases from Co-Firings of BioFuels

Biomasses burned in fluidised bed combustion: These are mainly woods and fibrous sludges containing a lot of nitrogen. The waste burnt produces harmful substances that depend on both the *combustion process, the fuel content of trace component* such as nitrogen, sulphur and chlorine and *the operating conditions of the furnace*. Similar results have been obtained by sewage sludge incineration (Lewis and Haug, 1999). In both studies air-staging techniques, suggested initially for coal (Lyngfelt, 1998), have been applied to minimize the NO_x emission hazard:

- Three (3) different air-staging cases tested for nitrogen emission minimization (Amand and Leckner) without limestone supply in an inert silica bed with excess air-ratio up to 1.23
 - Reversed air-staging without secondary air injection in the combustion chamber and air-ratio of 1.05 (Lyngfelt, 1998)
 - No air staging. All the air is introduced in the combustion chamber at air-ratio of 1.23
 - Severe air staging with increased amount of air in the cyclone outlet at a combustor air-ratio of only 0.94.
- Four (4) stage process (Lewis and Haug, 1999):
 - Stage 1: Sub-stoichiometric fluidized bed operation at a nominal 30% stoichiometric air-ratio (SAR) in a bubbling sand bed.
 - Stage 2: Sub-stoichiometric zone operating at nominal 80% SAR and a nominal residence time 2 seconds approximately.
 - Stage 3: Stoichiometric zone operating at a nominal 100 % SAR and a nominal residence time 2-2.5 seconds to complete the gas phase reduction of NO_x.
 - Stage 4: Excess air zone (afterburner) operating at a nominal 135 % SAR to minimize CO and unburned hydrocarbons.

Both examples show that the more efficient combustion more efficient hazard minimization in the emissions.

Table 2. Troubles of the fluidised bed combustion and the consequent potential hazards (arranged by the present author) - Some examples

| Fuel | | Combustion Process | | Fluidised bed type and Safety Measures | | Reference(s) |
|------|---|---|---|--|---|---|
| Coal | Co-firing waste or Coal admixtures | Troubles related to: | Hazard | Fluidised bed type | Safety Measure | |
| | No | Erosion & abrasion | Failure of cooling devices | All types except PFBC | Surface coating | Maude (1992) Leckner & Hogberg (1983) Leckner et al. (1985) Johnson & Leckner (1986) |
| | Alkali Vanadium Low-melting Alumino-silicates Iron Calcium or Magnesium | Fouling & Corrosion | Cooling device failure Uncontrolled bed temperature increase Sintering & Slagging | All types except PFBC | Fuel preliminary treatment Fluid bed temperature control | Bryers & Kramer (1977) |
| | Fiber sludge with high moisture content | Poor combustion Lower combustion | Increasing emissions | All types except PFBC | Fluid bed temperature control | Linderoth (1989) |
| | Fiber Sludge | Release of fuel volatiles due to insufficient burnout | High emissions of CO High emissions of HCl and SO ₂ High levels of N ₂ and NO _x High emissions of NH ₃ | CFB | Air-staging | Amand & Leckner |
| | Barks with high moisture content | | | | | Kraft & Orender (1993) |
| | Toxic liquids (TNT) | Fouling at the walls | Sintering Explosion of sintered waste | AFB | Keep the temperature < 700 °C | Grubor et al. (1999) |
| | Effluents from bleach-kraft mill | Fouling | Stack emissions of HCl and chlorinated organic compounds | All types except PFBC | Increasing the melting temperature through formation sodium titanates | Zeng and von Heiningen (2000) |

Emissions of Gases from Co-Firings of Shredded Wastes, Sewage Sludges and Household wastes

The "shredded" waste (Modigell et al., 1998) is mixture itself from vehicle utilization containing plastics and halogeneous hydrocarbons, ferrous - and non-ferrous metals and other inorganic metals. The shredded wastes as well as the sewage sludges are wastes with high contents of heavy metals and chlorine (Modigell et al., 1998). Because of low caloric values of these wastes the co-firing is usually performed.

The municipal solid wastes (MSW) become complex biofuels that are attractive for material recovery and reuse, combustion with energy recovery and composting. The increasing amount of paper and packaging cartons as components of MSW changes the performances of the combustion processes. The main problem arises from increased emission of NO_x (Sorum et al., 2001), chlorine and PAH (due to plastic packaging).

Heavy metal volatilization from shredded wastes and industrial sludges (e.g. Hg) usually condense in the cold parts of the flue gas cleaning equipment during the hot dust removal. The results of Modigell et al. (1998) shows that Cd and Hg completely evaporate during fluidized bed incineration and only ~ 12% of Pb remains solid. All the other heavy metals are solids under these conditions (850-870°C in the combustion chamber), only small amounts of Cu and Zn (<1%) are converted into the gaseous phases. Only slightly, decrease in temperature of 20°C leads to capture of ~44% Pb in the cyclone. The specific conditions of shredded waste fluidised bed combustion cause volatilization of Cd, Hg and Pb in metallic or chloridic form, while Cu and Zn are most as chlorides with very low partial pressures, whereas the major fractions are solids as oxidic substances. Thus, *two groups of heavy metal could be identified: volatile heavy metals* (Cd, Pb and Hg), which partially condense in the cyclone and **non-volatile heavy metals** (Cr, Ni, Zn) and **low-volatile Cu**. The increase of the bed temperature (~890°C) (by additional input of fuel) improves Pb volatilization and the total Pb is converted in the gas phase. Generally, a significant heavy metal accumulation in the dust filter ash has been observed (Modigell et al., 1998). The cyclone operates as a second reaction chamber where the heavy metal adsorption on the dust particles (e.g. the solids residues).

The problem is most important in the case of fluidised bed incineration of doped sludge (heavy metals in the form of metallic salts). Additions of sources of organic chlorine (PVC particles) in the combustion blend (Corrella and Toledo, 2000) affect the metal partitioning between the gaseous emission and the ash due to reaction of the heavy metals and yields of various metal chlorides. These experiments confirm the idea conceived above (see also the discussion on mercury emission).

The mercury emissions with respect to the efficiency of the cleaning equipment upon conditions of German fluidised bed sludge incinerators (13 stations) have been reported by (Saenger et al., 1999). In the flue gases of sewage sludge incinerators (depending on other gaseous components), a part of the elemental mercury is not oxidized. Secondly, when the

flue gas is cooling down mercuric and mercurous compounds may decompose to elemental mercury. Elementary mercury is presented mainly in the electrostatic filters. Elementary mercury in contrast to the ionic one is nearly insoluble in water and thus causes the wet scrubbers ineffective for its capture. The measurements of Saenger et al. (1999) correlated the amount of the elementary mercury with the amount of chlorine in the sewage sludge. The increasing chlorine content yields in more oxidized form of the mercury and the amount of the elementary. With very low chlorine content of the sludge elementary mercury escape in the flue gases reached up to 90%. The later fact indicates again, that *the chlorine content of the fuel* could be used as a factor controlling the heavy metal volatilization as well as *a risk-reducing factor*.

The attempt to apply adsorption (adsorbent injection into the flue gas or the use of fixed bed absorbers) was considered. The mercury is captured due to physical adsorption or chemisorption. The active carbon tests of Huang et al., (1996) indicate that lower temperatures and finer adsorbent grains are the favourable conditions for mercury capture. Chemical treatment of the active carbon with CaCl_2 (Matsumura, 1974) can increase its removal capacity (20-160 times) with respect to elementary mercury.

Saenger et al. (1999) suggested that the high sulphur content of the sewage sludge (and the resulting high SO_2 amount in the flue gas) could lead to impregnation of the active carbon (or often-used cheaper coke) with sulphur during the combustion process. The later requires adsorbent recirculation as process operation. Saenger et al. (1999) in station of Duren (Germany) have tested an alternative to the activated carbon. The mercury removal by its reaction with selenium to mercury selenides replaces the active carbon by a mineral matter (>90 wt % SiO_2 , Al_2O_3 , TiO_2 , FeO , MgO) impregnated with up to 5% metallic selenium. The removal efficiency was about 90 %.

Dioxins emissions. They are principle components of the emission gases from combustion of plastics (Franke et al., 1999, 2001) and other chlorine-containing fuels (Gerasimov, 2001). Different measures reducing the emission have been applied:

- ***Operation maintenance measures.*** Reductions of gas velocity (Fujiwara et al., 1995), control of the waste feed rate (Koyama et al., 1995) as well as secondary air injection (Koyama et al., 1995) were tested.

- **Bed composition.** The introduction of porous particles as Galleonite 251 or activated bauxites has been tested as approach to minimize the risk of dioxins emissions from combustion of polystyrene pellets (Franke et al., 1999). The porous solids capture the volatile matters and suppress their rapid evolution. The experiments of Franke et al. (1999) indicate that almost 50 % of the fed carbon rests on the porous particles thus increasing the residence time and improving the carbon conversion and as consequence minimizing the risk of hydrocarbon emissions.

PAH emissions. The combustion plastics (polystyrene, polyethylene, and polypropylene) as elements of municipal waste are the main source PAH (Wheatley et al., 1993). The coal combustion is a relatively clean process (Levendis et al., 1996) compared to the tire combustion where 10-100 times higher amounts of PAH exist. Coal-tire blends (Mastral et al., 2000) are attractive combustion blends due to the higher caloric power (Ekman et al., 1996) and the possibility to reduce the adverse environmental effects due to non-biodegradability and impossibility to recover their original components. In the case of coal-tire blends, several factors could increase the PAH emissions:

- **Incomplete combustion** (Mastral et al, 2000) since the PAH emission can be minimized working at high combustion efficiencies (Fangmark et al., 1993). Minimum PAH emission variations have been detected with 1/1 coal-tire blends that were minimized by increasing the combustion temperature (Mastral et al, 2000). However, for high volatile fuels the strong escape of unburnt gas from the bed into the freeboard (see the previous comments) (Scala, 1999; Scala et al., 2001) could lead to insufficient combustion (depending on the oxygen supply) and strong PAH emissions.
- **A significant amount of volatiles escaped from the burning bed** when high volatile fuels are combusted. This means that a potential measure is *the control of the combustion blend content or higher freeboard zone with a sufficiently high combustion temperature*. The later requires compromises in the fluidised bed design and operating modes.

FLUIDISED BED COMBUSTION SOLIDS BY-PRODUCTS

Emissions as Solid residues of fluidised bed combustion

Ash formation: The second principle by-product generated by the fluidised bed combustion. All the AFBC residues differ principally from solids residues of conventional pulverized coal

combustion ash (Mulder et al., 1995), so called PCC ash. It is inert particulate material composed mainly by unburned carbon, salts and metals. It is usually collected at the bottom of the combustion chamber (bottom ash) and in the air pollution separators. Thus, the ash is often a hazardous waste (Buron, 2000). Moreover, as mentioned above, the overloading of limestone could lead to hazardous ash containing quicklime, causing potential dangers when in contact with water or wet materials. The removal causes problems and consequent hazards due to operational characteristics of:

- Baghouse problems:
 - Insufficient characteristics of the bag material (Lewis and Haug, 1999).
- Cyclone and cyclone ash system related to cyclones plugs due to low capacity (Nilsson and Anderson, 2001)- comments on Vartan PFBC plant near Stockholm.
- Poor cyclone operation resulting on enormously high dust loading to the gas turbine and erosion problems - Escatron PFBC Plant (Spain) (Nilsson and Anderson, 2001)
- Hotgas ceramic filters (tubular type) - Wakamatsu PFBC Plant (Japan) (Nilsson and Anderson, 2001)

Health problems of AFBC solids residues are related to the toxicological and genotoxicological properties of the fly ash (Mulder et al, 1995). According to Vink (1985), many of the organic compounds in the fly ash have been determined to be carcinogenic. They hardly present in the in fly ashes and in the stack ashes in low concentration only (see below).

Heavy metals release: The heavy are components of wastes, which are very complex material systems containing a broad spectrum of noxious and toxic substances. An important intention in fluidised bed combustion technology is the inertization or separation of heavy metals in enable remaining ashes to be applied as building material (asphalt filers, sand-lime bricks, artificial gravel (Mulder et al., 1995) or applications in agricultural lands (Stout et al, 2001) (see below).

Saenger et al. (1999) reported that feeding of limestone in the combustion chamber to remove the sulphur increased up to 50% the amount of the mercury in the ash since the limestone can adsorb it. The adsorbed mercury detected was less $0.01 \text{ mgHg/ (kg dry ash)}$ and presented less than 0.1% of the total mercury input.

Environmental problems: Mainly they are addressed to the of the fly ash contaminations of surface and ground water (Mulder et al, 1995). Despite the increasing investigations on potential environmentally acceptable applications (see below), large quantities have to be disposed. The fly ash transport in a slurry form is technically preferable, but is environmentally less acceptable due the possibility to release toxic elements by the transport water. The Israeli experience with South-African and Colombian low-sulphur coals (Sheps-Pelgeg and Cohen, 2001) indicates very basic reaction (up to pH 13) of the ash with water. Furthermore, the most of the trace metals are dissolved in the groundwater, such as chromium (in its hexavalent form) that is carcinogenic. The later is addressed to specific criteria for ash disposals that could be concerned as *risk minimizing with respect to the potential leaching of poisoning trace metals by the groundwater*.

The **agricultural land disposals** of some fly ashes are mainly related to disposals as fertilizers. The **ashes** as AFBC residue components should be divided in four groups (Stout et al, 2001):

- **Lime** (e.g. quicklime) that is mainly a mixture of CaO and MgO. This is *highly caustic material* that can severely damage unprotected skin, lungs and eyes when exposed to water due to resulting exothermic reaction.
- **Essential plant nutrients** are those containing Ca, S, Mg, K and P. The metals as Fe, Mn, Mo, B, Cu and Zn are micronutrients existing in the ashes as oxides. This group does not cause hazards.
- **Heavy metals**. They exist probably as oxides. They are of concern, especially Cd, since they cause serious metabolic problems in animals and humans when they accumulated in the food chain. Compared to the sewage sludge AFBC residues contain very low levels of heavy metals. The oxide form of heavy metal in AFBC residues renders them much less available to plant than the organic forms in sewage sludge. Thus, the ash immobilization of the heavy metals *reduces the risk and there is no hazard* to animals consuming the plants.
- **Phytotoxic elements**. Levels of *Aluminium* in AFBC residues are slightly less than those existing in soils. Aluminium can be phytotoxic when it is solubilized at low pH (< 5.0). However, *Aluminium* toxicity is easy corrected by liming, so it is *minor hazardous concern* of AFBC residues.

- In addition to potential hazards to human, AFBC residues can be extremely corrosive to application agriculture equipment (Stout et al, 2001).

CONCLUSIONS

The risk-oriented concept in fluidised bed combustion description developed here collects well-known facts available in the literature. The point of view tries to stress the attention on all the stages of fluidised bed combustion technologies that can cause potential hazards and risk. All the steps from the fuel preparation through the combustion process up to the ash disposal can create hazards. In most of the cases the risk minimization is incorporated in the particular combustion technology (e.g. sorbent injection and staging combustion for examples), while in the other situations there are inherent hazards such as dust explosion, metal wastage and consequent system element failures, toxicity of the ash, etc.

The attempt of the present author is not oriented only toward a complete collection and description of the risk-related elements of fluidised bed combustion. More important solution that needs the efforts of many experts is the evaluation and weighting of the safety problems in fluidised bed combustion subsystems and entire plants. I think that this a challenging direction for further investigations.

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