

# Operating experience of low grade fuels in circulating fluidised bed combustion (CFBC) boilers

Ian Barnes

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IEA Clean Coal Centre  
14 Northfields  
London SW18 1DD  
United Kingdom

Telephone: +44(0)20 8877 6280

[www.iea-coal.org](http://www.iea-coal.org)

## Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

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## Abstract

Although subject to sometimes quite considerable short-term variations, the long term trend for the price of coal, along with other primary energy resources, is upwards. The need to protect the environment has resulted in a reduction in low-cost disposal routes for many waste materials (eg coal processing wastes and sewage sludge) and this has provided a driver to develop alternative ways of dealing with these arisings. Finally, the growth in the use of carbon-neutral renewable technologies has spurred interest in the use of biomass for energy production; on a stand-alone basis and in combination with coal.

These three factors are largely responsible for the use of the so-called 'low value fuels' for energy generation. One particular technology stands out as being particularly well suited to utilising low value fuels, circulating fluidised bed combustion (CFBC).

This report sets out examples of the range of low value fuels, their reserves and properties, with particular emphasis on coal-derived materials, the issues for CFB plant in utilising these fuels and selected examples of manufacturer and operator experience with purpose built, or modified CFB plant. Finally an up-to-date global inventory of CFB plants using a range of low value fuels is presented.

## Acronyms and abbreviations

API	American Petroleum Institute
B&W	Babcock and Wilcox
BFB	bubbling fluidised bed
C&D	construction and demolition
C&I	construction and industry
CFBC	circulating fluidised bed combustion
CV	calorific value
EIS	Environmental Impact Statement
FAO	Food and Agriculture Organisation (of the United Nations)
FBAC	fluidised bed ash coolers
FBHE	furnace bottom heat exchanger
Gt	gigatonnes
JV	joint venture
LHV	lower heating value
Lic	licence
MCR	maximum continuous rating
MDC	multi-cyclone dust collector
MJ	megajoule
MSW	Municipal Solid Waste
MWe	megawatt electrical
MWth	megawatt thermal
PCC	pulverised coal combustion
PET	polyethylene terephthalate
PSD	particle size distribution
RAC	rotary ash cooler
RDF	refuse-derived fuel
RDZ	reduced diameter zone
SCR	selective catalytic reduction
STP	standard temperature and pressure
WEC	World Energy Council

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## 1 Introduction

Although subject to sometimes quite considerable short-term variations, the long term trend for the price of coal, along with other primary energy resources, is upwards. The need to protect the environment has resulted in a reduction in low-cost disposal routes for many waste materials (eg coal processing wastes and sewage sludge) and this has provided a driver to develop alternative ways of dealing with these arisings. Finally, the growth in the use of carbon-neutral renewable technologies has spurred interest in the use of biomass for energy production; on a stand-alone basis and in combination with coal.

These three factors are largely responsible for the use of the so-called 'low value fuels' for energy generation. One particular technology stands out as being particularly well suited to utilising low value fuels, circulating fluidised bed combustion (CFBC).

This report sets out examples of the range of low value fuels, their reserves and properties, with particular emphasis on coal-derived materials, the issues for CFB plant in utilising these fuels and selected examples of manufacturer and operator experience with purpose built, or modified CFB plant. Finally an up-to-date global inventory of CFB plants using a range of low value fuels is presented.

## 2 Low grade fuels

### 2.1 Overview

The term 'low grade fuels' is generally used to describe materials that have an energy content that may be recovered by direct (eg combustion) or indirect (eg gasification) processes, but where that energy content is significantly lower than the range expressed in normal fossil fuels (oil, gas and coal). The lower energy content may be a consequence of low inherent potential in the organic material, or by the 'dilution' of the carbonaceous material by mineral matter and water. Additionally, the fuel may be considered low grade by virtue of having high concentrations of pollutant precursors such as sulphur. That said, some low grade fuels, such as waste plastics, may have an intrinsically high energy content although they are most frequently encountered in a diluted form such as in refuse-derived fuel (RDF).

Despite these drawbacks, low grade fuels can be a valuable resource and are increasingly exploited in combination with coal, or separately. Low grade fuels may be attractive for a number of reasons particularly in having a sufficiently low cost that justifies their use. Also, they may also otherwise be considered as waste materials that have a relatively high disposal cost and this cost can be offset or eliminated by using that waste for energy generation.

The range of low grade fuels, sometimes referred to as 'opportunity fuels' is vast. To illustrate the scope of materials that fall into this category, Outotec (2015) has published a list of materials that have been evaluated for energy generation (Table 1).

**Table 1 Opportunity fuels evaluated for energy production (Outotec, 2015)**

<b>Agricultural</b>	Peach wood	Paper sludge
	Pear wood	Oil soaked clay
Alfalfa seed straw	Peat	PET/Glycol liquid
Almond brush	Pecan shells	Petroleum tanker sludge
Almond shells	Pistachio shells	Petroleum coke
Almond wood	Pistachio wood	Polyolefins
Apple wood	Plum wood	Sontara
Apricot wood	Poultry derived fuel	Tyre derived fuel
Barley straw	Prune pits	Unburned fuel
Bean straw	Prune wood	
Cherry pits	Race track shavings	<b>Municipal waste</b>
Chicken litter	Race track straw	
Citrus trees	Rice hulls	Refused derived fuel
Coffee grounds	Rice straw	Wastewater treatment sludge
Corn cobs	Safflower stalks	
Corn kernels	Sunflower hulls	<b>Wood</b>
Corn stalks	Swine solids	
Cotton gin wastes	Tobacco sludges	Bark
Cotton seed hulls	Tomato pomace	Hardwoods
Cotton stalks	Walnut shells	Railroad ties
Cow manure	Walnut wood	Saw dust
Cubed garlic	Wheat midds	Softwoods
Fig culls	Wheat straw	Zinc borate OSB waste
Fig wood		Board plan waste
Garlic and onion skins	<b>Industrial waste</b>	Planer shavings
Grape canes		Slander dust
Grape pomace	Grease, scum and screenings	Slash
Grape scaffolds	Cardboard sludge	Urban wood waste
Grass straw	Auto shredded residue	Woodex pellets
Lignin cake	Cellulose absorbent	
Manure + wheat straw	Carpet scraps	<b>Fossil fuels, etc</b>
Nectarine wood	Char	Anthracite
Oat straw	Cellulose acetate	Coal dust
Olive pits	Distillation bottoms	Subbituminous
Orange peel and pulp	Charcoal	Bituminous
Paunch manure	Hospital waste	Lignite
Peach pits	Dried paper sludge	Sulphite liquor

The principal low grade resources worldwide that are available in sufficient quantity for sustained commercial exploitation include: biomass, peat, oil shale, oil sands, coal mill rejects, coal washery rejects, lignite and brown coals, petroleum coke, wood and fibre residue, refuse-derived fuel, plastics, sewage sludge and high chlorine and high sulphur coals. The following sections outline the properties of these materials and the approximate size of their reserves or annual arisings, where known.

## 2.2 Biomass

Although a low grade fuel as defined in the section above, biomass has attracted very significant attention as a resource over the past twenty years owing to its carbon-neutral delivery of energy. Biomass may be defined (Biofuels Association of Australia, 2015) as the biological material from living or recently living organisms such as wood, waste materials, gases and alcohol fuels. Biomass is commonly plant matter that is grown specifically in order to produce electricity or to produce heat. The primary components of biomass are carbon, hydrogen and oxygen. Nitrogen and small quantities of other atoms, including alkali, alkaline earth and heavy metals can also be found in biofuel resources. The industrial use of raw biomass materials for the production of pulp, paper, tobacco, pig iron so on, generates by-products such as bark, wood chips, black liquor, agricultural residues, which can also be converted to bioenergy. These by-products are considered further in other sections below. Biomass excludes organic materials such as fossil fuels which have been transformed by geological processes into substances such as coal or petroleum.

The global resource of biomass can be difficult to estimate since issues of sustainability and incentives for the agricultural development of biofuels, possibly over food production, are fundamental to defining the scope of supply. These issues have been discussed in depth by Adams (2013). Recent estimates of biomass availability by the World Energy Council (2013) have been arrived at by considering the primary sources to be wood (natural forests) and agricultural crop production.

More than half of the world's total forest area is located in five large forest-rich countries – the Russian Federation (809 million ha), Brazil (520 million ha), Canada (310 million ha), the USA (304 million ha), and China (207 million ha). In 2011, the largest wood fuel producers were India, China, Brazil, Ethiopia, and Nigeria.

According to the FAO Statistics (2013), approximately 1.5 billion ha, corresponding to about 12% of the world's land area, is used for crop production. If permanent meadows and pastures are included, the total agricultural land area increases to about 5 billion ha. Accessible agricultural land is very unevenly distributed among regions and countries, with approximately 90% in Latin America and Sub-Saharan Africa. Therefore expansion of agricultural land for producing biofuels has to take into account factors such as food supplies for an increasing population, water use, biodiversity, and agro-economics, which affect the future biofuel potential. Currently, the share of agricultural land to produce biofuels is less than 0.01% (0,05 million ha) a doubling of scale since 2005 mainly due to an increase of land area under oil crops, maize, as well as sugar cane and root to produce biofuels (FAO 2013). The use of sugar for biofuels is the highest (15% of total use) while the use of vegetable oils (5% of total use) and cereals (3% of total use) is still relatively low.

The many and varies sources of biomass, and the wide range of conditions under which the plant material grows means that the properties of the potential fuel can vary very significantly. Table 2 below, sets out the properties relevant to energy production for a range of biofuel feedstocks.

<b>Table 2 Proximate analysis, ultimate analysis and heating values of selected solid biofuels (Moghtaderi and Ness, 2007)</b>								
	<b>Alfalfa stems</b>	<b>Wheat straw</b>	<b>Rice hulls</b>	<b>Rice straw</b>	<b>Switch-grass</b>	<b>Sugar cane bagasse</b>	<b>Willow wood</b>	<b>Hybrid poplar</b>
Proximate analysis, %, dry fuel								
Fixed carbon	15.81	17.71	16.22	15.86	14.34	11.95	16.07	12.49
Volatile matter	78.92	75.27	63.52	65.47	76.69	85.61	82.22	84.81
Ash	5.27	7.02	20.26	18.67	8.97	2.44	1.71	2.70
Ultimate analysis, % dry fuel								
Carbon	47.17	44.92	38.83	38.24	46.68	48.64	49.90	50.18
Hydrogen	5.99	5.46	4.75	5.20	5.82	5.87	5.90	6.06
Oxygen, by difference	38.19	41.77	35.47	36.26	37.38	42.82	41.80	40.43
Nitrogen	2.68	0.44	0.52	0.87	0.77	0.16	0.61	0.60
Sulphur	0.20	0.16	0.05	0.18	0.19	0.04	0.07	0.02
Chlorine	0.50	0.23	0.12	0.58	0.19	0.03	<0.01	0.01
Ash	5.27	7.02	20.26	18.67	8.97	2.44	1.71	2.70
Elemental composition of ash, %								
SiO <sub>2</sub>	5.79	55.32	91.42	74.67	65.18	46.61	2.35	5.90
Al <sub>2</sub> O <sub>3</sub>	0.07	1.88	0.78	1.04	4.51	17.69	1.41	0.84
TiO <sub>2</sub>	0.02	0.08	0.02	0.09	0.24	2.63	0.05	0.30
Fe <sub>2</sub> O <sub>3</sub>	0.30	0.73	0.14	0.85	2.03	14.14	0.73	1.40
CaO	18.32	6.14	3.21	3.01	5.60	4.47	41.20	49.92
MgO	10.38	1.06	<0.01	1.75	3.00	3.33	2.47	18.40
Na <sub>2</sub> O	1.10	1.71	0.21	0.96	0.58	0.79	0.94	0.13
K <sub>2</sub> O	28.10	25.60	3.71	12.30	11.60	4.15	15.00	9.64
SO <sub>3</sub>	1.93	4.40	0.72	1.24	0.44	2.08	1.83	2.04
P <sub>2</sub> O <sub>3</sub>	7.64	1.26	0.43	1.41	4.50	2.72	7.40	1.34
CO <sub>2</sub> /other	14.80						18.24	8.18
Undetermined	11.55	1.82	−0.64	2.68	2.32	1.39	8.38	1.91
Higher heating value, constant volume								
MJ/kg	18.67	17.94	15.84	15.09	18.06	18.99	19.59	19.02

It is clear that not only the primary properties (energy and inert content) can vary significantly but also the trace elements that can have important impacts on plant performance and pollutant formation.

## 2.3 Peat

Peat is the surface organic layer of a soil, consisting of partially decomposed organic material, derived mostly from plants, that has accumulated under conditions of waterlogging, oxygen deficiency, acidity and nutrient deficiency. In temperate, boreal and sub-arctic regions, where low temperatures (below freezing for long periods during the winter) reduce the rate of decomposition, peat is formed from mosses, herbs, shrubs and small trees. In the humid tropics, it is formed from rain forest trees (leaves, branches, trunks and roots) under near constantly high temperature (International Peat Society, 2015). Peat may be considered as a low grade fuel intermediate between biomass and geologically older lignitic and brown deposits.

Peatland reserves are most frequently quoted on an area basis because the initial estimate of reserves normally arises through a soil survey or by remote sensing. Even where peat deposit thickness and total

peat volumes are known, it is difficult to quantify the reserves in energy terms because the energy content of in situ peat depends on its moisture and ash content. The organic component of peat deposits has, however, a fairly constant anhydrous, ash-free calorific value of 20–22 MJ/kg and, if the total quantity of organic material is known, together with the average moisture and ash content, then the peat reserve can be expressed in standard energy units.

The estimation of peat resources on a global scale is difficult and data for many countries are imprecise or only partially ascertained. Immirzi and others (1992) and Joosten and Clarke (2002), have estimated world peat reserves as approximately 4 million km<sup>2</sup>, equivalent to 3% of the world's land surface. Most of the world's peatland is in North America and the northern parts of Asia with large areas in northern and central Europe and in Southeast Asia, whilst some are in tropical Africa, Latin America and the Caribbean (Table 3). 85% of the global peatland area is in only four countries, Russia, Canada, USA and Indonesia.

As an intermediate between biomass and lignitic and brown coals, the properties of peat follow a roughly similar trend with peat having a higher moisture and volatile matter content than the coals. Typical properties of a fuel-peat compared with bituminous coal, lignite and wood are given in Table 3 below.

<b>Table 3 General chemical and fuel properties of a range of fossil fuels and wood (Lindström, 1980)</b>				
Chemical composition	Coal	Lignite	Peat	Wood
Carbon (C), wt%	76–87	65–75	50–60	48–55
Hydrogen (H), wt%	3.5–5.0	4.5–5.5	5–7	6–7
Oxygen (O), wt%	3–11	20–30	30–40	38–43
Nitrogen (N), wt%	0.8–1.2	1–2	0.5–2.5	<0.6
Sulphur (S), wt%	1–3	1–3	0.1–0.4	0.02–0.06
Fuel properties				
Volatile matter, wt%	10–50	50–60	60–70	75–85
Ash, wt%	4–10	6–10	2–15	0.1–2.0
Melting point of ash, °C	1100–1300	1100–1300	1100–1300	1350–1450
Bulk density, kg/m <sup>3</sup>	728–880	650–780	300–400	320–420
Effective calorific value of dry, MJ/kg	28–33	20–24	20–23	17–20

## 2.4 Oil shale

Oil shale is a term applied to sedimentary rock that contains solid bituminous materials that can be extracted to yield petroleum-like liquids when the rock is pyrolysed. Oil shale is formed through the deposition of silt and organic debris onto lake floors and sea beds. Over millions of years, heat and pressure transformed the materials into oil shale in a process similar to that thought to give rise to conventional oil. Oil shale generally contains enough bituminous material that it will burn without any additional processing, and it is sometimes known as 'the rock that burns'. Oil shale can be mined and used

as an energy source directly through combustion-based processes, or processed to generate oil by heating it to a high temperature (a process called retorting).

While oil shale is found in many places worldwide, by far the largest deposits in the world are found in the USA in the Green River Formation, which covers portions of Colorado, Utah, and Wyoming. Estimates of the oil resource in place within the Green River Formation range from 1.2 to 1.8 trillion barrels. Not all resources in place are recoverable; however, even a moderate estimate of 800 billion barrels of recoverable oil from oil shale in the Green River Formation is three times greater than the proven oil reserves of Saudi Arabia. Present US demand for petroleum products is about 20 million barrels per day. If oil shale could be used to meet a quarter of that demand, the estimated 800 billion barrels of recoverable oil from the Green River Formation would last for more than 400 years. (Oil Shale and Tar Sands Programmatic EIS, 2015).

Guo (2009) has surveyed oil shale from a number of locations and summarised the respective properties in Table 4 below.

<b>Table 4 Properties of shale oils from various locations</b>									
<b>Location</b>	<b>Specific gravity (API)</b>	<b>Elemental analysis (wt%)</b>					<b>Analysis of distillate (&lt;350), wt% of &lt;350°C cut</b>		
		<b>C</b>	<b>H</b>	<b>O</b>	<b>N</b>	<b>S</b>	<b>Saturates</b>	<b>Olefins</b>	<b>Aromatics</b>
Colorado, USA	0.943 (18.6)	84.90	11.50	0.80	2.19	0.61	27	44	29
Kukersite, Estonia	1.010	82.85	9.20	6.79	0.30	0.86	22	25	53
Stuart, Australia	–	82.70	12.40	3.34	0.91	0.65	–	–	–
Rundle, Australia	0.636 (0.91)	79.50	11.50	7.60	0.99	0.41	48	2	50
Irati, Brazil	0.919 (22.5)	84.30	12.00	1.96	1.06	0.68	23	41	36
Maoming, China	0.903	84.82	11.40	2.20	1.10	0.48	55	20	25
Fushun, China	0.912	85.39	12.09	0.71	1.27		0.54	37	25

## 2.5 Lignite and brown coals

During the process of coal formation the proto-coal transforms over time under heat and pressure when a concentration of carbonaceous material results. The degree of change from proto-coal through peat to anthracite is referred to as the rank of the coal. The lowest rank coals that are exploited commercially are the lignitic and subbituminous coals, also known as brown coals. These low rank coals are also considered to be low grade fuels because of their high moisture content and low heating value and as a consequence they usually require specific technologies for their successful use in power generation and other industrial processes.

In common with other relatively low value fuels, there is no free-market mechanism for low rank coals used in power generation. This is because their low energy content makes transport uneconomic over longer distances. The cost of a low rank coals such as lignite, per unit of energy including transport, would be higher than for hard coal, which is its main competitor. For this reason, it is common to build lignite-fired power plants adjacent to lignite mines. A power plant and surface mine then form a single economic entity. Lignite is usually transported by dedicated infrastructure, typically a conveyor belt, and delivered directly to the nearby power plant (Katambula and Gupta, 2009).

Lignitic and brown coals have been estimated to account for approximately 50% of global coal reserves, with as much as 50% of those reserves being economically recoverable (Mills, 2011). Unlike the higher rank 'hard coals', the major deposits are concentrated in just seven countries: Russia, the USA, Australia, Germany, Greece, the Czech Republic, and Serbia.

Recent estimates of lignitic and brown coal reserves are given in Table 5 (WEC, 2013).



**Table 5 Low grade coal: proved recoverable reserves at end-2011 (Mt)**

	Subbituminous	Lignite	Total
Albania		794	794
Argentina	550		550
Australia	2100	37200	39300
Austria		333	333
Belarus		100	100
Bosnia-Herzegovina		2369	2369
Brazil	6630		6630
Bulgaria	190	2174	2364
Canada	872	2236	3108
Central African Republic		3	3
Chile	155		155
China	33700	18600	52300
Czech Republic		871	871
Ecuador		24	24
Germany		40500	40500
Greece		3020	3020
Greenland	183		183
India		4500	4500
Indonesia	28017		28017
Italy	50		50
Japan		10	10
Kazakhstan		12100	12100
Korea (Democratic Peoples' Republic)	300		300
Korea (Republic)	126		126
Kyrgyzstan		812	812
Laos		499	499
Macedonia (Republic)		332	332
Malawi	2		2
Mexico	300	51	351
Mongolia		1350	1350
Morocco		40	40
Nepal	1		1
New Zealand	205	333	538
Nigeria	169		169
Norway	5		5
Pakistan	166	1904	2070
Philippines	170	105	275
Poland		1287	1287
Portugal		33	33
Romania	1	280	281
Russian Federation	97472	10450	107922
Serbia		13400	13400
Slovakia		260	260
Slovenia	24	199	223
Spain	300	30	330
Thailand		1239	1239
Turkey		8380	8380
Ukraine	16577	1945	18522
USA	98618	30176	128794
Uzbekistan		1853	1853

Lignitic and subbituminous coals are characterised by a high moisture content, and frequently a high mineral matter (ash) content. The presence of high percentages of inert materials reduces the recovered energy content of the coals 'as-fired'. Additionally, these coals may have a high sulphur content with implications for gaseous emissions, and chemical species such as alkali metals that can give rise to problems of slagging and fouling within a boiler.

The properties of lignitic and subbituminous coals can vary significantly, depending on the geology of the region in which they were formed. Zhu (2012) collated data on these coals from a number of sources to set out the variability than can be expected (Table 6).

<b>Table 6 Properties of lignites from different countries (Zhu, 2012)</b>				
<b>Country</b>	<b>Moisture content, % as-mined</b>	<b>Ash content, % db</b>	<b>Sulphur content, % db</b>	<b>CV, MJ/kg LHV</b>
Australia	46–70	1–7.4	0.28–1.74	9.8–15.2
Bulgaria	23–56	20–48	0.9–7.0	6.7–15.0
Canada	32–41	8–25	0.3–1.1	10.6–17.0
Chile	10	14.4	0.9–1.0	
China	19.6–50	8.6–40	0.2–4.7	9.0–13.3
Colombia	17	25	0.7	16.8
Czech Republic	9.6–55.0	10–40	0.37–6.0	9.0–20.0
Germany	40–63	1–53	0.15–3.6	6.7–15.0
Greece	41–65	3.5–25	0.3–1.0	5.0–11.0
India	6–55	5–48	1.5–4.5	10.0–12.0
Indonesia	35–75	1–15	0.1–2.4	<17.4
Kosovo	35–50	12–21	<1.0	5.8–8.4
Laos			0.7–1.1	8.0–10.0
Malaysia	15–25	4–18	0.05–0.3	4.5–6.2
Myanmar	9.7	8.9	0.93	
New Zealand	38.0–45.0	5.0–30.0	0.3–4.6	13.0–19.0
Philippines	55–60	15	0.3–0.6	9.5
Poland	50–55	5–11	0.59	5.0–10.3
Romania	40–43	30–40	1.2	7.0–8.6
Russia	16.5–58	8.4–45	0.3–7.7	6.0–15.0
Serbia	43–55	18–25	0.5–0.9	6.8–7.5
Spain	8–50	14–70	1.2–>9.0	7.0–17.0
Slovenia	36	14	1.4	11.3
Slovakia	15.2–33.9	20.7–33.9	1.4–2.0	10.7–11.6
Thailand	12–49	10–55	10.5	5.0–10.0
Turkey	10–60	10–56	0.2–4.7	4.6–22.3
USA	30–44	4–20	0.2–1.4	5.0–17.4
Ukraine	30–40	29–46	Up to 3.3	12.4
Vietnam		20–40	2.5–6.2	10.4–18.4
Under some national categorisation systems, certain examples may be considered as subbituminous coals				

## 2.6 Oil sands

Oil sand is a naturally occurring mixture of sand, clay or other minerals, water and bitumen, which is a heavy and extremely viscous oil that must be treated before it can be used by refineries to produce usable fuels such as gasoline and diesel (CAPP, 2013). Bitumen is so viscous that at room temperature it acts much like cold molasses. Each grain of oil sand has three layers: a layer of water surrounding the grain of sand, with bitumen surrounding the water to form the outer layer. The bitumen is much heavier than other crude oils. Oil sands are often referred to as tar sands or bituminous sands – all these terms are equivalent.

Oil sand can be found in several locations around the globe, including Venezuela, the USA and Russia, but the Athabasca deposit in Alberta is the largest, most developed and utilises the most technologically advanced production processes. Canada's oil sand deposits are located in three major areas in Alberta: Athabasca-Wabasca, Peace River, and Cold Lake. The Cold Lake deposit extends over into neighbouring Saskatchewan. Between them, they cover over 140,000 square kilometres. There are currently more than 20 active mining and in situ oil sands projects in these three areas. Canada has about 170 billion barrels of oil in the oil sands that can be recovered economically with today's technology, making it second only to Saudi Arabia as an oil resource country. The total Canadian bitumen reserve is estimated to be about 2.5 trillion barrels.

Located in eastern Venezuela, north of the Orinoco River, the Orinoco Oil Belt is of a similar geographic extent as that of the Canadian oil sands. The deposits are not bitumen but extra-heavy oil. The Venezuelan deposits are less degraded than the Canadian deposits and, due to their equatorial location, are at a higher temperature. Therefore they are easier to extract by conventional techniques, although they are still too viscous to transport by pipeline or process in normal refineries. The Venezuelan product has a high sulphur content and particulate emission making it difficult to meet international environmental regulations.

Oil sands are generally processed in specialised facilities to yield a product range similar in scope and properties to that obtained from conventional crude oil (Figure 1). However, like oil shale described above they may be used for their energy content in combustion-based processes (Darling, 2007).

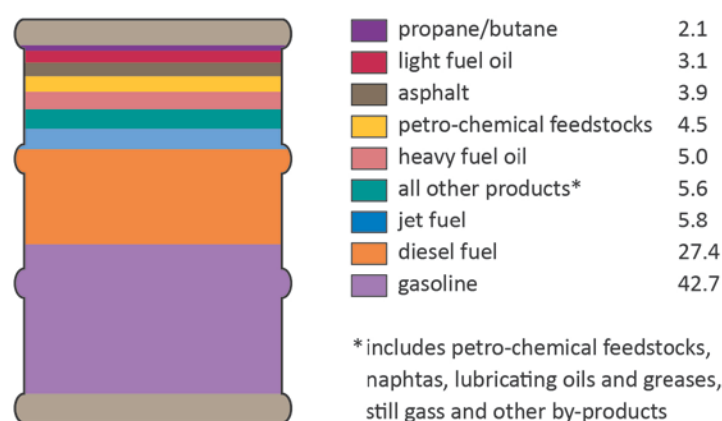


Figure 1 Average output from a barrel of oil derived from Canadian oil sand (%) (CAPP, 2013)

## 2.7 Coal mill rejects

In some industrial processes, coal is required to be milled to a fine powder before use. By far the most common application is pulverised coal fired generation, the dominant technology for producing electricity from coal, worldwide. The steel industry also produces a significant quantity of pulverised coal (PC) for use in the production of steel from iron ore. The coal mills that pulverise the coal operate to exclude materials that would be detrimental to the industrial process, generally adventitious components such as rocks and stones and ‘tramp’ metals from mining and coal processing activities. One particular component of coal that is strongly represented in the mill reject stream is iron pyrites ( $\text{FeS}_2$ ). Pyrite is a relatively hard mineral compared to coal and requires a correspondingly higher effort to pulverise it to the same degree as accompanying coal particles. So, despite the fact that pyrite has a recoverable energy content it is rejected from the milling process as the recoverably energy is less than that would be expended in milling it.

With the very large industrial base using pulverised coal, the quantity of mill rejects produced annually is significant. With a composition that includes some harder coal and pyrite there is an energy recovery opportunity for mill rejects. As a low value resource mill rejects could only be used locally, but for a large industrial complex using significant quantities of pulverised coal, a dedicated facility could be economically viable. Given the need to capture sulphur-derived pollutants that would arise from burning pyrite, a CFB facility, with limestone-based sulphur capture would be an obvious choice.

## 2.8 Coal washery rejects

Much of the coal mined globally is prepared to meet end-user requirements such as limits on the proportion of fine coal and ash forming minerals in the product. These preparation methods which generally involve a water-based washing technique generate residues of fine material which can have a range of compositions from a useable coal product to very high ash, surface moisture and sulphur content waste (Compliance, 2009). Very significant amounts, estimated as approximately 61 Gt have been deposited around the world in coal heaps or in slurry ponds (Lewitt, 2011). However, changes to the value of coal and developments in coal preparation and utilisation technologies have enabled increasing amounts of these materials to be recovered and used.

Schimmoller and others (1995) proposed that there are five main factors that determine the quality of recovered coal fines:

- parent coal characteristics;
- mining technique;
- preparation procedures;
- efficiency of the preparation plant;
- degree of oxidation.

Leonard and Lawrence (1973) illustrated how such a variation could arise in their history of a hypothetical coal depository reflecting changes in coal processing (Table 7).

Table 7 History of a hypothetical US refuse pile (Leonard and Lawrence, 1973)				
Year	Mining	Preparation	Reject	Store
1917	Not mechanised to any extent	Picking and screening	Handpicked rocks and screened undersize	Fine material (mainly organic coal) dumped with rocks. Fines tend to concentrate in interior of pile, rocks along edges.
1920	Greater selectivity in mining	Facility enlarged, more rigorous sorting and sizing	Handpicked rocks and screened undersize	Increase in amounts deposited
1923	Some mining machinery introduced, selectivity reduced		Rocks, fine coal and other dilutants	Increase in amounts deposited, more higher ash and sulphur material
1925		Concentrators added		Less fuel value, relatively higher in rock and ash than ever previously
1929		Rigorous preparation		Limited growth, relatively large amount of fines
1933	Additional mechanisation			Fluctuating tonnages of high ash/high fuel value material placed
1940			High ash, moderate sulphur material	Fuel rich areas re-mined
1945	More advanced equipment	More advanced equipment installed	High ash, high sulphur, moderate fuel value material	
1950	Additional mechanisation	Crushers added and process efficiency improved	High ash, high sulphur, very low fuel value material	
1969			High ash, high sulphur, low to moderate fuel value material	Much more material being deposited. Older sections re-mined to recover previously discarded fuel
1972		New more costly concentration technology installed	Medium ash, high sulphur, moderate fuel value material	Large amounts deposited but old areas of moderate ash, moderate sulphur and moderate fuel value material being re-mined

Several workers have attempted to summarise the properties of global coal processing residues, including Dorka (2009). The huge range of coal types makes this an almost impossible task but in general terms and for utilisation considerations the energy and ash contents are key considerations and as indicative ranges for these parameters, energy contents vary from 5 to 30 MJ/kg db and ash contents from 10% to 80% db.

## 2.9 Petroleum coke

Petroleum coke (petcoke) is a by-product of the oil refining process. As refineries worldwide seek to operate more efficiently and extract more gasoline and other high value fuels from each barrel of crude oil, a solid carbon residue known as petcoke is produced as a residual after refining.

The chemical and physical characteristics of petcoke are a function of the crude oil and refining technology used by the refinery. Petcoke can be hard or relatively soft. Physically, petcoke can resemble large sponges with numerous pores, or it can resemble small spheres, ranging in size from a grain of sand to a large marble. Chemically, petcoke can include a variety of elements and metals in a wide range of concentrations. Depending on these physical and chemical characteristics, petcoke is typically used in either an energy recovery application or in an industrial application, as a source of carbon.

Fuel grade petcoke represents roughly 80 per cent of worldwide petcoke production, and is typically very high in heating value, produces virtually no ash when burned, and is most commonly used in electric power plants and cement kilns.

The USA is the world's largest producer of petcoke, accounting for 40% of supply in 2011, but production in China and India has grown and now accounts for nearly a quarter of global output. By 2016 it is forecasted that these two countries could contribute one third of world supply, which is expected to reach 170 Mt (Commodities Now, 2012).

Petcoke basically comes in two types termed as 'fluid coke' and 'delayed coke'. Fluid coke typically contains about 5% volatiles and because of its small particle size is not generally very suitable for combustion in CFB boilers. Delayed coke contains 8–15% volatiles and sulphur in the range of 3–8%, although some petroleum cokes are available with less than 1% sulphur. The ash content of petroleum coke is typically very low, usually less than 1–2%. Because of the low ash content additional bed material is required for CFB applications. The heavy metals content of the ash is generally high with Vanadium and Nickel contents ranging at 500–3000 ppm each, although petcoke with >10,000 ppm Vanadium also exist. Because of the fuel particle characteristics, inherent moisture is very low in petcoke. Most of the water is present as surface moisture. If allowed to drain for several days, the moisture content will typically stabilise at 1–5% (*see* Table 8).

Table 8 Typical 'delayed coke' analysis (Góral and Wylenżek, 2012)	
Moisture	2–10%
Ash	0.3–5%
Volatiles	8–15%
LHV	25–33 MJ/kg
Sulphur	3–8%
Vanadium	500–3000 ppm

Vanadium content in petroleum coke is very important because of the possibility of generating low-temperature-melting compounds that can cause fluidisation problems in the solids circulating loop. Low melting compounds can also deposit on backpass heat transfer surfaces and result in under-deposit corrosion. The Vanadium content has a relatively small influence on the sintering process in CBF technology. The presence of large CaO content from calcination of limestone in the bed material causes Vanadium capture and ties it up in higher melting compounds, minimising or eliminating potential deposition problems. Because of the extremely low ash (<2%) and high sulphur contents of petcoke, limestone is used in the considerable majority of bed materials of the CFB. Limestone sizing is very important for desulphurisation, not only for efficient sulphur capture and effective fluidisation, but also fuel mixing, uniform temperatures and heat transfer. Limestone can be considered an attractive addition when firing high Vanadium petcoke, because of its Magnesium content which has vanadium-absorbing properties.

## 2.10 Wood and fibre residue

Waste wood arises from a wide variety of sources, in varying quantities and levels of purity. The main three areas in which waste wood arises are, Construction and Demolition (C&D), Municipal Solid Waste (MSW) and Construction and Industry (C&I). A feature of waste wood arisings, particularly from C&D and MSW, is that both tonnages and sources are unpredictable and materials are often mixed with other types of waste. As such, there is uncertainty over the exact tonnage of global waste wood arisings.

It is likely to be relatively difficult to segregate waste wood from household collections due to the relatively erratic and unpredictable nature of waste wood arisings as the majority of household waste is food, packaging and paper. Therefore the most significant accessible waste wood arisings are considered to be those in the construction and demolition sector. Typically, construction waste consists of shuttering used in the manufacture of concrete, which is often plywood, containing nails/screws and treated (with chemicals and preservatives) to prolong life. Demolition waste wood is often mixed with other types of demolition waste, such as rubble, reinforcing bars, tiling etc.

The contributors to the C&I waste wood sector cover a wide range of activities which means that there are no readily available data for the many sources of this waste.

Large producers of waste wood, such as the panelboard and furniture industry typically have a degree of self-sufficiency through established processes for the recovery or reuse of waste materials. For example, a number of companies in the furniture sector operate biomass boilers.

A particular arising in the C&I sector are forestry residues which include biomass not harvested or removed from logging sites in commercial forests, as well as material resulting from forest management operations. Forestry waste includes logging residues, imperfect commercial trees, dead wood, and other non-commercial trees that need to be thinned from crowded, unhealthy, fire-prone forests. Forest thinning is necessary to help some forests regain their natural health, but for smaller woodlands the cost of removing the wood cannot be recovered through timber sales due to their poor quality.

The properties of waste wood reflect those of the parent material, although special attention must be paid to possible contaminants such as metal, paint (in the case of demolition sources) and other additives that may give rise to operational and pollution concerns.

## 2.11 Refuse-derived fuel

Refuse-derived fuel (RDF) is a fuel produced by shredding municipal solid waste (MSW). Once the non-combustible materials such as glass and metals are removed the RDF material consists largely of organic, plastic and biodegradable waste. The residual material can be sold in its processed form or it may be compressed into pellets, bricks or logs and used as a fuel or in recycling process.

RDF can be used in a variety of ways to produce electricity. It can be used alongside traditional sources of fuel in coal power plants. In Europe RDF can be used in the cement kiln industry and RDF has been cofired with coal and used as a coal replacement.

In the production of RDF, recyclable product contents such as metal are removed from the mix, as are heavy fractions and unshreddable items. Following the drying and sizing process the remaining lighter material for thermal processing makes up approximately 40% of the initial feedstock material. In this way valuable fuels can be generated from waste previously dumped into landfill sites in an unprocessed form.

As the biogenic share is 50% (wood, paper, organic substances), CO<sub>2</sub> emissions are reduced by this amount in combustion; this makes the use of alternative fuels attractive as regards co-combustion, particularly in high energy consumption sectors such as the paper and cement industries.

RDF may be considered as a refined form of MSW. The World Bank (2012) has estimated that the global MSW generation is approximately 1.3 billion tonnes per year or an average of 1.2 kg/capita/day. It is to be noted however that the per capita waste generation rates would differ across countries and cities depending on the level of urbanisation and economic wealth.

The material composition of the waste that goes to produce RDF varies considerably, based on the region and the season. Table 9 gives an example analysis of a sample of RDF.



Table 9 Example properties of RDF (Johari and others, 2014)	
Parameter	Content
Heating value, (GCV)	14.43 MJ/kg
Moisture content	25%
Ash content	10 wt%
Volatile matter	90 wt%
Carbon	50.9 wt%
Hydrogen	6.7 wt%
Oxygen	26.7 wt%
Nitrogen	1.6 wt%
Chlorine	0.25 wt%
Sulphur	0.06 wt%

Points to note are the low energy content (very dependent on the plastics content) and high volatile content.

## 2.12 Plastics

Waste plastics are generally recycled in the industry in which they arise, or sent to landfill. The principal route to utilisation as a fuel is via RDF as set out in the section above.

## 2.13 Sewage sludge

Sewage sludge is regarded as the residue produced by the wastewater treatment process, during which liquids and solids are separated. Liquids are discharged to aqueous reprocessing facilities, while solids are removed for further treatment and final disposal. The constituents removed during wastewater treatment include grit, screenings and sludge. Of the constituents removed by effluent treatment, sludge is by far the largest in volume (Metcalf and Eddy, 1991). Prohibitions in developed countries against the disposal of sludge in seas and rivers have led to considerable quantities of material for which alternative uses are sought. The properties of these materials are summarised in Table 10 below.

**Table 10 Typical chemical composition and properties of untreated/digested sludge**

Item/sludge	Untreated primary		Digested primary		Activated range
	Range	Typical	Range	Typical	
Total dry solids (TS), %	2.0–8.0	5.0	6.0–12.0	10.0	0.83–1.16
Volatile solids (% of TS)	60–80	65	30–60	40	59–88
Grease and fats (% of TS)			5–20		
Ether soluble	6–30	–	–	18	–
Ether extract	7–35	–		–	5–12
Protein (% of TS)	20–30	25	15–20	18	32–41
Nitrogen (N, % of TS)	1.5–4	2.5	1.6–6.0	3.0	2.4–5.0
Phosphorous (P <sub>2</sub> O <sub>5</sub> , % of TS)	0.8–2.8	1.6	1.5–4.0	2.5	2.8–11.0
Potash (K <sub>2</sub> O, % of TS)	0–1	0.4	0.0–3.0	1.0	0.5–0.7
Cellulose (% of TS)	8.0–15.0	10.0	8.0–15.0	10.0	–
Iron (not as sulphide)	2.0–4.0	2.5	3.0–8.0	4.0	–
Silica (SiO <sub>2</sub> , % of TS)	15.0–20.0	–	10.0–20.0	–	–
Alkalinity (mg/L as CaCO <sub>3</sub> )	500–1500	600	2500–3500		580–1100
Organic acids (mg/L as H <sub>ac</sub> )	200–2000	500	100–600	3000	1100–1700
Energy content MJ/kg	10000–12500	11000	4000–6000	200	8000–10000
pH	5.0–8.0	6.0	6.5–7.5	7.0	6.5–8.0

## 2.14 High chlorine and high sulphur coals

Power plant operators have tended to avoid high chlorine and high sulphur coals that arise in certain coalfields as these fuels are associated with an increased risk of corrosion and higher emissions of sulphur dioxide, if unabated. However, economic factors are leading to an increased use of these fuels. Issues related to high chlorine and high sulphur coals are similar to those posed by certain biomass feedstocks. These are considered further below.

## 2.15 Summary

Globally a very significant resource exists in the form of the so-called low value, or low grade fuels, and these materials can be a valuable resource that is increasingly exploited in combination with coal, or separately. These fuels are attractive for a number of reasons, especially in having a sufficiently low cost that justifies their use. Furthermore, as otherwise waste materials that have a relatively high disposal cost, this cost can be offset or eliminated by using them for energy generation.

The properties of low value fuels vary extremely widely, depending on their origin. Many are high in the relatively inert components of mineral matter and water, while others contain elements that can be deleterious to combustion technology and may be significant pollutant precursors. Despite these drawbacks, the use of these materials has increased significantly in recent years and is likely to continue this trend for the foreseeable future.

### 3 CFBC plants utilising low grade fuels

#### 3.1 Benefits of CFBC

Circulating fluidised bed combustion plants have evolved from earlier bubbling bed fluidised bed combustion (FBC) technology where primary combustion air is injected from beneath a bed of fuel suspending the particles and giving them fluid-like flow properties. In bubbling fluidised beds (BFB) low fluidising air velocities are employed to prevent fine particles from being carried out of the bed, but circulating fluidised beds use higher fluidising air velocities which entrain particles throughout the boiler. The flue gases are fed into solid separators (typically cyclones) that return solid bed and ash to the lowest part of the combustor and thus prevent unburnt fuel from leaving the furnace (Figure 2). This creates a recycle loop through which fuel particles can pass 10 to 50 times until complete combustion is achieved. The prolonged combustion time results in much lower temperatures (800–900°C) than those found in PCC. As with PCC, the unit size has been steadily increasing with 600 to 800 MW supercritical CFBC commercially available and larger units under development. Notable CFBC installations include the supercritical high efficiency 460 MW CFBC unit in Łagisza, Poland and in China utility CFBC even at subcritical conditions has managed to capture a significant share of the country's rapidly growing coal capacity, and the recent commissioning of the world's largest supercritical CFBC unit may mark the beginning of similar growth at this scale.

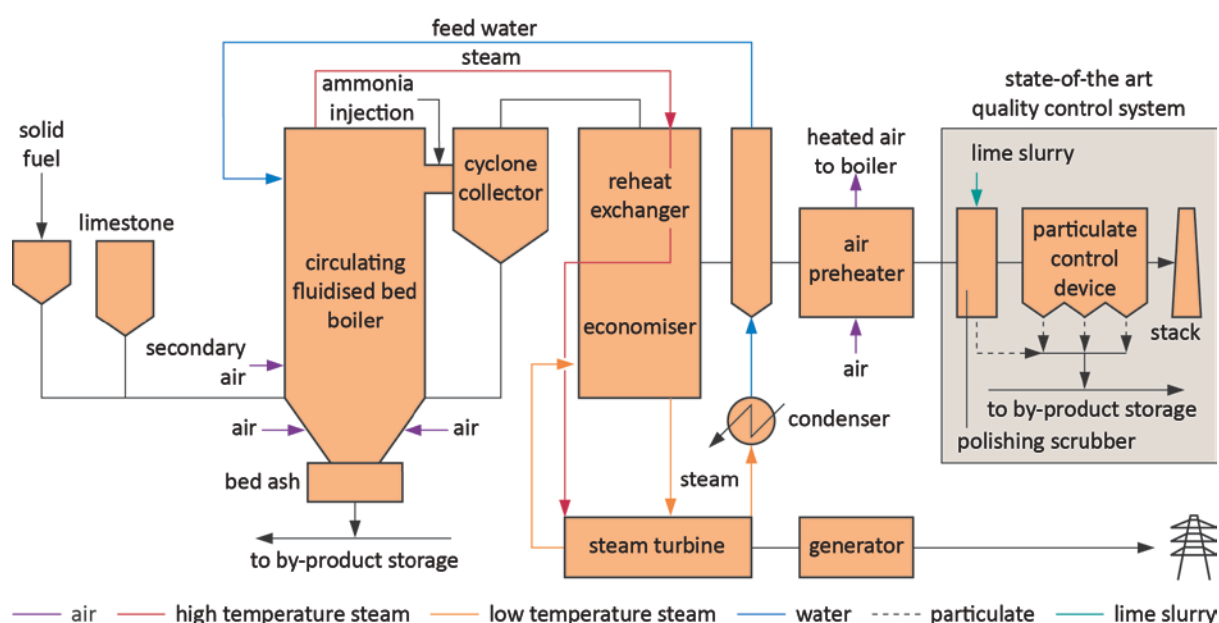


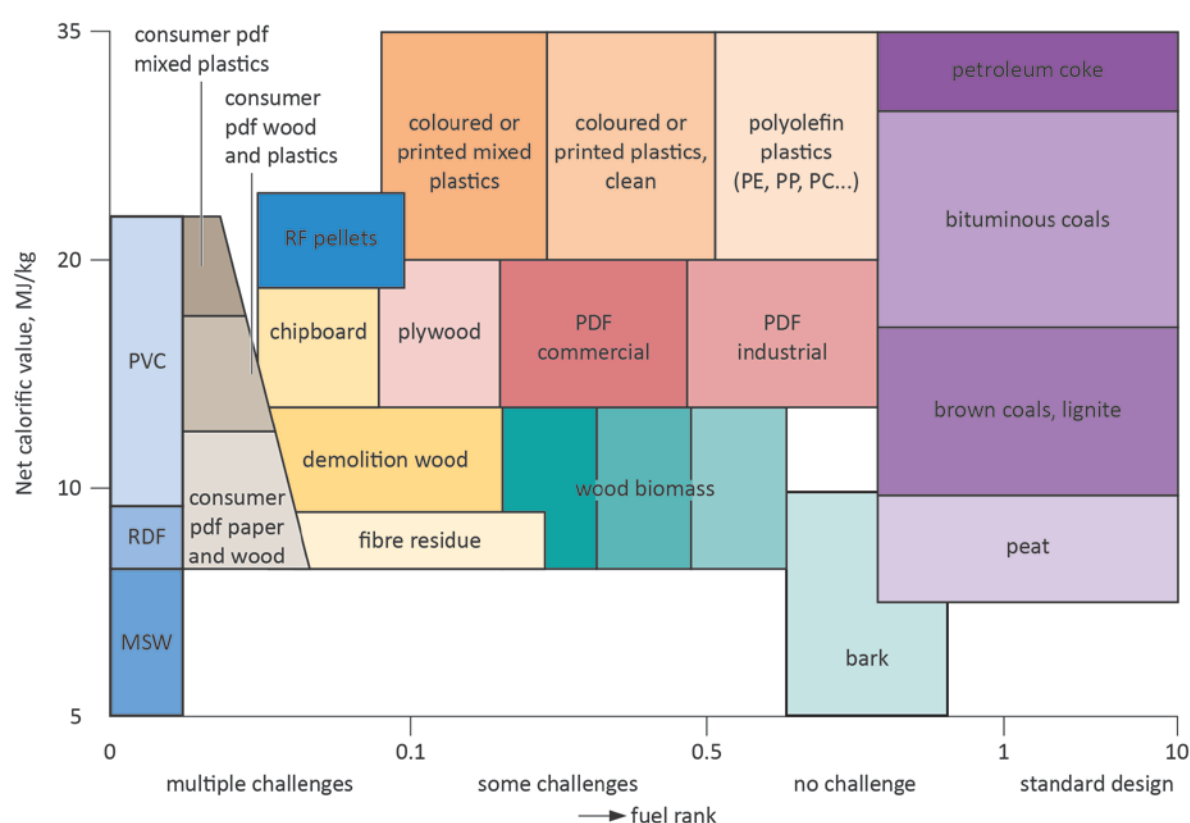
Figure 2 A generic plant based on CFBC technology

CFBC plants are particularly well suited to burning low grade fuels or mixtures of these materials with other fuels, eg coal. A large amount of inert bed material involved in the process makes it possible to have considerable variation in fuel properties, or to change fuels online without significant disruption to the combustion process. Circulating solids improve heat transfer and make it possible to burn also high energy content fuels while maintaining the combustion temperature in the region 850–900°C. A low

combustion temperature minimises fouling and slagging of heat surfaces since ash melting and softening points are generally much higher than combustion temperature in CFB. The low temperatures also make emission control more straightforward. CFB's solids circulation provides a long residence time for fuel and limestone particles meaning high combustion efficiency and low sorbent consumption.

### 3.2 Technical issues for CFBC plants firing low grade fuels

As mentioned above, a major strength of CFBC plant is its ability to utilise a wide range of fuel types for energy production. That said, different fuels present challenges to the technology. The benefits of using different fuels must be carefully weighed against the plant design and operating practice modifications, the recoverable energy content of the fuel and the cost of that fuel. Koornneef and others (2007) have summarised these sometimes conflicting requirements in Figure 3 below.



**Figure 3** A categorisation of fuels regarding to the challenges on CFBC boiler design (Koornneef and others, 2007)

Yamamoto (2001) set out the issues relating to the utilisation of a low value fuel such as biomass for different combustion technologies (Table 11).

**Table 11 Comparison of various solid combustion schemes**

Combustion system	Stoker combustion	BFB (Bubbling fluidised bed)	CFB (Circulating fluidised bed)	Burner combustion
<b>Mechanism of combustion</b>				
Flow of solid fuel	Transported on stoker	Fluidised by combustion air in a layer of the bed material	Fluidised by combustion air and circulated through the combustion chamber and cyclone	Moving in association with the combustion air
Combustion zone	On the stoker	Within and on the surface of the bed material	Entire area of the combustion furnace	Entire area of the combustion furnace
Mass transfer in the combustion chamber	Slow	Limited within the concentrated zone	Active vertical movement, and associated with heat transfer	Limited to the direction of gas flow
Controllability of combustion	Slow response	Medium response	Quick response	Quick response
Low excess air combustion	Difficult	Possible	Possible	Possible
<b>Fuel</b>				
Applicability to various fuels	Fair	High	High	Limited
Fuel pretreatment	Generally not necessary	Generally not necessary	Lumps must be crushed	Fine crushing necessary
<b>Environmental load</b>				
Low SO <sub>x</sub> combustion	In-furnace desulphurization not possible	Poor in-furnace desulphurisation	High rate of in-furnace desulphurisation	In-furnace desulphurization not possible
Low NO <sub>x</sub> combustion	Difficult	Not compatible with in-furnace desulphurisation	Compatible with in-furnace desulphurisation	Low NO <sub>x</sub> burners available (limited applicability)
<b>Others</b>				
Appropriate facility size	Small	Small to medium	Medium to large	Large

In his discussion of the suitability of CFB for utilising low value fuels, Kokko (2013) points out that CFB was originally developed to burn a variety of different kind of low grade fuels which are not suitable for pulverised coal or grate-fired boilers. A large amount of inert bed material involved in the process makes it possible to have considerable variation in fuel properties or to change fuels online without any significant disturbance to the combustion process. Circulating solids improves heat transfer and make it possible to burn also high calorific value fuels while limiting the combustion temperature to the region of 850–900°C. Suitable fuels are limited mainly by the fuel feeding system when considering biomass or waste based fuels. Fuel must be crushed to a size smaller than 200 mm. The fuel crusher is frequently located at the fuel receiving station. Alternatively, pelletised fuel or for example sawdust can be burned in a CFB without pre-preparation. Coal must be crushed below 10 mm and coal must have a separate silo and silo discharger but the rest of the feeding system can be common for coal and the secondary fuels.

Fuel chemical composition can vary widely for CFB applications. Renewable fuels are typically low in sulphur and high in chlorine and alkali metals, such as potassium and sodium. These components can set

limitations in steam parameters to minimise corrosion if the plant design is to burn one type of fuel only. In CFB high temperature corrosion can be minimised by locating the finishing superheater (and reheater) inside bed material in the cyclone loop seal.

The heating value of a CFB fuel can vary from high moisture biomass to petroleum coke without any significant issues for boiler design. A small quantity of fossil fuel (coal or petcoke) with low grade renewable fuel is sometimes cofired to keep the energy content of the fuel mixture high enough for efficient combustion.

Emissions of NO<sub>x</sub> are minimised in CFB owing to the relatively low operating temperature that prevents significant amounts of thermal NO<sub>x</sub> formation. Sulphur dioxide control is achieved by injecting limestone into the furnace. Primary NO<sub>x</sub> level in CFBs is normally around 200 mg/Nm<sup>3</sup> and that can be reduced 60% by ammonia injection into the cyclone inlets (SNCR). Catalyst (SCR) is not often used in CFBs but with SCR NO<sub>x</sub> emission can be as low as 10% of primary NO<sub>x</sub>.

Renewable fuels are typically very low in sulphur and hence no sulphur dioxide control is needed. With high sulphur fuels (coal, pet coke) 90–95% reduction in SO<sub>2</sub> emission can be achieved by limestone injection. With renewable fuels the chlorine content can be reasonably high at 0.1–1.0%. In such cases some emission control is needed for HCl. A typical method is to use dry flue gas cleaning integrated into the bag house filter (BHF). Dry sorbent – typically calcium hydroxide (Ca(OH)<sub>2</sub>) is injected into the flue gas duct before the BHF. Dry flue gas cleaning removes acidic gases (HCl, HF and SO<sub>2</sub>) and dioxins/furans are reduced by activated carbon injection if required.

Based on Metso Power's experience of a wide range of fuels, Kokko summarises the plant issues for the basic properties of a low value fuel thus:

The fuel's moisture content is generally not considered to be a significant issue. Fuel is usually burned as received. Moisture content can vary from good quality coal's 6–7% up to biomass at 60% moisture content. A moisture content exceeding 60% will require a support fuel to improve the energy content of the fuel mixture.

The heating value of the fuel can vary widely and quite often correlates to the moisture content of the fuel. Biomass, with moisture content 60%, has an energy content around 6.5 MJ/kg (LHV) as-fired, and the highest energy content is petroleum coke with at 32 MJ/kg (LHV). There are some waste coals or coal washing residues having an energy content as low as 4.5 MJ/kg. For these materials, the moisture content is low and the reason for the low heating value is an extremely high ash content.

Ash content can also vary widely with different fuels. In petcoke the ash content is <1% and for wood-based biomass is around 2 %. At the other end of the scale are waste coals with a 60%+ ash content and the highest so far which has been burned alone by Metso without support fuel is a coal washing reject with a 75% ash content.

Sulphur content is very low in wood-based biomass, only 0.01-0.05 %. The other extreme is petcoke which contains normally 6-8 % of sulphur.

Chlorine content is a challenge in recycled fuels because of possible problems of corrosion, and the formation of chlorine-containing pollutants. In refuse derived fuel (RDF) the chlorine content can be greater than 1%.

Turning to specific issues for a range of CFB fuels, the following generalisations may be drawn.

#### **Wood-based biomass**

Since biomass has a low heating value, its high moisture content and low density mean that a large volume of fuel is needed to meet generation requirements. Additionally, fuel may also come from different sources and the chemical composition may vary. Wood-based biomass is the easiest fuel to utilise in a CFB boiler. In the worst case the chlorine content can be 0.05% and the ash content 5% but high temperature corrosion can be controlled by locating the finishing superheater (and reheater) inside the bed material and limiting the steam temperature in the convective superheaters below the temperature at which corrosive species form. With an accurate fuel analysis the corrosion risk can be calculated quite accurately with semi-empirical proprietary calculation tools.

#### **Agro-based biomass**

Agricultural biomass is much more challenging fuel than wood-based biomass. Agro biomass includes such fuels as miscanthus, energy grass and straw which is widely available. Processing residues from the food industry are also becoming significant; this category includes corn stover, rapeseed cake, bagasse from sugar canes, olive pressing waste and others. All these fuels are annual crops taking a lot of fertiliser from the soil and they are rich in chlorine, nitrogen, phosphorus and potassium. Agro fuel challenges are an order of magnitude more difficult than for woody biomass. Typically bed agglomeration, slagging in the furnace and high temperature corrosion on superheaters are issues. All these are caused by low melting ash and semi-solid sticky deposits. Chlorine and alkali contents are much higher than in woody biomass and this is the main contributing factor. With agro biomass steam values can be similar to those for wood-based biomass when the chlorine content is less than 0.3% and the lead content is low in the fuel ash. With higher chlorine content, steam temperatures must be controlled to be lower than with woody biomass – for example slightly over 500°C steam for a 1.0% chlorine content. Control of sulphur-related corrosion is the same as with woody biomass – locating the final superheater in the loop seal and the use of sulphur based additives together with an online alkali-chloride analyser. Agglomeration and furnace slagging can be minimised by injecting kaolin into the furnace without any need to reduce combustion temperature.

Where agro biomass is the main fuel it is good practice to have the fuel pelletised in order to help with fuel feeding.

### Recycled fuels

Recycled fuels are the most challenging category of fuels. Recycled fuels can include recycled/demolition/construction wood and refuse derived fuel (RDF). In this fuel group chlorine contents can be as high as 0.5–1%, although sulphur is reasonably low and the ash content typically 5–10%. However the alkali (Na+K) content can be very significant. The risk for high temperature corrosion increases when metal surface temperature exceeds 450°C. Recycled fuels typically contain high concentrations of trace metals with low melting points, such as zinc, lead, tin and aluminium (Zn, Pb, Sn and Al) and those metals further decrease the ash melting point through eutectic formation. This means the boiler design differs significantly from that for biomass based fuels, in order to minimise corrosion on boiler surfaces.

With waste fuels the steam temperature is limited to 470–520°C and pressure to 60–80 bar. The design of the final superheater is different compared to that for the biomass fuels and features a coaxial double tube design which gives a reasonable lifetime with these very challenging fuels. Also the convective superheaters are protected by adding an ‘empty pass’ in between the cyclone and the second pass. In the empty pass the flue gas temperature is decreased to 650°C in order to reduce fouling of the superheaters and this also reduces the risk for high temperature corrosion. In the empty pass there are only water-cooled membrane walls and no other heat surfaces. Empty pass walls are kept clean by using water sootblowers.

### 3.3 Summary

Unlike competing technologies such as pulverised coal fired plant, CFBC plants are particularly well suited to burning low grade fuels or mixtures of these materials with other fuels, eg coal. This arises from basic design factors such as the large amount of inert bed material in a CFBC which makes it possible to have considerable variation in fuel properties, or to change fuels online without significant disruption to the combustion process. The circulating solids improve heat transfer and make it possible to burn also high energy content fuels while maintaining the combustion temperature in the region 850–900°C.

However, certain fuel properties can pose challenges to the design and operation of a CFB plant, specifically the low inherent energy content, a high proportion of inert material and the presence of components that can give rise to problems of ash deposition and corrosion within the boiler. Different manufacturers have tackled these issues to ensure the availability of reliable plant with considerable success. It is safe to say that CFB-based plants are the technology of choice for utilising low value fuels, either singly or in combination with coal.



## 4 Engineering solutions to CFB issues – B&W's experience

Maryamchik and Wietzke (2012) recently presented a summary of B&W's CFB boiler operating experience, new commercial projects and developments in boiler design and process. Of particular interest to this study are the evolutionary developments that have occurred to deal with the challenges of utilising low value fuels.

In the B&W Internal Recirculation Circulating Fluidised Bed (IR-CFB) boiler (Figure 4), the circuit begins with an economiser that exits to the steam drum. Water from the drum feeds the natural circulation furnace enclosure and division wall circuits. Steam from the drum exits to the horizontal convection pass enclosure. The steam then flows to in-furnace wing walls, exits to pendant superheater surface, and then exits the boiler. In IR-CFB designs with reheat, pendant reheat surface will also be located in the horizontal convection pass.

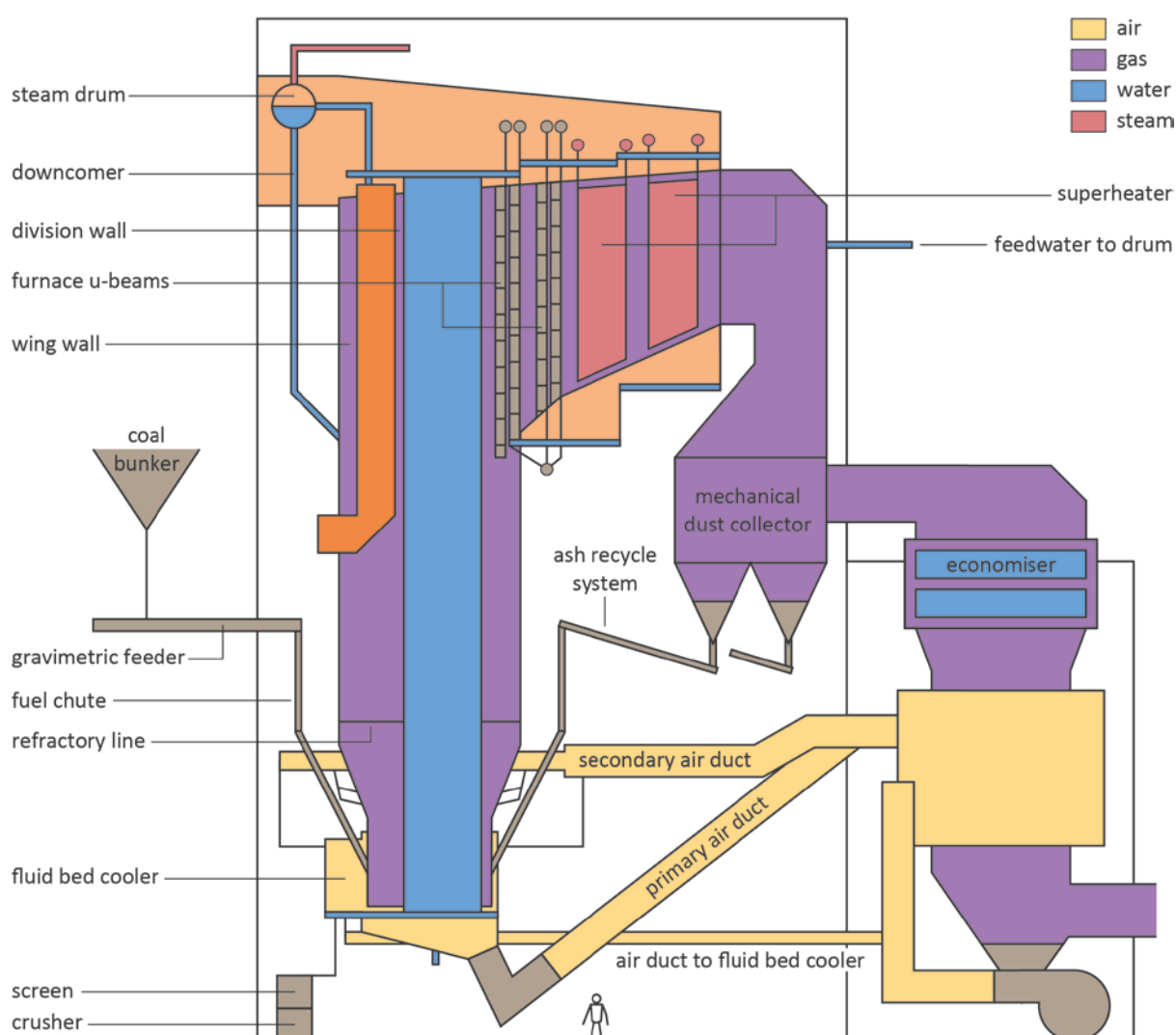
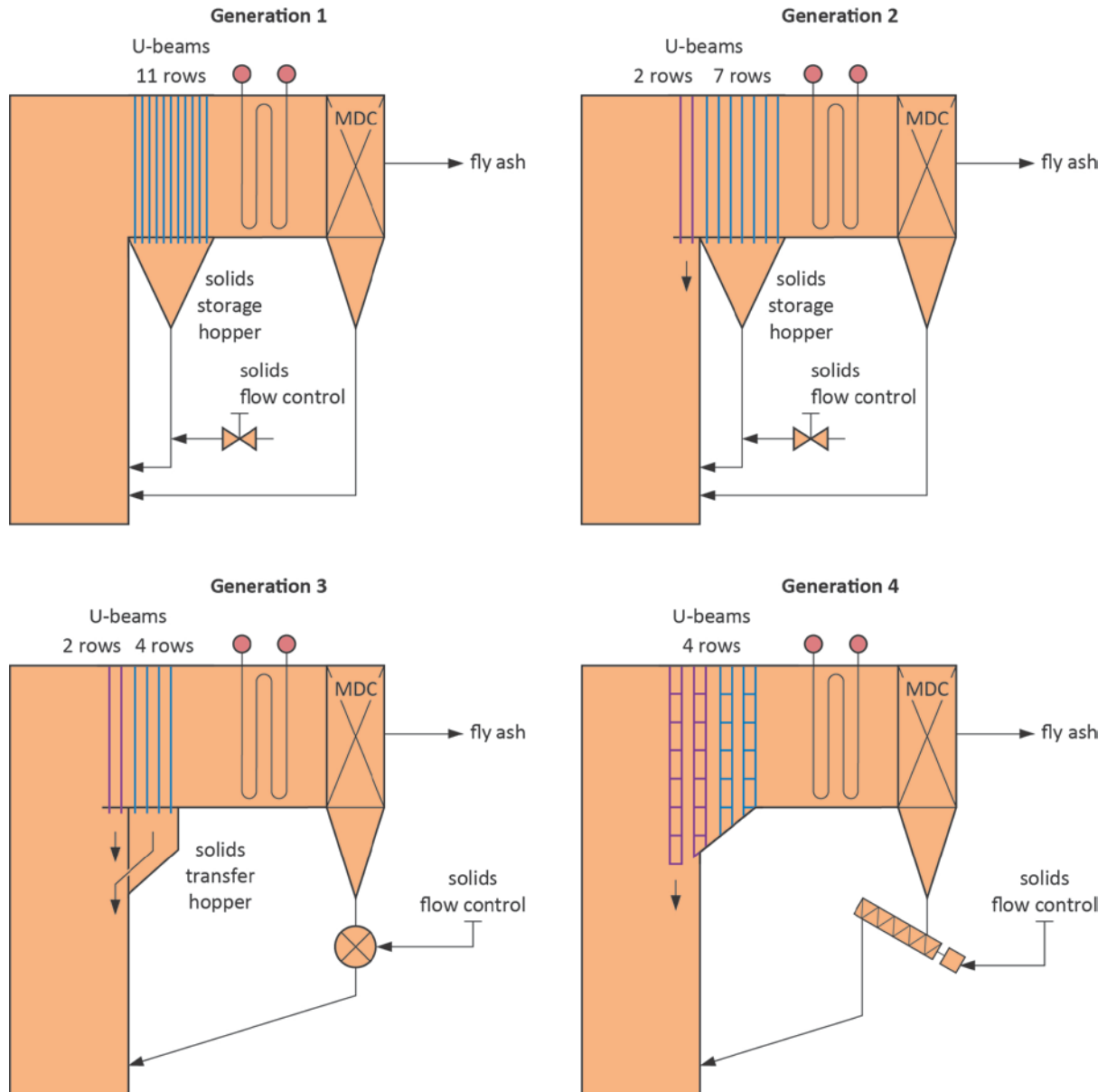


Figure 4 B&W internal recirculation circulating fluidised bed boiler (Maryamchik and Wietzke, 2012)

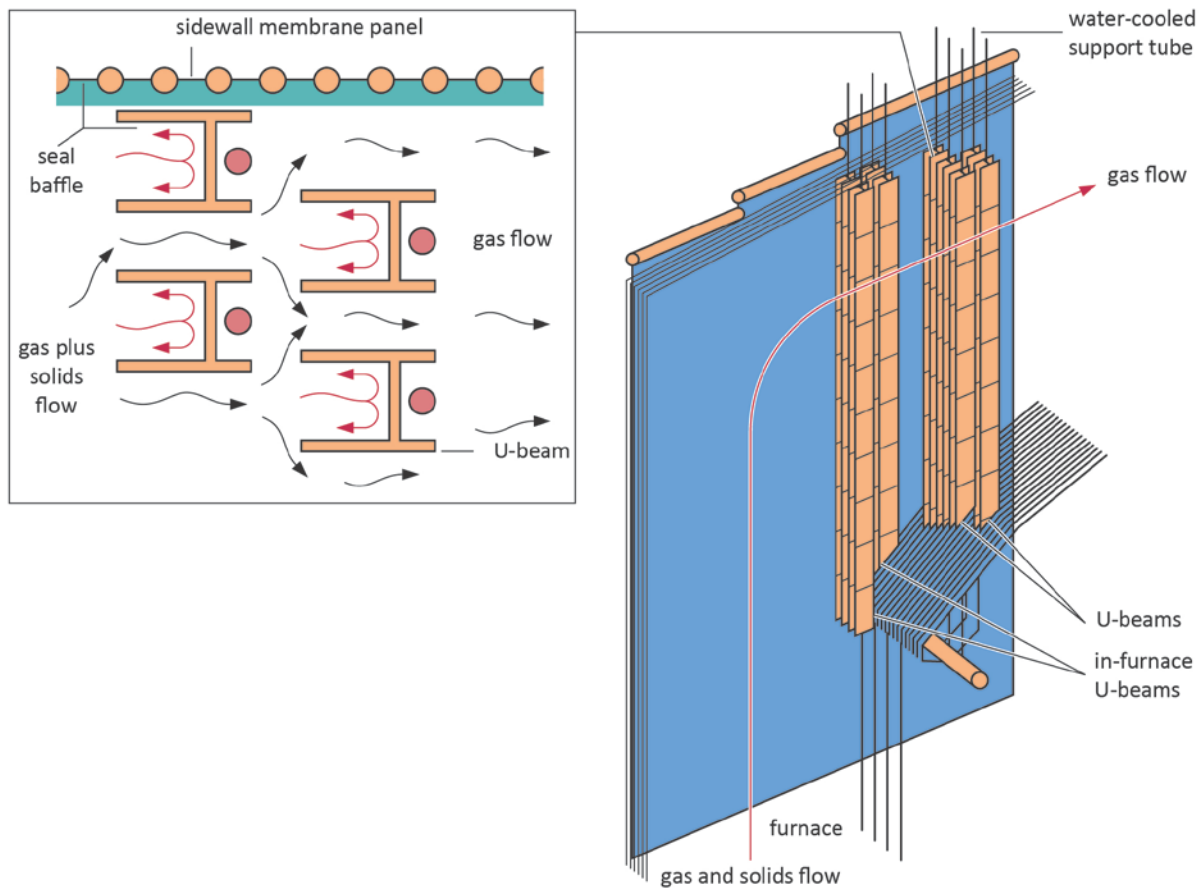
On the flue gas side of B&W PGG IR-CFB boilers, a two-stage solids separator is featured. The primary stage is an impact solids separator located at the furnace exit collecting the bulk of the solids (95% to

97%) that are then returned to the furnace by gravity. The primary separator is arranged as an array of U-shaped vertical elements (U-beams). The secondary separation stage, typically a multi-cyclone dust collector (MDC), is located in the lower gas temperature region of the boiler convection pass, ie, 250°C to 510°C. The U-beam separator design has evolved through several generations (Figure 5), starting with 11 rows installed externally to the furnace with solids recycle through non-mechanical, controllable L-valves, to the current design featuring a total of four rows, two of which are located in the furnace.



**Figure 5 U-beam separator design generations** (Maryamchik and Wietzke, 2012)

While each U-beam in earlier designs was made as a single piece hung from the top, the current design consists of segments, each being supported independently from a water-cooled tube (Figure 6).



**Figure 6 Segmented U-beam particle separators** (Maryamchik and Wietzke, 2012)

During the same period, the design of the MDC separator has been improved for better efficiency, reliability and maintainability. The MDC solids recycle system has evolved from dense-phase pneumatic transport to gravity conveying. The design of a solids separator is fundamental to CFB combustion technology since it has a major impact on the boiler layout, cost, fuel and sorbent utilisation, operational flexibility and reliability. The reported advantages of recent boiler developments are outlined below:

#### **High solids collection efficiency**

The collection efficiency of the two-stage solids separator is intrinsically high due to the greater efficiency of the MDC. Higher solids collection efficiency helps to achieve greater inventory of fine circulating particles in the furnace that provides: a) higher furnace heat transfer rate, b) better control of furnace temperature, and c) better carbon and sorbent utilisation due to the increased residence time of fine particles.

#### **Controlled furnace temperature**

The furnace temperature is controlled in response to load changes and variations of fuel and/or sorbent properties by controlling the solids recycle rate from the MDC. The recycle rate at high boiler loads is set to achieve the upper furnace density required to maintain the target furnace temperature. At low loads, the recycle rate directly controls the dense bed temperature.

***Low auxiliary power***

The auxiliary power requirement is lower for impact separator-type boilers since the total pressure drop across the two-stage separator (U-beams + MDC) is only 1 kPa. In addition, high-pressure air blowers for fluidisation of returning solids are not needed.

***Uniform gas flow***

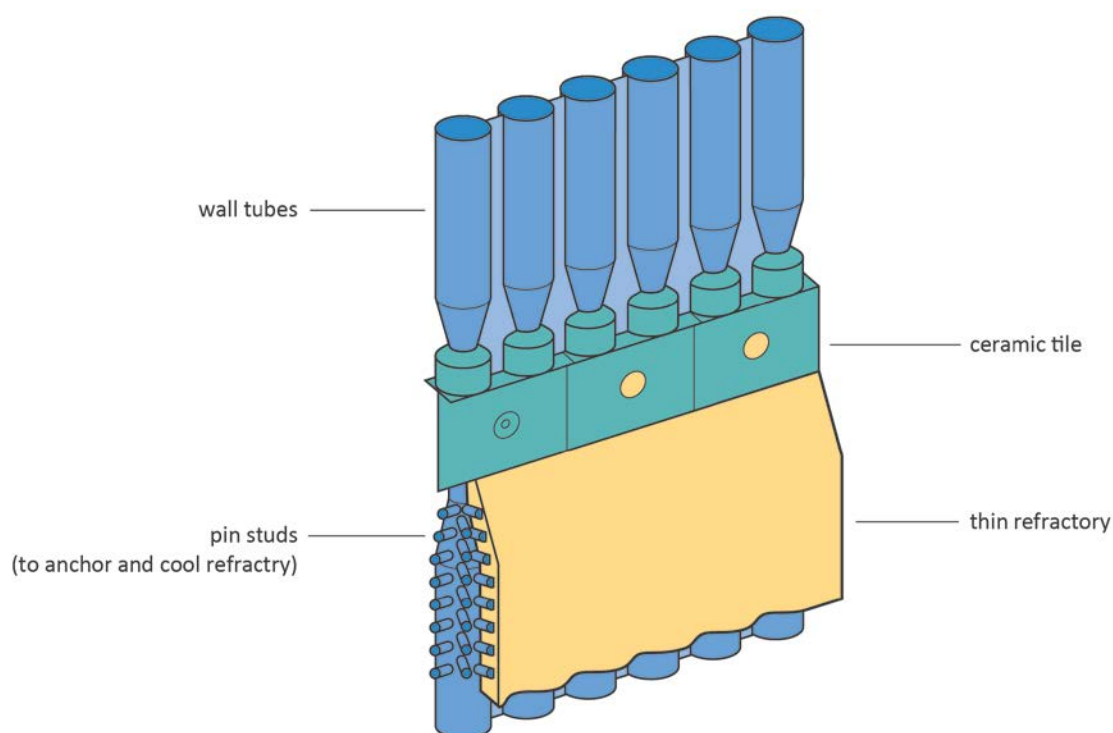
The gases exiting from the furnace to the U-beam separators positioned across the furnace width provide for a uniform two-dimensional gas flow pattern. This allows placement of in-furnace heat transfer surfaces as needed over the entire furnace height and width, including the region adjacent to the rear wall in the upper furnace. Selection of the furnace height can be based on combustion and sulphur capture considerations rather than heating surface requirements. Combined with high collection efficiency of the two stage solids separator, this allows reduced furnace height.

***High solids separator reliability***

U-beams and MDC have high reliability and low maintenance since they do not include any maintenance-intensive components such as refractory, solids return seal, expansion joints, vortex finders, etc. The U-beam design has evolved through 25 years of operating experience with updates and improvements. The current designs have proven to require essentially no maintenance, with the U-beams typically lasting for 20 years or longer. Throughout this time, U-beams do not indicate any erosion. This is attributed to low gas velocity, not exceeding 7.8 m/sec, along with downward falling ash particles within the U-beam channel serving to capture incoming particles. Thus, solids collection occurs primarily as ash contacting other ash particles, not ash contacting metal. MDC internals made of ceramics have now been in use for 11 years with essentially no maintenance.

***Minimal refractory use***

The amount of refractory used in B&W PGG CFB boilers is reported to be 80% to 90% less than that used for similar capacity CFB boilers with non-cooled hot cyclones and 40% to 50% less than CFB boilers with cooled cyclones. Thus, the start-up time is not limited by the rate of temperature rise of the refractory; instead it is limited by adding heat to the pressure parts, like all other non-fluid bed boiler technologies. An example of reduced diameter zone (RDZ) design for erosion protection at the upper refractory edge of heat exchanger surfaces is shown in Figure 7 below.



**Figure 7** Reduced Diameter Zone (RDZ) design for erosion protection at the upper refractory edge  
(Maryamchik and Wietzke , 2012)

### **Dynamic load change**

Dynamic load change response is achieved due to the absence of massive refractory and the ability of furnace inventory adjustment using variable ash recycle rate from the MDC.

### **Wide turndown ratio**

A wide turndown ratio (5:1) without auxiliary fuel is possible due to the selection of furnace velocity and controllable solids recycle.

Table 12 below presents a summary of B&W experience with a range of fuels, including low value fuels.

**Table 12 Recent B&W CFB boiler experience (Maryamchik and Wietzke, 2012)**

Start-up year	Customer and plant Location	Mfg by	Eng by	No of units	Output MWth	Steam flow TPH	Op pressure bar	Steam temp °C	Fuels
2012	Grasim Industries Bharuch, Gujarat, India	Licence	Licence	4		175	110	542	Indian coal, Indonesian coal, Petcoke, Lignite
2012	India Cements, Vishnupuram, AP, India	Licence	Licence	2		115	110	542	Indian coal, Imported coal, Petcoke
2012	JK Paper Rayagada, Orissa, India	Licence	Licence	1		165	110	542	Indian coal, Wood dust, ET sludge
2012	Rohit Ferro-tech Jaipur, Orissa, India	Licence	Licence	2		150	110	542	Indian coal, Washery rejects, Char
2012	Simadhri Steel Andhra Pradesh, India	Licence	Licence	1		210	110	542	Coal, Washery rejects
2012	Suryadev Alloys & Power, Phase 2 Gummidipoondi, Tamilnadu, India	Licence	Licence	1		330	110	875	Indonesian coal, African coal, Indian coal, Char, Petcoke
2012	Ultratech Cements Rawan, India	Licence	Licence	1		135	112	1004 540	Indian coal, Washery rejects, Petcoke
2012	Ultratech Cements, Ltd Rajashree, Kamataka, India	Licence	Licence	2		115	112	542	Indian coal, Washery rejects, Petcoke
2012	Vicat Sagar Cements Gulbarga, Karnataka, India	Licence	Licence	1		130	89	515	Imported coal, Indian coal
2012	Wonder Cement Udaipur, Rajasthan, India	Licence	Licence	1		160	105	535	F Grade coal, Petcoke
2011	Arkansas River Power Authority Lamar, CO, USA	B&W PGG	B&W PGG	1	125	163	109	532	Coal
2011	Meenakshi Power Andhra Pradesh, India	Licence	B&W/ Licence	2	374 (w/ RH)	886 402	378 26	1004 540	Indonesian & Indian coals
2011	Jaiprakash Associates Churk, UP, India	Licence	Licence	4	180	250	110	540	Coal, Washery rejects, Petcoke
2011	My Home Cement Andhra Pradesh, India	Licence	Licence	1	173	240	109	540	Coal, Washery rejects
2011	Bajaj Hindustan, Ltd Uttar Pradesh, India	Licence	Licence	4	137	190	109	540	Coal

Table 12 – continued

Start-up year	Customer and plant Location	Mfg by	Eng by	No of units	Output MWth	Steam flow TPH	Op pressure bar	Steam temp °C	Fuels
2011	Longulf Yemen Sugar Company Yemen	Licence	Licence	1	69	85	65	485	African coal
2010, 2011	National Cement Company Yemen	Licence	Licence	2	52	72	88	520	African coal
2010, 2011	Indian Metals & FerroAlloys Choudwar, Orissa, India	Licence	Licence	2	173	240	100	540	Coal, Washery rejects
2010, 2011	Kamachi Sponge & Iron Chennai, India	Licence	Licence	2	109	150	95	515	Coals, Char, Washery rejects, Petcoke
2011	Great River Energy Spiritwood, ND	B&W	B&W	1	275	365	123	541	Lignite
2011	Bhubaneswar Power Orissa, India	Licence	Licence	2		275	95	542	Coal, Washery rejects
2011	Pasupata Acrylon Ltd, Kashipur, India	Licence	Licence	1		50	67	490	Rice husks, Coal
2011	Suryadev Alloys & Power, Phase 1 Cummidipoondi, Tamilnadu, India	Licence	Licence	1		330	110	540	Indonesian coal, African coal, Indian coal, Char, Petcoke
2011	Welspun Anjar, Gujarat, India	Licence	Licence	1		350	110	542	Indonesian coal, Indian coal, Lignite, Petcoke
2010	ACC Chanda, Maharashtra, India	Licence	Licence	1	89	110	64	485	Coal, Washery rejects
2008, 2009	Altratech Cements, Ltd, Hirmi, Chattisgarh, India	Licence	Licence	2	83	115	97	540	Coal, Petcoke, Washery rejects
2009	BILT Power Ballarshah, Maharashtra, India	Licence	Licence	1	128	160	65	480	Indian & imported coals, Bamboo dust, Sludge
2009	AG Processing, Inc. Hastings, Nebraska	B&W	B&W	1	87	136	10	541	PRB coal
2009	Aluminum do Norte do Brazil, SA Alunorte	Licence	B&W/ Licence	1	270	340	91	487	Bituminous coal (high volatile); Light oil (diesel) for startup
2009	GHCL, Ltd, Veraval, Gujarat, India	Licence	Licence	1	89	125	104	510	Indonesian coal, Lignite, Petcoke

Table 12 – continued

Start-up year	Customer and plant Location	Mfg by	Eng by	No of units	Output MWth	Steam flow TPH	Op pressure bar	Steam temp °C	Fuels
2008	UltraTech Cement, Ltd, Maharashtra, India	Licence	Licence	1	83	115	99	540	Indian coal, Washery rejects
2008	Grasim Cement AP, India	Licence	Licence	1	83	115	97	540	Coal, Lignite, Petcoke
2008	Grasim Industries, Ltd Rawan, Chihatisgarh, India	Licence	Licence	1	83	115	97	540	Coal, Petcoke, Washery rejects
2008	Saurashtra Cement Gujarat, India	Licence	Licence	1	80	110	86	520	Coal, Lignite, Petcoke
2008	UltraTech Cement, Ltd, Hirmi, CG, India	Licence	Licence	2	83	115	97	540	Coal, Petcoke, Washery rejects
2008	Grasim Industries Kotputli, Rajasthan, India	Licence	Licence	2	73	224 102	96	1004 540	Coal, Lignite, Petcoke
2006	Indian Rayon & Ind. Veraval, Gujarat, India	Licence	Licence	1	76	231 105	88	950 510	Lignite, Petcoke, Indonesian coal, Oil, Gas
2005	Kanoria Chemicals, Ltd, Renukoot, UP, India	Joint venture	Joint venture	1	89	242 110	67	905 485	High ash coal
2004	Konya Sugar Corporation, Cumra, Turkey	Licence	B&W/ Licence	2	55	165 75	43	806 430	Lignite



## 5 Examples of CFB plants utilising low value fuels

The challenges posed by low value fuels have spurred the suppliers and operators of CFB plant to devise cost-effective solutions for their efficient use. The following sections set out examples of plant burning different fuels, and the experience of doing so.

### 5.1 Bhavnagar circulating fluidised bed combustion plant

In 2010, Bharat Heavy Electricals Limited, contracted Doosan Lentjes to provide engineering services for the design and construction of two 250 MWe CFB boilers, to be commissioned at Bhavnagar Power Plant in India's Gujarat state (Doosan Lentjes, 2015). The units are designed to burn high ash, high-sulphur and high-moisture lignite and use high-pressure, natural-draft boilers capable of operating over a wide load range. Key project data are summarised in Table 13 below.

Table 13 Key project data – Bhavnagar circulating fluidised bed combustion plant	
Customer	Bhavnagar Energy Company Ltd (BECL)
Main project partner	Bharat Heavy Electricals Ltd
Location of power station	Bhavnagar, Gujarat, India
Main fuels	High-moisture and high-sulphur local lignite
Award date	2010
Start-up date	2013
Number of lines	2
Plant capacity	250 MWe
Thermal capacity	610 MWth
Live steam	810 mg/h 540/173°C/ bar
Reheat steam	685 mg/h 540/43°C/bar
Feedwater	255°C
Emissions	
SO <sub>2</sub>	515 mg/m <sup>3</sup> (STP)
NO <sub>x</sub>	350 mg/m <sup>3</sup> (STP)
Dust	100 mg/m <sup>3</sup> (STP)
Thermal efficiency (ASME)	77%

### 5.2 Gardanne – Coal to biomass conversion

Doosan Lentjes are providing services for the major biomass conversion and turbine upgrade project for E.ON's coal-fired Provence power plant in Gardanne, France. Once complete, Gardanne will become France's largest biomass-fired power plant (Doosan Lentjes, 2015b).

The new biomass unit will be converted from the existing coal-fired Provence 4 unit. It will provide up to 170 MWe of power with base production of more than 7500 hours per year until 2034, which corresponds to the annual electrical consumption of 440,000 households. The investment will reduce the overall CO<sub>2</sub> balance by 600,000 tonnes per year. Key project data are summarised in Table 14 below.

Table 14 Gardanne – Coal to biomass conversion	
Customer	Societe Nationale d'Electricite et de Thermique (E.ON France)
Location of power plant	Gardanne, Provence, France
Main project partner	Doosan Babcock
Main fuels	Biomass, waste wood (11%-th), discard coal (13%-th)
Award date	2013
Start-up date	2015
Number of lines	1
Plant output	170 MWe
Thermal capacity	386 MWth
Superheater outlet pressure	165 bar-g
Live steam	441 t/h; 566/165°C/bar
Reheat steam	406 t/h; 565/33°C/bar
Process steam	10 t/h; 345/34 °C/bar
Feed water	433 t/h; 244°C
Design fuel	
LHV	12 MJ/ kg
Ash	10.4%
Moisture	33.1 %
Sulphur	0.11 %
Emissions (corrected to 6% O <sub>2</sub> , dry, monthly average)	
SO <sub>2</sub>	150 mg/m <sup>3</sup> (STP)
NO <sub>x</sub>	150 mg/m <sup>3</sup> (STP)
Dust	19 mg/m <sup>3</sup> (STP)
Thermal efficiency	90%
Turbine	Four-body turbine, 1 HP, 1 IP, 2 LP stages

### 5.3 Starobeshevo circulating fluidised bed combustion

Doosan Lentjes designed, supplied, constructed and commissioned the CFB-based boiler island for the anthracite and anthracite sludge-fired 210 MWe Donbasenergo power plant in Starobeshevo, Ukraine, owned and operated by Donbasenergo (Doosan Lentjes, 2015c).

The design was based on a CFB Boiler already in operation in Tisova: a 110 MWe capacity plant in the Czech Republic. The compact CFB design incorporated water cooled, integrated fluidised bed heat exchangers and seal pots. Despite the existing model, the Starobeshevo plant design was complicated by the need to support the 100 MWe higher capacity as well as the challenging combustion properties of the low reactive anthracite and anthracite sludge being used. The Starobeshevo plant uses local anthracite coal and dried anthracite sludge (culm), which would otherwise be dumped. The plant has been in successful commercial operation since January 2011. Key project data are summarised in Table 15 below.

Table 15 Starobeshevo circulating fluidised bed combustion		
Customer	Donbasenergo	
Location of power plant	Starobeshevo, Ukraine	
Main fuels	Anthracite, anthracite sludge	
Award date	2000	
Start- up date	2005	
Plant output	1 x 210 MWe	
Thermal capacity	616 MWth	
Live steam	670/538 t/h; 545/542°C , 134/25 bar	
Feedwater	244°C	
Minimum load	40%	
<b>Design fuel</b>	<b>Anthracite</b>	<b>Anthracite sludge</b>
LHV	25.1 MJ/kg	12.9 MJ/kg
Ash	16.7%	50.6%
Moisture	7.0%	8.0%
Volatiles	4.0%	5.0%
Sulphur	2.1%	1.2%
Emissions (corrected to 6% O <sub>2</sub> dry)		
SO <sub>2</sub>	200 mg/m <sup>3</sup> (STP)	
NO <sub>x</sub>	200 mg/m <sup>3</sup> (STP)	
CO	250 mg/m <sup>3</sup> (STP)	
Dust	30 mg/ m <sup>3</sup> (STP)	
Flue gas temperature	130 °C	
Thermal efficiency (acc DIN 1942)	90.5%	

#### 5.4 CFB boiler for oil shale at Narva, Estonia (Alstom)

In January 2011, Alstom signed a full turnkey EPC contract with Narva Elektriijaamad AS, to supply a 300 MW steam power plant based on Alstom's circulating fluidised bed (CFB) boiler technology. The plant was designed for reduced environmental impact and increased operational flexibility and to be able to burn oil shale, peat and up to 50% cofiring of wood chips. Despite the high nitrogen content of the fuel, the required 150 mg/Nm<sup>3</sup> emissions can be met without an additional denitrification system. The CFB technology will be fitted with large tubular air preheaters, an option preferred to the conventional rotating regenerating air preheaters to maximise boiler efficiency. The boiler is designed to operate at 92.3% boiler efficiency (LHV basis). Key project data are summarised in Table 16 below.

Table 16 CFB boiler for oil shale at Narva, Estonia	
Configuration	Dual grate – 4 cyclones
Boiler efficiency (LHV basis)	92.3%
Main steam flow	850 t/h
Superheater outlet steam pressure	178 bar
Superheat/reheat steam temperature	543°C/568°
Nitrogen oxides	150 mg/Nm <sup>3</sup> without an additional denitrification system
Sulphur dioxide	200 mg/Nm <sup>3</sup> without limestone injection

Gauvillé and others (2011) recently described the experience of Alstom in developing CFB technologies to burn low value coal-derived fuels in plants located in the PR China, and France.

### 5.5 Baima CFB Demonstration Power Plant

The Baima CFB Demonstration Power Plant is located in China's Sichuan province. The plant was constructed by Alstom Power Boilers and was at the time one of the world's largest CFB boilers at 300 MWe. The arrangement of the major components of the Baima CFB boiler is shown in Figure 8. The fuel for the project was local anthracite with a very high ash and sulphur content. The ash content of the coal was 35%, as received, and its energy content 18.5 MJ/kg also, as received. The volatile matter content of the coal was low, at 8.5% weight as received. The specification for the plant stipulated that a high combustion efficiency was required, together with low emissions without backend flue gas cleaning, such as sulphur dioxide scrubbers or selective catalytic reduction of nitrogen oxide emissions. The coal properties and key boiler design data are summarised in Table 17 below.

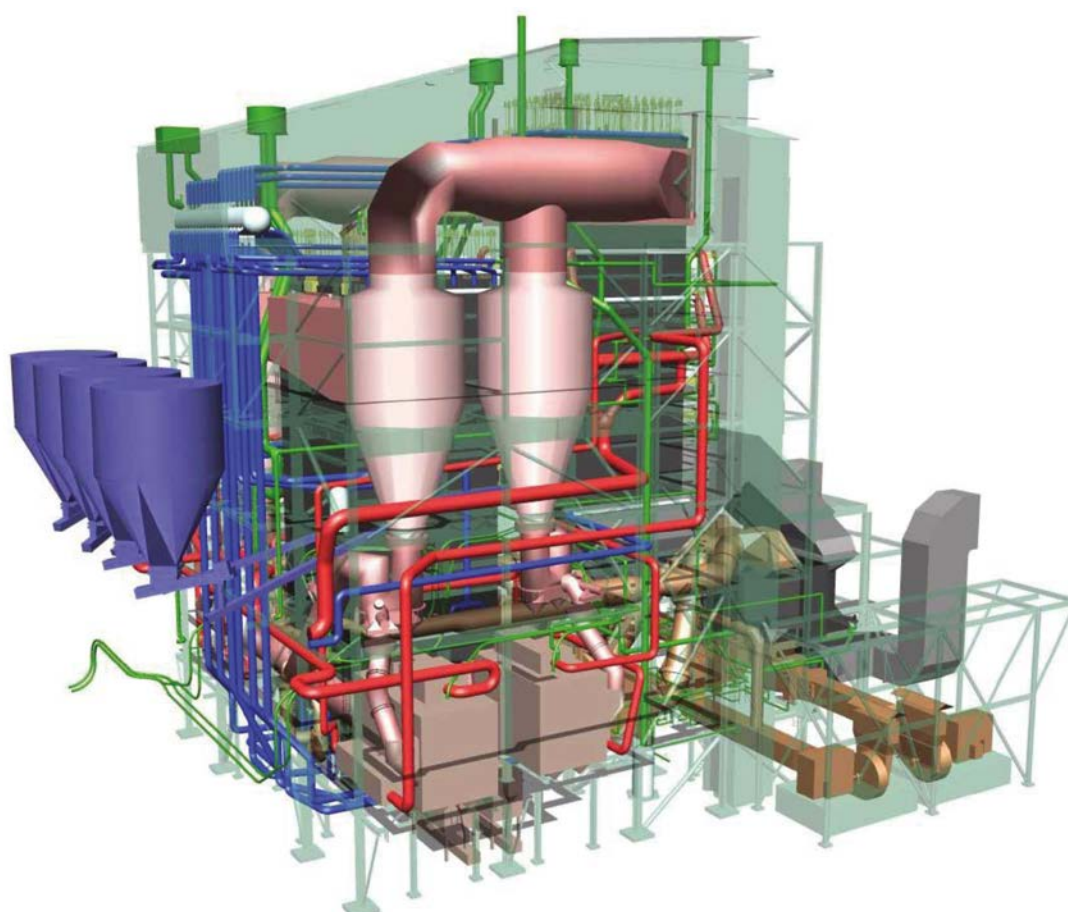


Figure 8 Baima CFB boiler arrangement (Alstom, 2011)

Table 17 Baima CFB boiler – main data		
Steam conditions at MCR		Property
Main steam flow	1025	t/h
Main steam pressure	174	bar
Main steam temperature	540	°C
RH steam flow	844	t/h
RH steam pressure	37	bar
RH steam temperature	540	°C
Feedwater temperature	281	°C
Fuel analysis		
Volatile matter	8.55	%
Fixed carbon	49.2	%
Ash	35.27	%
Moisture	7.69	%
Sulphur	3.54 to 4.30	%
Energy (LHV)	18.5	MJ/kg
Emissions levels		
SO <sub>2</sub>	600	mg/Nm <sup>3</sup> @ 6% O <sub>2</sub>
NO <sub>x</sub>	250	mg/Nm <sup>3</sup> @ 6% O <sub>2</sub>
Particulates	100	mg/Nm <sup>3</sup> @ 6% O <sub>2</sub>

Based on the design coal properties, the potential uncontrolled sulphur dioxide levels in the flue gas were calculated to be approximately 10000 mg/Nm<sup>3</sup> (@ 6% O<sub>2</sub> dry gas) and as high as 14000 mg/Nm<sup>3</sup> for the highest sulphur content coal. As sulphur dioxide emissions were required to be lower than 600 mg/Nm<sup>3</sup> when burning the design coal the subsequent sulphur capture efficiency was calculated as close to 94%. In the CFB design selected, sulphur capture was performed by injecting limestone into the furnace through four ports located in the return ducts from the seal pots to the furnace. The calcium carbonate content in the limestone chosen for use at the plant was within 90% to 92%. The two major challenges for the Baima project in terms of performance were considered to be combustion efficiency and limestone consumption. The 250 mg/Nm<sup>3</sup> NO<sub>x</sub> emission limit required had already been demonstrated at other Alstom units. Specifically, test campaigns with a low rank fuel at the Emile Huchet 250 MWe CFB power plant located in Provence, France had demonstrated the ability to maintain the NO<sub>x</sub> emissions below the limit by adjusting the combustion temperature exercising close control over the air staging.

To achieve the high performance required from the Baima plant, Alstom implemented the following basic design principles:

- maintain uniform furnace temperature within the range 880–900°C where the limestone reactivity was proven to be maximised and the carbon burnout close to the expected figure;
- ensuring evaporative duty with the furnace water walls and extended walls located in the furnace. To achieve this, superheating or reheat heating surfaces were moved into the external fluidised beds;
- the cyclone and the inlet duct were designed to achieve the highest possible capture efficiency. Several designs were tested on a cold flow model. The selected design was able to retain the fine

particles of lime and carbon in the solid loop and hence improve the performance by increasing circulating solids residence time. Furthermore high capture efficiency led to an increase in the circulating ash flow, ensuring a high heat transfer and a uniform temperature in the furnace as well as good contact between CaO particles and SO<sub>2</sub> rich flue gas for optimum sulphur removal;

- air staging in the bottom part was carefully adjusted for burning anthracite based on Alstom's previous experience. The ratio of primary air rate flow to total air flow was increased. Secondary air was properly distributed around the furnace enclosure and in the core of furnace through air ports located on the both sides of internal walls ('pant leg' furnace arrangement) and over two levels;
- coal was injected with the limestone in the return ducts from the seal pots to the furnace to allow pre-mixing with the circulating ash before being fed into the furnace;
- return ducts were arranged to create a circulating ash flow at the entrance into the furnace, on the centre-line of the fluidisation grate. This arrangement takes advantage of the high momentum balance of circulating ash to achieve good penetration and mixing of all the solids along the furnace grate. Uniform distribution of coal and limestone was reached and matched the air distribution;
- bed inventory was also increased, compared to that from other commercial CFB units burning higher rank fuel.

Performance tests were carried out on the Baima unit in June 2007. The combustion and emissions profile from these tests are summarised in Table 18.

<b>Table 18 Baima CFBC performance test results</b>			
<b>Baima performance tests</b>	<b>BECR performance test 1</b>	<b>BECR performance test 2</b>	<b>Design</b>
Date	26 June 2007	27 June 2007	BECR
Coal quality stability	good	good	good
Coal LHV, MJ/kg	15.38	16.49	18.5
Ash, %	43.5	40.5	35.5
LHV boiler efficiency, % (corrected)	>93	>93	<92
Added Ca/S (corrected)	<1.5	<1.7	<2.0
Sulphur capture, %	>95	>94	>94
SO <sub>2</sub> emission, mg/Nm <sup>3</sup> @ 6% O <sub>2</sub> dry	<600	<600	600
CO emission, mg/Nm <sup>3</sup> @ 6% O <sub>2</sub> dry	<150	<130	NA
NO <sub>x</sub> emission, mg/Nm <sup>3</sup> @ 6% O <sub>2</sub> dry	<100	<100	250

The heat loss due to the unburned carbon was less than 3% calculated on an LHV basis. Commissioning was, however, reported as challenging as coal supplied for the plant failed to meet the contracted coal specification. Whereas the contractual ash content was specified within 30% to 40%, the actual ash content as received was very often higher than 50%. This caused problems in the bottom ash removal system and the coal crushing system, but not in the combustion process itself, demonstrating CFB's tolerance to such difficult conditions. A large proportion of the mineral matter in the coal supply was in the form of stones that caused rapid wear of hammers in the secondary crusher. Consequently, the expected coal particle size distribution, important for achieving the design conditions, was never reached.

Thirty per cent of particles were larger than 3 mm with a maximum size around 15 mm. Hence, coarse particles had to be extracted from the fluidised bed ash coolers (FBACs) but the high amount of ash including many oversized particles led to a coarse ash build-up inside the FBAC tube bundles and a lack of heat exchange. Ash temperature at the FBAC discharge was therefore excessive, triggering trips of the downstream mechanical ash conveyors.

A design modification of the FBACs was considered, but the plant owner decided to remove the FBACs and to replace them by rotary ash coolers (RACs). The replacement took place in September 2007. Since October 2007, when the four RACs were put into operation, there have been no problems in the ash extraction system even though the thermal performance of the coolers was lower than expected. Cooler thermal capacity was improved during the planned outage in July 2008 by increasing RAC length by approximately 20%. Each RAC was installed in the same footprint of the FBAC, which was dismantled. The inlet of the ash cooler was kept through the cone valve and a vent to the flue gas duct was installed. The water quality and pressure were taken into consideration and this led to a thick shell for the cooler. Figure 9 shows the design principle of the RAC and this type of cooler is widely used in P R China.

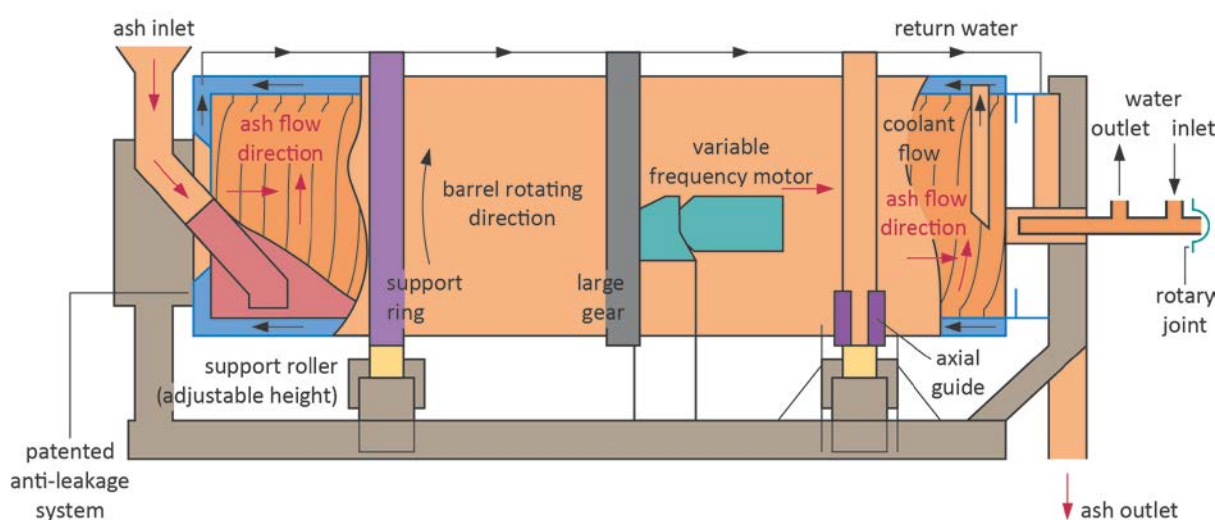


Figure 9 Rotary ash cooler (Gauvillé and others, 2011)

The boiler operated successfully when the FBACs were replaced with RACs, however, coarser particles in the bed brought out some erosion of water walls at the junction with the refractory lining. A kick-out was installed by the customer over one meter of tube wall and the erosion rate dropped significantly. Due to the high silica content in the fly ash along with the ash rate in the flue gas, a low flue gas velocity was maintained in the heat recovery back pass. No tube erosion was then observed. The CFB boiler was designed with a four-sector regenerative air heater, one sector for the primary air located between two sectors dedicated to secondary air. These sectors are in contact with the remaining fourth sector through which the flue gas passes. The sootblowing system was not as efficient as expected, with some ash being blown up by the air stream. Control dampers, secondary and primary air ducts and the fluidising nozzles were eroded and some of the fluidising nozzles were replaced three years after the start of commercial operation. The design of the sealing joints as well as the location and number of sootblowers needs to be



carefully considered when choosing a regenerative air heater. An additional challenge was to handle the variability of the coal quality while operating the CFB-based power plant in automatic mode. For example, coal flow varied from 120 t/h up to 200 t/h for the same power output of 300 MW over one hour. If the unit was operated under boiler follow mode, main steam pressure was controlled by the coal feeders. Changes in electric power demand however, acting simultaneously on the HP turbine throttle valves and on the boiler load demand through a feed-forward controller, required close attention from the operators as the unit responded quickly. When the coal quality was fluctuating too much, the unit was operated under turbine follow mode. In this case, electric power demand drives the speed of coal feeders. The main steam pressure is then controlled by the HP turbine throttle valves. It was possible to control the main and reheat steam at the rated temperatures while the boiler was operated between 100% and 50% MCR and with a main steam pressure set point from 120 to 170 bar. Despite the challenges raised by such variable coal properties, the bed temperature was kept at around 880°C, and good combustion and good sulphur capture were achieved.

## 5.6 Emile Huchet CFB plant

Emile Huchet is a captive power plant close to coal mines and burns low grade coal residues. It is located in Carling in the Lorraine coal basin and has a total installed capacity of around 1100 MWe. It burns either so-called 'schlamms', a by-product from coal washing plants with no market value, or coal slurry, which is schlamms conveyed with water from coal washing plants via pipelines to the power plant. Both schlamms and slurry are then filtered and dried before sending them to the pulverised coal boilers.

In 1987 a decision was taken to replace the 125 MWe pulverised coal boiler (unit 4) and Alstom were commissioned to specify a plant to meet several technical challenges:

- meet the SO<sub>2</sub> and NO<sub>x</sub> emission limits, in compliance with the clean coal combustion regulations;
- burn the schlamms efficiently that are currently pre-dried for use in pulverised coal boilers;
- avoid, as far as possible, energy-intensive drying of the schlamms and slurry;
- create value from the large amount of schlamms that has accumulated in settling ponds over decades.

CFB was specified as the most promising technology to meet all these challenges. Sulphur dioxide emissions complied with regulation limits due to the sulphur removal achieved by the injection of limestone into the furnace. NO<sub>x</sub> emissions could also be achieved as typical low CFB combustion temperatures avoid thermal NO<sub>x</sub> production.

The key challenge for the plant was to burn a mixture of two fuels: schlamms as dried fuel with a lower heating value of about 21 MJ/kg, and a coal slurry as wet fuel having a 33% water content, half of the schlamms's lower heating value and producing a significantly higher flue gas volume.

Due to the coal mining process, schlamms solids are very fine particles. This requires good management of the solid inventory, which must be maintained high enough in the furnace to achieve the required performances. The cyclone design is critical for capture of particulate emissions.



The 367 t/h natural circulation CFB boiler was designed to fire the local residues at the steam conditions shown in Table 19 below. The coal residue is a medium-volatile bituminous coal characterised by a high ash content (30% to 45% on dry basis) and 33% moisture content, along with an energy content of 42 MJ/kg for the dried schlamms, and 21 MJ/kg for the slurry. The detailed analysis is given in Table 19.

Table 19 Emile Huchet unit 4, CFB boiler main data			
Steam conditions at MCR	Units		
Main steam flow	t/h	367	
Main steam pressure	bar	133	
Main steam temperature	°C	540	
RH steam flow	t/h	338	
RH steam pressure	bar	30	
RH steam temperature	°C	540	
Feedwater temperature	°C	242	
Fuel analysis		Schlamms	Slurry
Proximate			
Volatile matter	%	21.19	11.79
Fixed carbon	%	45.05	25.06
Ash	%	25.76	30.15
Moisture	%	8.00	33.00
Ultimate			
C	%	52.27	29.08
H	%	3.50	1.95
N	%	0.58	0.32
S	%	1.66	0.92
O	%	8.23	4.58
LHV	MJ/kg	20.3	10.5
Emissions levels			
SO <sub>2</sub>	mg/Nm <sup>3</sup> @ 6% O <sub>2</sub>	330	330
NO <sub>x</sub>	mg/Nm <sup>3</sup> @ 6% O <sub>2</sub>	300	300

The average particle diameter of the coal residue by mass (d<sub>50</sub>) was within the range 75 to 250 microns and the maximum size did not exceed 3 mm, therefore no crushing system was required. However, the particle size distribution (PSD) of the fuel was contrary to the requirements of the CFB process and solid fuel fragmentation over time compounded the issue. The technical challenge was to design cyclones that would allow the maximum retention of particles in the furnace, for two reasons: Particle loss is to be avoided since if bed material escapes the cyclone make-up is required to maintain the bed inventory. Sand was contemplated for this purpose, but it is relatively expensive and leads to potential erosion issues. The second reason was to maximise the coal particle residence time in the furnace to secure the highest combustion efficiency.

Other technical challenges included:

- Potential (uncontrolled) sulphur dioxide levels in the flue gas were close to 4500 mg/Nm<sup>3</sup> (@ 6% O<sub>2</sub> dry gas). To achieve the required 330 mg/Nm<sup>3</sup> SO<sub>2</sub> emission, the sulphur removal rate must be close

to 92.5%. Sulphur capture was achieved by the injection of limestone through several ports located in the bottom part of furnace. In practice, the limestone delivered to site was finer than recommended with a d50 of 50 microns and a maximum size not greater than 600 microns.

- Air staging in the bottom part was implemented to mitigate NO<sub>x</sub> emissions. During the design phase the primary air flow was set up at 40% of the overall air flow, whatever the fuel. Cap nozzles were chosen to distribute the primary air over the fluidising grate.
- The conceptual design for the plant was based on a furnace with a single grate, two cyclones and two external fluidised bed heat exchangers – one for the control of the bed temperature and one for reheat steam temperature control.
- Schlamms were injected in the return ducts from the seal pots to the furnace to allow for pre-mixing with the circulating ash before entering into the furnace. Return ducts were arranged to generate a circulating ash flow at the entrance into the furnace, onto the centre-line of the fluidisation grate.
- Coal slurry was injected at approximately one meter above the fluidising grate through six separate lines, each including a variable positive-displacement pump and a slurry gun with air-assisted atomisation.
- Bottom ash was cooled in fluidised bed ash coolers (FBACs).
- the cyclones were designed to operate with a flue gas velocity in the barrel close to 5.5 m/s at the plant's maximum continuous rating when burning coal slurry. This led to an internal diameter of 8 metres. The cyclones were laid out on the lateral sides of the furnace and shifted towards the heat recovery back-pass. This layout provides a long connecting duct from furnace to barrel and the required duct angle, both enhancing the pre-collection of the particles impinging the duct extrados (see Figure 10).
- A test campaign was launched on a cold flow model to validate the selected design.
- Several designs of cyclone with different layouts were investigated. Figure 10 highlights the main results.
- Two air heaters were installed, one tubular air heater for the heating of primary air and a regenerative air heater for the secondary air.

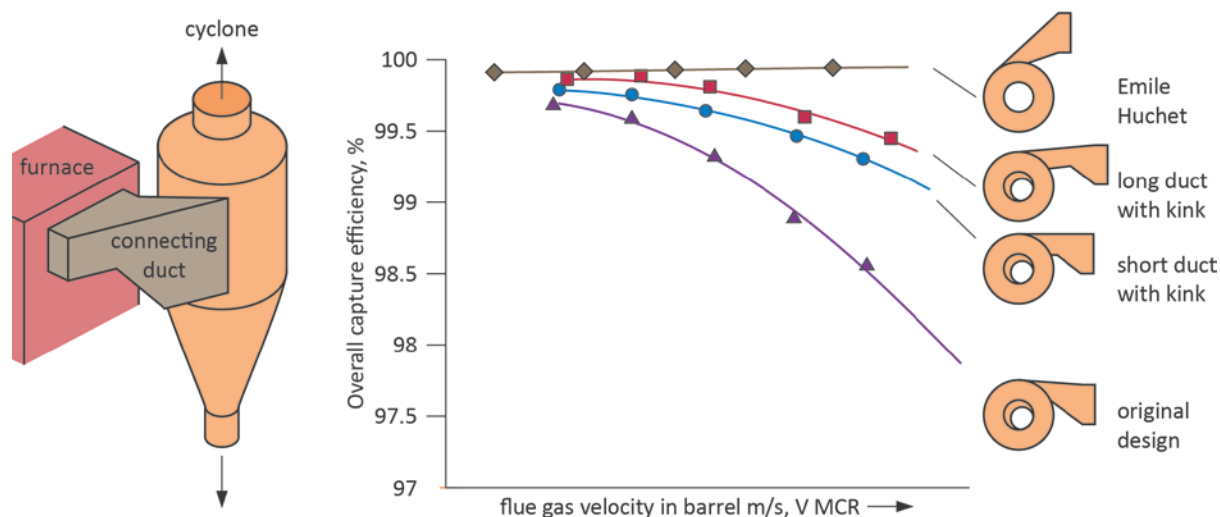


Figure 10 Overall capture efficiency in relation to the general cyclone layout (Gauvillé and others, 2011)

The Emile Huchet CFB boiler has been in commercial operation since 1990 after passing the performance tests at maximum continuous rating (MCR) as reported in Table 20. The heat loss due to the unburned carbon was less than 1.5% on LHV basis with schlamms and higher with coal slurry. The carbon content in the fly ash was less than 6%.

Table 20 Summary of Emile Huchet CFB performance tests						
Fuel	Guarantees		Performance test			
	Schlamm	Slurry	Schlamm		Slurry	
Main steam flow, t/h	367		369	374	375	375
Main steam temperature, °C	541 ± 3		539	539	540	543
RH steam temperature, °C	539 ± 3		542	543	543	543
Boiler efficiency %, LHV	89.3	86.5	89.4	90.2	86.2	87.5
Unburnt C loss %, LHV			1.4	1.2	2.55	1.71
SO <sub>2</sub> emission, mg/Nm <sup>3</sup>	<300		53	142	139	145
NO <sub>x</sub> emission, mg/Nm <sup>3</sup>	<300		245	292	109	101
Ca/S molar ratio	<2.5		1.8	0.7	1.8	1.7
Fly ash/bottom ash split, %/%			70/30	60/40	62/38	58/42
Unburnt C in fly ash, %			6.0	5.6	5.0	3.8
Unburnt C in bottom ash, %			1.2	1.0	0.4	0.4

The tests demonstrated that boiler could be operated with a mixture of schlamms and coal slurry. The combustion temperature in the furnace could be set up within the range 850–860°C, whatever the fuel mix, by controlling the heat pick-up in the external fluidised bed heat exchangers.

Although the fuel and limestone were very fine, the amount of fly ash leaving the cyclones never exceeded 70% of the overall ash produced by the coal and the limestone. High solid concentration was measured in the upper part of furnace leading to a high solid flow in circulation in the furnace-cyclone-seal-pot loop. This promoted some ash build-up and plugging in the cones of the cyclones. The primary air flow when operating with slurry was dropped in order to reduce the ash loading at the top of furnace and hence operate the boiler in safe conditions.

The pressure drop of the fluidising nozzles in the furnace was found to be too low, thus promoting ash back sifting. A few holes of the inner tube were plugged to create a sufficient pressure drop of around 45 mbar at MCR.

The thermal performance of the ash cooler and the ash extraction capacity were improved by moving the location of the ash vent, to the back of the FBAC. This allows a reduction of the internal ash recirculation between the ash cooler and the furnace via the vent and the discharge pipe from the furnace to FBAC.

The CFB Solid Management software developed by Alstom for the calculation of solid flows in the CFB system has been reported as showing good consistency with the field test data. This tool is currently used for setting up the expected capacity of ash extraction systems as well as the ash flow in circulation in the furnace which is required to calculate heat transfer factors and performances for new CFB developments. An example of actual versus predicted particle size distributions at Emile Huchet is given in Figure 11 below.

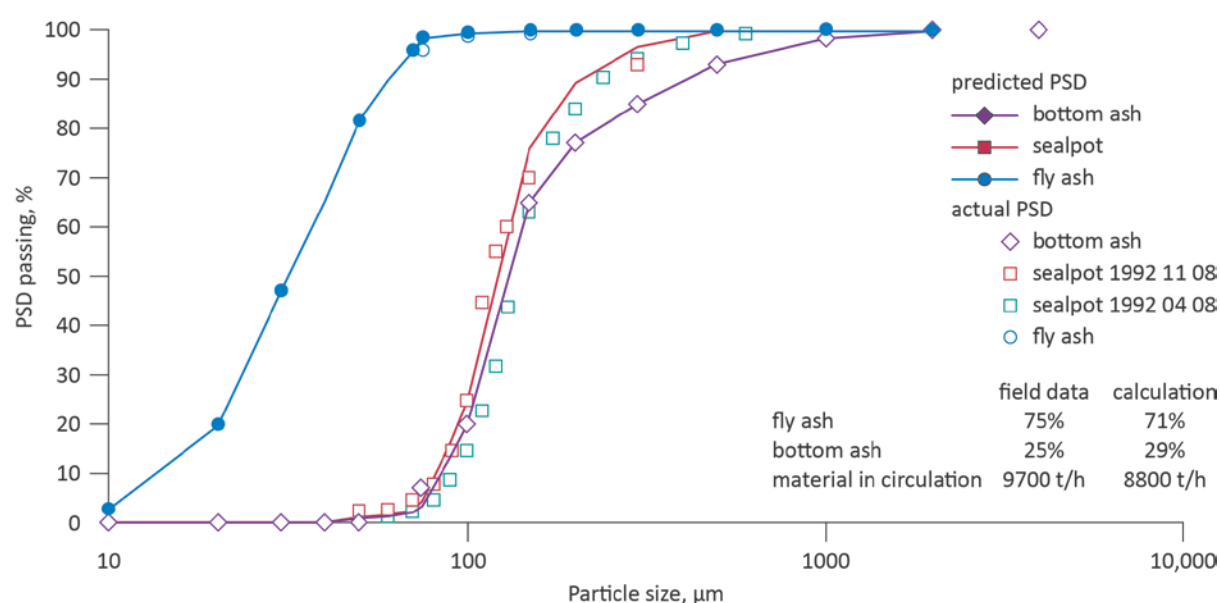


Figure 11 Actual versus predicted particle size distributions at Emile Huchet (Gauvillé and others, 2011)

The Emile Huchet plant, now owned by E.ON is scheduled to be mothballed in June 2015 (ICIS, 2013).

## 5.7 Cleco Power's Madison Unit 3

Peltier (2010) described Cleco Power's construction of a new 600 MW CFB facility, Madison Unit 3, for burning petcoke to generate power (Figure 12).



**Figure 12** Madison Unit 3, a 600 MW CFB for burning petcoke (Peltier, 2010)

The rationale behind the choice of fuel was price, as petcoke is much less expensive than the alternatives costing a fraction of the cost of western subbituminous or eastern bituminous coals delivered to the Gulf Coast, or even locally available lignite. Since the cost of fuel is typically around 50% of the life-cycle cost of a new solid fuel-fired plant, the low cost of petcoke was projected to generate considerable savings over the alternatives. Madison's projections indicated the proposed unit has the potential to save more than \$4 billion over 30 years over a conventionally fuelled plant.

The plant was designed to be as fuel-flexible as possible and was based on two 50%-sized CFB boilers supplied by Foster Wheeler Corp. As part of the CFB design, limestone was mixed with the petcoke in the CFB bed in order to promote complete combustion and remove sulphur. NO<sub>x</sub> emissions were minimised by the relative low bed temperature in the CFB. Table 21 summarises the key performance data for Madison Unit 3.

**Table 21 Key performance data for Madison Unit 3**

Parameter		Details
Net plant heat rate		600 MW
Turbine throttle conditions		165 bar, 565°C
		41 bar,
Fuel		1,500,000 tonnes per year of petcoke
Emissions	NO <sub>x</sub>	0.108 kg/MWh
	SO <sub>2</sub>	0.232 kg/MWh
	CO	0.155kg/MWh
	PM10	0.019 kg/MWh
	Hg	90% removal
Boiler	Type	Subcritical, circulating fluidised bed. Two units
	Steam pressure	176 bar
	Steam temperature	565°C/565°C
	Maximum continuous rating	962 tonnes per hour
Turbine	Type	Combined HP and IP casing, tandem double flow LP sections
	Rotational speed	3600 rpm
	Condenser vacuum	0.12 bar
	Feedwater heaters	Seven stages of feedwater heating
Generator		Hydrogen cooled, water cooled stator with static excitation system
		876 MVA
Water source		Cooling water, service water and plant feedwater make-up come from Lake Rodemacher

Post CFB, the unit has additional flue gas treatment, including a selective non-catalytic reduction system to reduce NO emissions, and a dry lime scrubber to complete the SO<sub>x</sub> removal process. Provisions for activated carbon injection for mercury control are included in the plant design, should the regulatory requirements for controlling mercury from petcoke-fired plants change. As a final treatment step, a pulse jet fabric filter polishes the exhaust gases, removing at least 99.9% of the remaining fine particulates.

To maintain maximum flue flexibility, certain plant components were sized for the worst-case fuel. For example, the conveying system was sized for lignite fuel and its higher moisture and ash content. Ash disposal components, including the stripper coolers, Nuva feeders, fly ash economiser and air heater hoppers, and baghouse hoppers, were also up-sized to account for higher-ash lignite fuel. Bottom ash (about 45% of the total) is separated from the fly ash, conditioned, and conveyed to a separate silo. Each silo was sized for three days' storage, and a subcontractor periodically moved the partially hydrated ash to an onsite storage basin prior to sale. Ash silos were kept separate from the main plant to facilitate the sale of fly ash.

## 5.8 Polaniec biomass power plant

GDF Suez is the owner and operator of Polaniec biomass power plant, the world's largest biomass power plant (Power technology, 2015). The project is 80% fuelled by wood chips and 20% by agricultural waste (see Figure 13). The \$290 million biomass power plant was built at the site of the existing 1800 MW Polaniec power station in Polaniec, Poland. The plant became operational in November 2012. The existing Polaniec power plant has eight 225 MWe turbines fed by coal and biomass. The biomass unit was planned



initially for a capacity of 190MW, but increased to 205MW during the construction stage. It features a circulating fluidised bed (CFB) boiler, designed to burn biomass fuel exclusively.



**Figure 13 Polaniec Biomass Power Plant, Poland** (Power Technology, 2015)

The environmental impact assessment (EIA) for substituting the coal fired boiler with CFB boiler was conducted during 2009-10. Construction of the biomass fuelled power plant was undertaken to complement the European Union's target to generate 15% of energy from renewable sources by 2020 and the plant is expected to reduce carbon dioxide emissions by about 1.2 Mt/y.

The new biomass power plant will use up to 890,000 t of wood chips and 222,000 t of agricultural waste annually. Wood chips are produced during the chipping process at the fuel yard, while the agricultural wastes are supplied from within 100 km radius of the plant.

The CFB boiler has a steam flow of 570 t/h, steam pressure of 127.2 bar and a temperature of 565°C. The steam generated by reheating has a pressure of 20 bar and a temperature of 565°C.

The heating surfaces are provided with moderate thermal loading and the fuel is added to the furnace along with additives to prevent accumulation of unwanted materials and fouling of the furnace. Measures to avoid corrosion and fouling of the convective pass are also taken into consideration by applying corrosion resistant materials. Corrosion and fouling of the boiler is constantly checked by the online diagnostics systems which have been installed.

## 5.9 Surat high sulphur Indian lignite CFB plants

India's demand for coal-based electric power is forecast to increase dramatically over the next few decades (Barnes, 2014) and coal resources of relatively low quality are considered necessary to meet this demand, including high sulphur lignites. Lakshminarasimhan and others (2013) have described BHEL's experience in utilising this challenging fuel in a 2 x 125 MWe CFB units at Surat that have been modified specifically to burn the high sulphur lignites efficiently. Their principal findings are summarised below.

The fuel and steam design parameters of the 125 MWe CFBC units are set out in Table 22 below.

Table 22 Design parameters of BHEL's Surat plant					
Parameters	Units	Design	Parameters	Units	Value
Main Steam			Proximate Analysis (as-fired)		
Flow	kg/s	112.5	Moisture	%wt	40.0
Pressure	bar	134.6	Ash	%wt	15.0
Temperature	°C	540	Volatile matter	%wt	20.0
Reheat Steam			Fixed carbon (by diff)	%wt	25.0
Flow	kg/s	93.3	High Heating Value	MJ/kg	12.56
Outlet Pressure	bar	33.2	Ultimate Analysis (dry ash free)		
Outlet Temperature	°C	540	Carbon	%wt	66.9
Feed Water			Hydrogen	%wt	4.9
Temperature	°C	236.8	Sulphur	%wt	13.3
			Nitrogen	%wt	0.9
			Oxygen	%wt	14.0

### Plant configuration

The pre-crushed lignite is extracted from the storage bunkers by two variable speed extraction drag-link chain conveyors and fed into the seal pot through rotary valves and slide gates, which can isolate the fuel feed system from the combustor in case of an emergency. The system has two parallel coal feed lines, both of which need to be operated for optimal fuel combustion. Inert material such as bed ash or sized sand, required for initial start-up, is fed to the combustor directly by gravity through a rotary valve. Pre-sized limestone stored in silos is gravity fed through variable speed rotary valves at a rate based on the SO<sub>2</sub> content in the flue gas.

Ash is removed from four different locations in the system. Coarse bed ash from the lower combustor, bed ash from the FBHE, fly ash from the collection hoppers below the convective pass and air heater sections, and fly ash from the electrostatic precipitator. In order to maintain an appropriate solids inventory in the combustor, bed ash is extracted continuously from the lower combustor and furnace bottom heat exchanger (FBHE) through a cooled ash discharge.

Combustion air is supplied to the combustor in two main streams. Two fans supply pre-heated primary air that is introduced through a wind box and grate assembly located at the bottom of the lower (refractory lined) section of the combustor. Similarly two fans supply preheated secondary air, which is



delivered into the lower combustor region through multiple ports in the walls. Fluidising air for FBHEs, seal pots, ash coolers and purge & seal air also form part of the combustion air. Flue gas leaves the combustor and passes through the cyclones, convective pass, tubular air heaters, and electrostatic precipitators. Two centrifugal-type induced draft fans ensure near atmospheric pressure at the outlet of the cyclones. The convective back pass consists of horizontal superheater, reheater and economiser surfaces with tubular air heaters for additional heat recovery.

The start-up system consists of two independent start-up burners supplied with air from the secondary air fans arranged on the sidewalls of the combustor. These are used for preheating the combustor system and the ash inventory to the ignition temperature of fuel oil. Fuel oil lances (six units) are then used to further heat up the ash inventory to the ignition temperature of the lignite fuel.

Feed water enters the in-line horizontal economiser tubes located in the convective back pass. The steam drum receives sub-cooled water from the economiser and feeds the evaporators. The evaporative surfaces of the boiler consist of the combustor water walls, the FBHE water walls and a tube bundle in the FBHE. A system of down-tubes, distribution supply pipes and headers and relief tubes ensure adequate flow through the evaporator circuits. Drum internals separate and purify the saturated steam before it feeds the steam-cooled hanger tubes and the enclosure of the convective pass. The steam is further heated in the superheater stage I (a horizontal in-line tube bundle) located above the economiser in the convective pass. After a first stage attemperation the steam flows to the second stage superheater, which is arranged in two parts in the FBHEs. The second stage attemperation is arranged between second stage superheater and the final superheater. The final superheater is the first heat transfer surface in the back pass and is an in-line horizontal tube bundle.

Cold reheat steam enters the first stage reheater located in the FBHE. The final reheater stage is located in the convective pass after the final superheater and before the economiser. Reheat steam temperature is primarily controlled by the FBHE cone valve, that controls the ash flow through the FBHE containing the reheater. A spray type attemperator located between two stages of reheater is used as a secondary control.

### **Operating experience**

There were three occurrences of unit outage due to ash hold-up in the cyclone at very low loads of about 20 MW and one suspected blockage of the cyclone standpipe at about 70 MW load. An investigation into the incidents concluded that the most probable cause was the recarbonation of calcined limestone that had not reacted with sulphur.

The remedial steps were taken to prevent further outages attributable to cyclone standpipe blockage were:

- the limestone feed size was checked continuously with additional sampling;
- the limestone feeder size was optimised by fitting blanking plates to some of its feed cells;

- the operation procedure was revised to maintain higher combustor temperatures before commencing limestone addition;
- the incorporation of automatic air pulsing at the junction of the cyclone and standpipe to disturb any agglomeration.

It was also found from sampling that the limestone size was much finer than recommended. This resulted in a high throughput during low loads because the SO<sub>2</sub> measurement was not available to control the volumetric feeder of the limestone.

After incorporation of these changes, the issue was resolved. The timing of pulsing air has been subsequently reduced, as it was found that the gas temperature is a key parameter in avoiding the formation of sticky deposits.

Heavy and rapid deposit build-up on the flue gas side of the heat transfer tubes has also been experienced in the back pass of the boiler. The deposit build up was most severe at the low temperature superheater tube bank. There were also growths of ash deposits in the final stage reheater tube bank during the initial period of operation. This deposit increased the gas-side pressure drop and in turn forced the operation of the ID fans at high current loads, causing boiler trips.

The deposit problem occurred during boiler loading after resolving the cyclone blockage problem when the limestone feed rate was increased to maintain the SO<sub>2</sub> emissions within limits. The formation of sticky deposits as in the cyclone was suspected as the initiator for the formation of these deposits. In order to determine if this was correct, samples were taken by a probe in the back-pass tube location to collect initial ash deposits, before long term exposure converted the calcium carbonate to calcium sulphate. The results of the detailed study clearly indicated that recarbonation of free lime followed by slow sulphation of the deposit was the primary mechanism of fouling. Improvements in the soot blowing mechanism along with an increase in its frequency have helped in overcoming the fouling issue.

After the implementation of high pressure soot blowers (Figure 14) along with a fluidisation arrangement for smooth evacuation of the ash falling onto the hoppers, full load operation with limestone addition to ensure sulphur capture of more than 98% (versus 97% design) was achieved.



before sootblowing

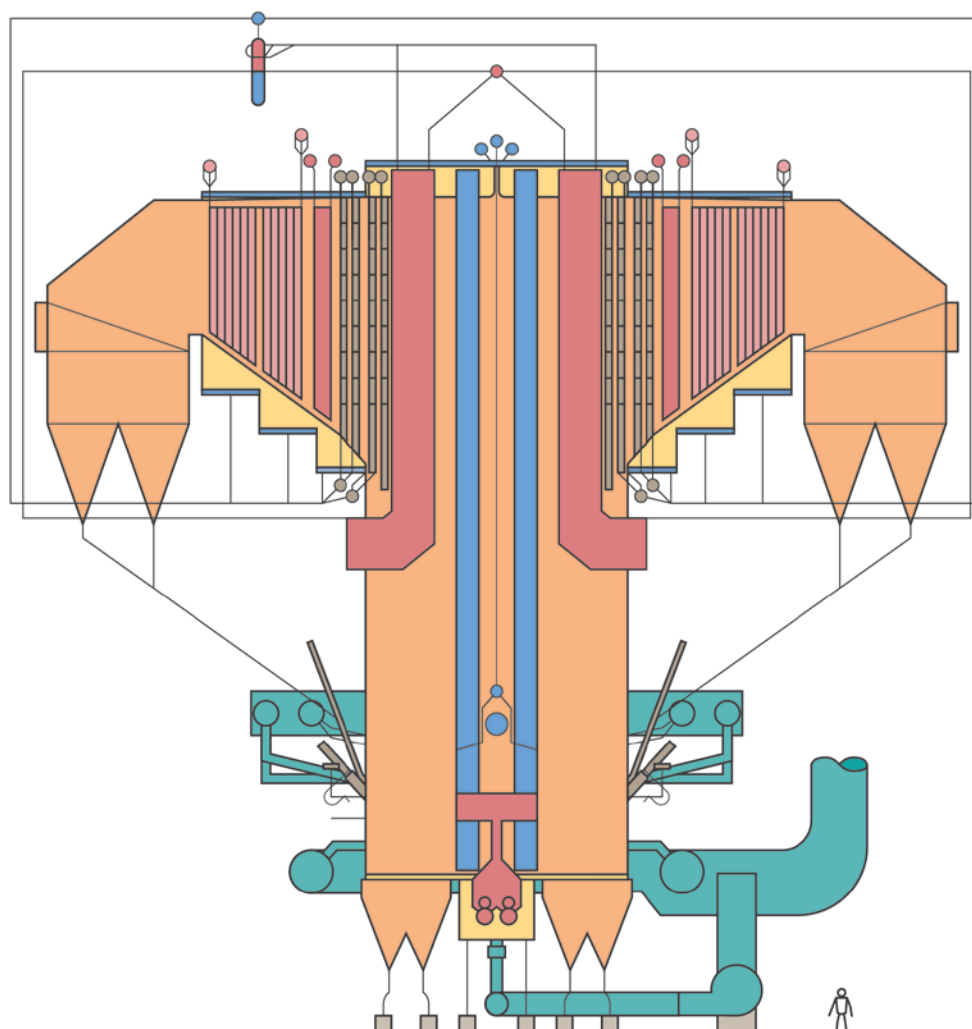


after sootblowing

**Figure 14 Implementation of high pressure soot blowers on gas path** (Lakshminarasimhan and others, 2013)

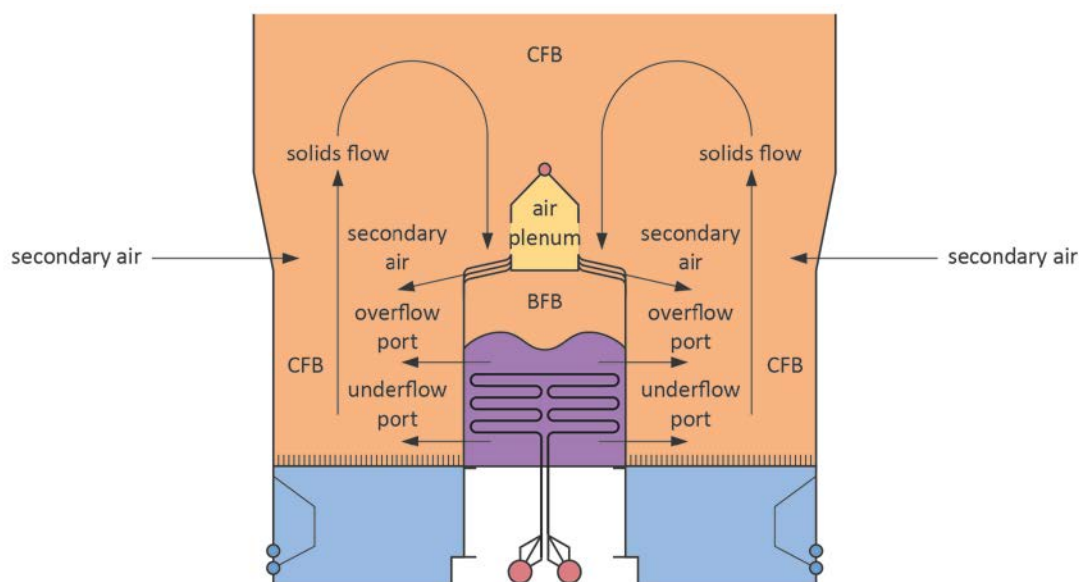
### 5.9.1 B&W's high sulphur Indian lignite experience

Anderson and others (2014) described their experience of burning Indian washery rejects in a supercritical once-through CFB unit. This type of unit has been developed based on the experience and expertise obtained from B&W's CFB, BFB, and supercritical once-through boiler designs. Figure 15 sets out the layout of this type of unit featuring an in-bed heat exchanger (IBHX).



**Figure 15 B&W supercritical once-through CFB with IBHX** (Anderson and others, 2014)

The boiler aspect ratio of the supercritical CFB design has been optimised by using dual primary zones in the furnace sharing a common upper furnace shaft. This reduces the furnace enclosure perimeter by making it squarer as opposed to rectangular. In addition, an air plenum is introduced in the centre of the furnace providing secondary air to each of the primary zones. This allows increased furnace depth while maintaining secondary air penetration within industry standards for emissions. Internal to the furnace between the dual primary zones is a bubbling fluidised bed (BFB), designated IBHX. The bubbling bed is fluidised at approximately 1 m/s compared to the CFB which is typically fluidised at approximately 5 m/s. Due to the entrainment in the CFB furnace, solids are transported into the BFB as shown in Figure 16. A surplus of solids is carried into the BFB, and for mass balance, the equivalent amount of solids flows through the underflow ports and overflow ports. Solids flow through the underflow port is varied through localised slumping, and is thus controllable. Excess solids that do not flow through the tube bundle through the underflow port flow out of the overflow ports, maintaining a constant bubbling bed level, and therefore constant pressure differential across the bed. Ultimately, the ability to control solids flow through the underflow port can be directly related to the ability to control absorption in the tube bundle and has been verified through hot pilot testing facilities located at Southeast University in Nanjing, China.



**Figure 16 IBHX Functionality** (Anderson and others, 2014)

Supercritical once-through CFB is claimed to be a good technology for washery rejects as it combines the benefits of a CFB (fuel flexibility, ash contents up to 60%, heating values as low as 1800 kcal/kg, low emissions), and the benefits of a BFB having in-bed surface (exceptional heat transfer characteristics), with the benefits of supercritical circulation (superior plant efficiency with steam conditions capable of greater than 270 kg/cm<sup>2</sup> with 600°C superheat, 60°C reheat). In addition, a two-stage separation system (proven technology in India through 18 CFBs firing washery rejects) offers significant advantages over cyclone technology.

For high ash fuels, as is the case with washery rejects, a reliable bottom ash handling system is required to handle the quantity and constant removal of ash from the CFB. Water-cooled screws have been successfully operating for over 20 years in an IR-CFB boiler in Ebensburg, Pennsylvania, USA (waste fuel with 40% to 50% ash). As a result, the plant has experienced no forced outage time due to the ash handling system. Similarly, successful operation of water-cooled rotary ash coolers for waste fuel with a high ash removal rate at a 250 t/h washery rejects boiler located at a ferro-alloy unit in eastern India has been demonstrated. Again, no forced outages have been experienced due to the ash handling system. The cooling water in the ash handling system can utilise an open or closed loop system — the open loop system being the most simple and the closed loop system providing the advantage of improved plant efficiency and reduced water consumption in regions where water availability is scarce. Heat is recovered to the system with low pressure condensate heating.

Although a CFB plant is capable of burning a wide range of fuels, Nakao and others (2011) have drawn attention to the issues that arise when a plant burns different fuels on a short-term basis and in particular, blends of fuels. They described JFE Engineering's experience of the combustion of a range of waste-derived fuels where fluctuations in the combustling point, local high temperature, instability of the properties of the combustion gas, and similar problems tend to following variations in the properties of the fuels. To address these issues they developed a combustion control system which made it possible to

achieve optimum stable combustion and demonstrated its applicability on commercial plants. In summary, in conventional combustion air flow control, the air flow rate settings for primary combustion air and secondary combustion air are a function of the energy content of the fuel input. Thus, the combustion velocity, main combustion location, burnout point, etc, change, depending on changes in the input ratio/properties of the fuels and the boiler load. In some cases, this results in deviations and a local rise in the furnace temperature. On the other hand, in order to suppress thermal NO<sub>x</sub>, it is necessary to keep the furnace temperature within a certain range, and to prevent generation of agglomerated ash deposits, the temperature in the entire furnace must not exceed 1000°C. Prevention of excessive rises in the temperature of downstream parts, such as the cyclone outlet temperature, is also important from the viewpoint of protection of the bag filter and other equipment. The authors developed a control system using rule-based control, in which the target temperatures in the various parts of the furnace are set based on the fuel charging ratio and past temperature records, and the balance of the combustion air flow rates from the four air injection ports is adjusted so as to follow those targets. In this combustion air balance control, optimum combustion of the fuel is maintained in all parts of the furnace as far as possible, and the temperatures in the various parts of the furnace are smoothed by changing the balance of air injected into the furnace for the four inlets. A demonstration test was conducted in two CFB plants and the effect was confirmed that the furnace temperature and exhaust gas condition could be stabilised, and the fan driven power could be reduced by the reduction of combustion air.

## 6 Discussion and conclusions

Globally a very significant resource exists in the form of the so-called low value, or low grade fuels, and these materials can be a valuable resource that is increasingly exploited in combination with coal, or separately. These fuels are attractive for a number of reasons, especially in having a sufficiently low cost that justifies their use. Furthermore, as otherwise waste materials that have a relatively high disposal cost, this cost can be offset or eliminated by using them for energy generation.

The properties of low value fuels vary extremely widely, depending on their origin. Many are high in the relatively inert components of mineral matter and water, while others contain elements that can be deleterious to combustion technology and may be significant pollutant precursors. Despite these drawbacks, the use of these materials has increased significantly in recent years and is likely to continue this trend for the foreseeable future.

Unlike competing technologies such as pulverised coal fired plant, CFBC plants are particularly well suited to burning low grade fuels or mixtures of these materials with other fuels, eg coal. This arises from basic design factors such as the large amount of inert bed material in a CFBC which makes it possible to have considerable variation in fuel properties, or to change fuels online without significant disruption to the combustion process. The circulating solids improve heat transfer and make it possible to burn also high energy content fuels while maintaining the combustion temperature in the region 850–900 °C. A low combustion temperature minimises fouling and slagging of heat surfaces since ash melting and softening points are generally much higher than combustion temperature in CFB. The low temperatures also make emission control also more straightforward. CFB's solids circulation provides a long residence time for fuel and limestone particles meaning high combustion efficiency and low sorbent consumption.

However, certain fuel properties can pose challenges to the design and operation of a CFB plant, specifically the low inherent energy content, a high proportion of inert material and the presence of components that can give rise to problems of ash deposition and corrosion within the boiler. Different manufacturers have tackled these issues to ensure the availability of reliable plant with considerable success. It is safe to say that CFB-based plants are the technology of choice for utilising low value fuels, either singly or in combination with coal.

## 7 References

**Adams, D (2013).** *Sustainability of biomass for cofiring*. CCC/230, London, UK, IEA Clean Coal Centre, 63 pp (Dec 2013)

**Alstom (2011)** Case study: Baima – China. Circulating Fluidised Bed (CFB) Boiler. Alstom Power, Brown Boveri Str. 7, 5401 Baden, Switzerland

**Anderson S, Nair R, Subramaniam C R (2014).** Efficient Combustion of Waste Fuel with Supercritical CFB Technology. Presented to NTPC Global Energy Technology Summit 2014, November 7-9, 2014, New Delhi, India. Available at <http://www.doka.ch/DokaCoalTailings.pdf>, Zurich, Switzerland, Swiss Centre for Life

**Barnes D I (2014).** *Upgrading the Efficiency of the World's Coal Fleet to Reduce CO<sub>2</sub> Emissions*. CCC/237, London, UK, IEA Clean Coal Centre, 99 pp (Jul 2014)

**Biofuels Association of Australia (2015).** What is biomass? Available at: <http://www.biofuelsassociation.com.au/>

**Canadian Association of Petroleum Producers (CAPP) (2013)** The facts on oil sands. Available from: <http://www.oilsandstoday.ca>

**Commodities Now (2012)** Petroleum Coke: Global Industry Markets and Outlook. *Commodities Now Magazine*. London (Aug 2012)

**Compliance (2009)** 20-23 March 1995. Washington, DC, USA, Coal & Slurry Technology Association, Cycle Inventories Ecoinvent Centre, 29 pp (November 2009)

**Darling S (2007)** CFB Technology. Clean, Economic and Efficient Steam and Power Generation for the Oil Sands Industry. GEPAFTP October 11, 2007.

**Doka G (2009)** Life Cycle Inventory of the disposal of lignite spoil, coal spoil and coal tailings.

**Doosan Lentjes (2015a)** Bhavnagar circulating fluidised bed combustion plant. Available at: <http://www.doosanlentjes.com/en/cfbt/>

**Doosan Lentjes (2015b)** Gardanne – Coal to biomass conversion. Available at: <http://www.doosanlentjes.com/en/cfbt/>

**Doosan Lentjes (2015c)** Starobeshevo circulating fluidised bed combustion. Available at: <http://www.doosanlentjes.com/en/cfbt/>

**FAO (2013)** FAO Statistical Yearbook 2013. *World food and agriculture*.

**Gauvillé P, Foucher J-C, Moreau D (2011)** Achievable combustion efficiency with Alstom's CFB boilers for burning discard coal. FSA 2011, Industrial Fluidisation South Africa: 31–45. Edited by A. Luckos & P. den Hoed Johannesburg: Southern African Institute of Mining and Metallurgy (2011)

**Góral D, Wylenżek A (2012)** Foster Wheeler Energia Polska The efficient coal alternative: Petroleum coke-fired CFB boilers in Europe. Presented at Coal Gen Europe Warsaw, Poland. February 14-16, 2012

**ICIS (2013)** Closures of coal-fired plants support French winter peak contracts. Retrieved from <http://www.icis.com/>

**Immirzi, C P, Maltby, E, Clymo, R S (1992)** The Global Status of Peatlands and their Role in Carbon Cycling. A Report for Friends of the Earth by the Wetland Ecosystems Research Group, University of Exeter. Report No. 11. Friends of the Earth, London, UK.

**International Peat Society (2015)** Available at: <http://www.peatsociety.org/>



- Johari A, Mat R, Alias H, Hashim H, Hassim M H, Zakaria Z Y, Rozainee M (2014)** Combustion Characteristics of Refuse Derived Fuel (RDF) in a Fluidized Bed Combustor. *Sains Malaysiana* 43(1)(2014): 103–109
- Joosten, H, Clarke, D (2002)** Wise Use of Mires and Peatlands, International Mire Conservation Group and International Peat Society, Jyväskylä, Finland.
- Guo H (2009)** Coal, oil shale, natural bitumen, heavy oil and peat – Vol. II -The Chemistry of Shale Oil and Its Refining.
- Katambula H, Gupta R (2009)** Low-grade coals; a review of some prospective upgrading technologies. *Energy & Fuels*; 23 (7); 3392-3405 (July 2009)
- Kokko A (2013)** CFB's Fuel Capabilities – Utilisation of Wide Range of Local Fuels. *Power Gen Asia*. October 2-4, 2013. Impact Exhibition & Convention Centre, Bangkok, Thailand.
- Koornneef J, Junginger M, Faaij A (2007)** Development of fluidised bed combustion – an overview of trends, performance and cost. *Progress in Energy and Combustion Science*; 33 (1); 19-55 (Feb 2007)
- Leonard J W, Lawrence W F (1973)** Waste coal reclamation. In: ACS Division of Fuel Chemistry
- Lewitt M (2011)** *Opportunities for fine coal utilisation*. CCC/185, London, UK, IEA Clean Coal Centre, 94 pp (Aug 2011)
- Lindström, O (1980)**. The technology of peat. *Ambio* 9: 309-313
- Lakshminarasimhan M, Ravikumar B, Lawrence A, Muthukrishnan M (2013)** High Sulphur Lignite Fired Large CFB Boilers-Design and Operating Experience: In: *10th International Conference on Circulating Fluidised Beds and Fluidisation. Technology - CFB-10*, Eds, ECI Symposium Series, Volume RP7 (2013)
- Maryamchik M, Wietzke D L (2012)** B&W PGG IR-CFB: Operating Experience and New Developments. 21st International Fluid Bed Combustion Conference Naples, Italy June 3-6, 2012
- Metcalf, Eddy (eds) (1991)** Wastewater engineering—treatment, disposal and reuse. 3rd ed. New York, USA: McGraw Hill (1991)
- Mills S J (2011)** *Global perspective on the use of low quality coals*. CCC/180, London, UK, IEA Clean Coal Centre, 80 pp (Jan 2011)
- Moghtaderi B, Ness J (eds) (2007)** Coal-biomass cofiring handbook, Cooperative Research Centre for Coal in Sustainable Development, Pullenvale, Qld, Australia, 284 pp, (2007)
- Nakao N, Shimamoto, Yamamoto K (2011)** CFB Combustion Control System for Multiple Fuels. JFE Technical Report No. 16 (Mar 2011)
- Oil Shale and Tar Sands Programmatic EIS (2015)** Available at: <http://ostseis.anl.gov/eis/index.cfm>
- Outotec (2015)** Outotec Energy Products. Available at: <http://www.outotec.com/>
- Peltier R (2010)** Cleco's Madison Unit 3 uses CFB technology to burn petcoke and balance the fleet's fuel portfolio. *Power* 08/01/2010 Available at: <http://www.powermag.com/>
- Power technology (2015)** Polaniec Biomass Power Plant, Poland. Available from <http://www.power-technology.com/>
- Schimmoller B K, Jacobsen P S, Hucko R E (1995)** Prospects for reclaiming fine coal from slurry ponds. In: *International Technical Conference on Coal Utilization & Fuel Systems*. 20th international technical conference on coal utilization and fuels systems, Clearwater, FL (United States), 20-23 Mar 1995.
- WEC (2013)** World Energy Resources: Coal. Published by the World Energy Council 2013

**World Bank (2012)** What a waste: a global review of solid waste management. Urban development series knowledge papers.

**Yamamoto K (2001)** Biomass Power Generation by CFB Boiler. NKK Technical Review No.85 (2001)

**Zhu Q (2012)** *Update on lignite firing*. CCC/201, London, UK, IEA Clean Coal Centre, 75 pp (Jun 2012)

Appendix - Global CFB plants utilising low grade fuels

Country	UNIT	PLANT	COMPANY	MW	STATUS	Year	UTYPE	FUEL	FUELTYPE	ALT.FUEL	SSMMR	BOI/TYPE	TURBM/R	TURBTYPE	GENM/R	GENTYPE	SLFOW	SPRESS	STYPE	STEMP	REHEAT1	REHEAT2	PARTICL	PARTM/R	SOCCTL	FGM/R	NOXCTL	NOXM/R	AE	CONSTRUC	COOL
AUSTRALIA	ARBON ISLAND MILL 1	ARBON ISLAND MILL	IPP INDUSTRIES HOLDINGS PTY LTD	200	1997	2015	LIG	BIOMASS	COAL	SP/NEI	ACFR	ABB	BB	WH			13.9	45	SUBCR					ACFR	N/A						
AUSTRALIA	CLAYTONTON 1	CLAYTONTON	CLAYTON POWER ENERGY LTD	200	1998	2015	REF	BIOMASS	COAL	SP/NEI	ACFR	ABB	BB	WH			13.9	45	SUBCR					ACFR	N/A						
AUSTRALIA	TUMUT MILL 1	TUMUT MILL	IPP INDUSTRIES HOLDINGS PTY LTD	200	1997	2015	WOOD	BIOMASS	LIG	COAL	SVARNER	ACFR	ABB	ABB	ABB			60	SUBCR				MUL/BH	ACFR	N/A						
AUSTRIA	ALTHEIM PLANT 1	ALTHEIM PLANT	WIENER HAGER MOBEL GMBH	0	2009	1990	2015	WOOD	OIL	BIRO	ACFR	SIEMENS		SIEMENS					SUBCR					ACFR	N/A						
AUSTRIA	ALTHEIM PLANT 2	ALTHEIM PLANT	WIENER HAGER MOBEL GMBH	1	2009	1990	2015	WOOD	OIL	BIRO	ACFR	SIEMENS		SIEMENS					SUBCR					ACFR	N/A						
AUSTRIA	HEILGENKRUZ 1	HEILGENKRUZ	BIOMASSE KW HEILGENKRUZ	11.4	2009	2009	2015	WOOD			ACFR	MAN	MARCA C11				11.9	105	SUBCR					ACFR	N/A						
AUSTRIA	HANAUER RIESEN 1	HANAUER RIESEN	WERNER ENERGIE KUNDSCHNITTE BOM	24.1	2009	2009	2015	WOOD	NONE	PW	ACFR	SIEMENS	SET-400	SIEMENS			12.5	50	SUBCR					ACFR	N/A						
AUSTRIA	TIMELEAM 3A	TIMELEAM 3A	ENERGIE AG OBERNOSTERREICH	14.3	2009	2009	2015	WOOD	BIOMASS	AUSTENG	ACFR	BBC		BBC			13.9	45	SUBCR					ACFR	N/A	SCR	PW		REPO/INT	REPO/INT	
BELGIUM	LANGERBERGUE STORA 2	LANGERBERGUE STORA	STORA ENSO OY	4	2009	2013	2015	WOOD	ROP	METSO	ACFR	SIEMENS		SIEMENS			45	65	SUBCR				BH	METSO	FGD	METSO				POBYR	
BELGIUM	DOSTROZEBKE 1	DOSTROZEBKE	ABS ENERGY	25.1	2009	2010	2015	WOOD	NONE	PW/D	ACFR	MAN	MARCO-04				12	88	SUBCR					ACFR	N/A						PROKON
BRAZIL	PORTO TRIMBATAS S1	PORTO TRIMBATAS	MINERAGAO RIO DO NORTE SA	8	2009	1987	2017	WOOD	NONE	DUTO	ACFR			NO-METAL			12	66	SUBCR					ACFR	N/A						PROKON
CANADA	WINDFORTHVILLE COGEN 1	WINDFORTHVILLE COGEN	ENERGY ENERGY INC	2	2009	2010	2015	REF	COAL	WINDFORTHVILLE	ACFR								SUBCR					ACFR	N/A						PROKON
CANADA	WINDFORTHVILLE COGEN 2	WINDFORTHVILLE COGEN	ENERGY ENERGY INC	23.8	2009	2010	2015	WOOD	COAL/OIL	DUTO	ACFR						41.8	85	SUBCR				BH	ACFR	N/A						PROKON
CANADA	DAPP 1	DAPP	PORTSTAR BIOMASS GROUP LLC	1	2009	2000	2017	PEAT	WOOD	BW	ACFR	DRESSER		EMC				82	SUBCR					ACFR	N/A						PROKON
CANADA	POINT ACORN 1	POINT ACORN	NOVA SCOTIA POWER INC	210	2009	1994	2017	COKE	COAL	PHRO	ACFR	TOSHIBA		TOSHIBA			157.1	124	SUBCR				BH	ACFR	N/A						PROKON
CANADA	WHITECOURT 1	WHITECOURT	CARTROPE INFRASTRUCTURE CORP	21.5	2009	1994	2017	WOOD	NONE	DUTO	ACFR	GE		GE			27.7	95	SUBCR				BH	ACFR	N/A						PROKON
CHILE	MAUK SANJA RE 1	MAUK SANJA RE	MAUK SANJA RE	80	2009	1994	2015	WOOD	NONE	PW	ACFR	SIEMENS	SET-400	SIEMENS					SUBCR					ACFR	N/A						PROKON
CHILE	TALCAHUANO REFINERY 1	TALCAHUANO REFINERY	PETROPOWER ENERGIA LTDA	76.1	2009	1998	2015	COKE	NONE	PW	ACFR	GE		GE			65.7	103	SUBCR					ACFR	N/A						PROKON
CHILE	VINALES 1	VINALES	ARAUCO GENERACION SA	4	2009	2012	2015	WOOD		METSO	ACFR	SIEMENS		SIEMENS			58.1	85	SUBCR					ACFR	N/A						PROKON
CHINA	BAOYING COGEN 1	BAOYING COGEN	GCL-POLY ENERGY HOLDINGS LTD	19	2009	2009	2015	BIOMASS	COAL	JIN-BOL	ACFR	NANJING	FX		SIEMENS			20.8		SUBCR				ESP	ACFR	N/A					PROKON
CHINA	BAOYING COGEN 2	BAOYING COGEN	GCL-POLY ENERGY HOLDINGS LTD	19	2009	2009	2015	BIOMASS	COAL	JIN-BOL	ACFR	NANJING	FX		SIEMENS			20.8		SUBCR				ESP	ACFR	N/A					PROKON
CHINA	CHANGCHUN BIOMASS 1	CHANGCHUN BIOMASS	CHANGCHUN BIOMASS	15	2009	2010	2015	BIOMASS	STRAW											SUBCR					ACFR	N/A					PROKON
CHINA	CHANGCHUN BIOMASS 2	CHANGCHUN BIOMASS	CHANGCHUN BIOMASS	15	2009	2010	2015	BIOMASS	STRAW											SUBCR					ACFR	N/A					PROKON
CHINA	DEIZING WTE 1	DEIZING	CHINA POWER NEW ENERGY DEV CO	4	2009	2010	2015	REF			ACFR									SUBCR					ACFR	N/A					PROKON
CHINA	GUOXIN SIYANG 1	GUOXIN SIYANG	JINOSU GUOXIN NEW ENERGY DEV	12	2009	2009	2015	BIOMASS	STRAW		ACFR									SUBCR					ACFR	N/A					PROKON
CHINA	GUOXIN SIYANG 2	GUOXIN SIYANG	JINOSU GUOXIN NEW ENERGY DEV	12	2009	2009	2015	BIOMASS	STRAW		ACFR									SUBCR					ACFR	N/A					PROKON
CHINA	HANGZHOU QIAO1	HANGZHOU QIAO1	HANGZHOU JINJIANG GROUP CO LTD	8	2009	2009	2015	REF	COAL	HANGZHOU	ACFR									SUBCR					ACFR	N/A					PROKON
CHINA	HANGZHOU QIAO2	HANGZHOU QIAO2	HANGZHOU JINJIANG GROUP CO LTD	8	2009	2009	2015	REF	COAL	HANGZHOU	ACFR									SUBCR					ACFR	N/A					PROKON
CHINA	HARBIN WTE 1	HARBIN WTE	HARBIN CITY GOVERNMENT	2	2009	2002	2017	REF		EBARA	ACFR	EBARA								SUBCR				BH	ALSTOM	DCSB	ALSTOM				PROKON
CHINA	HEBEI LINGDA 1	HEBEI LINGDA	HEBEI LINGDA ENV-FRIENDLY ENER	12	2009	2009	2017	REF		WUKI	ACFR									SUBCR				BH	DCSB/AC						PROKON
CHINA	HEBEI LINGDA 2	HEBEI LINGDA	HEBEI LINGDA ENV-FRIENDLY ENER	12	2009	2009	2017	REF		WUKI	ACFR									SUBCR				BH	DCSB/AC						PROKON
CHINA	HEFEI CITY 1	HEFEI CITY	HEFEI THERMOELECTRIC GROUP CO	11	2009	2012	2015	REF	NONE		ACFR									SUBCR					ACFR	N/A					PROKON
CHINA	HEFEI CITY 2	HEFEI CITY	HEFEI THERMOELECTRIC GROUP CO	11	2009	2012	2015	REF	NONE	PSIA	ACFR									SUBCR					ACFR	N/A					PROKON
CHINA	HEFEI CITY 3	HEFEI CITY	HEFEI THERMOELECTRIC GROUP CO	6	2009	2012	2015	REF	NONE	PSIA	ACFR									SUBCR					ACFR	N/A					PROKON
CHINA	JIANGSUJIANG 1	JIANGSUJIANG	CHINA LONGJIAN POWER GROUP	19	2009	2010	2015	BIOMASS	RICE		ACFR									SUBCR					ACFR	N/A					PROKON
CHINA	JIANGSUJIANG 2	JIANGSUJIANG	CHINA LONGJIAN POWER GROUP	19	2009	2010	2015	BIOMASS	RICE		ACFR									SUBCR					ACFR	N/A					PROKON
CHINA	KAOJI FENGDU 1	KAOJI FENGDU	WUHAN KAOJI POWER INVEST CO	12	2009	2010	2015	BIOMASS	WOOD	HANGZHOU	ACFR	SIEMENS	SET-400	SIEMENS	10.5KV		33.3	133	SUBCR				BH	ACFR	N/A						PROKON
CHINA	KAOJI FENGDU 2	KAOJI FENGDU	WUHAN KAOJI POWER INVEST CO	12	2009	2010	2015	BIOMASS	WOOD	HANGZHOU	ACFR	SIEMENS	SET-400	SIEMENS	10.5KV		33.3	133	SUBCR				BH	ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 1	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 2	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 3	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 4	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 5	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 6	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 7	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 8	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 9	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 10	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 11	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 12	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 13	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 14	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 15	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 16	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 17	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 18	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 19	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR	NANJING		NANJING			18.1	48	SUBCR					ACFR	N/A						PROKON
CHINA	KAOJI JIANLI 20	KAOJI JIANLI	WUHAN KAOJI POWER INVEST CO	12	2009	2009	2015	BIOMASS	AGWST		ACFR																				

Appendix – Global CFB plants utilising low grade fuels																															
Country	Plant	Company	MW	Status	Year	UTYPE	FUEL	FUELTYPE	ALTUEL	SSMFR	BOILTYPE	TURBMFR	TURBTYPE	GENMFR	GENTYPE	FLOW	SPRESS	STYPE	STEMP	REHEAT1	REHEAT2	PARTCTL	PARTMFR	SO2CTL	FGDMFR	NOXCTL	NOXMFR	AE	CONSTRU	COOL	
POLAND	DOSTOLEA MILL 2	DOSTOLEA MILL	20	OPR	2010	OT/TS	BIOMASS	COAL/PWST	METSO	ACFB	HANGZHOU							SUBCR				ESP		ACFB	N/A			POYRY	POYRY		
POLAND	PODAMEC BI	PODAMEC	30	OPR	2010	OT/TS	WOOD	AGWST	PW	ACFB	DAMEN	TE	DOIMEL				156	12	SUBCR	515	58		ESP		ACFB	N/A	SCR		PW	PW	OTF
POLAND	SWIEDE PULP MILL 6	SWIEDE PULP MILL	30	CON	2010	OT/TS	BIOMASS	WOOD		ACFB	SKODA		SEDOA											ACFB	N/A						
POLAND	IZCZCIN 4	IZCZCIN	72	OPR	2000	OT/TS	WOOD	COAL	METSO	ACFB	ALSTOM		ALSTOM				63.9	70	SUBCR	510				ACFB	N/A					POLUDNIE	
ROMANIA	PETROTEL PLOIESTI 4	PETROTEL PLOIESTI	30	OPR	2010	OT/TS	COKE	OIL	PW	ACFB							72.2	100	SUBCR	540			ESP		ACFB	N/A			ISPE		MDT
RUSSIA	MIZ-4 NO 1	MIZ-4	6	OPR	2000	OT/TS	REF			HOLTER	ACFB	KALUGA										BH		SEMI-DRY		SCR					
RUSSIA	MIZ-4 NO 2	MIZ-4	6	OPR	2000	OT/TS	REF			HOLTER	ACFB	KALUGA										BH		SEMI-DRY		SCR					
SCOTLAND	CAMERONBRIDGE DIAGEO 1	CAMERONBRIDGE DIAGEO	6	OPR	2010	OT/TS	BIOMASS	BIOGAS	ENMAX	ACFB							35.0	85	SUBCR				COMB						DALKIA	DALKIA	MDT
SCOTLAND	MARINCHE MILL NEW 1	MARINCHE MILL NEW	60	OPR	2014	OT/TS	WOOD			METSO	ACFB	SIEMENS	SST-800	SIEMENS								BH		OL/AC		PGR		AKER	AKER	AIR	
SOUTH KOREA	HUSOK-4 BIOMASS 1	HUSOK	10	CON	2010	OT/TS	BIOMASS	COAL/WOOD	PW	ACFB												BH	PW	CF	N/A					GSEC	OTS
SOUTH KOREA	HUSAN WTE 1	HUSAN WTE	25.10	OPR	2010	OT/TS	REF	REF		AUSTENG	ACFB																		POSCO	POSCO	AIR
SOUTH KOREA	DAEGU GREEN ENERGY WTE 1	DAEGU GREEN ENERGY	10	CON	2010	OT/TS	REF	REF		PW	ACFB																		GSEC	GSEC	
SPAIN	ENCE HUELVA 1	ENCE HUELVA	50	OPR	2010	OT/TS	WOOD		GAS	ANDRITZ	ACFB	SIEMENS		SIEMENS			50	100	SUBCR	500			ESP		CF	N/A	SNCR		OHL-ES	OHL-ES	
SUDAN	EL GALI-4 NO 1	EL GALI	50	OPR	2009	OT	COKE		CWPC	ACFB	HARBIN		HARBIN											ACFB	N/A				NEPDI	CMEC	
SUDAN	EL GALI-4 NO 2	EL GALI	50	OPR	2009	OT	COKE		CWPC	ACFB	HARBIN		HARBIN											ACFB	N/A				NEPDI	CMEC	
SWEDEN	ABYVERKET 1R	ABYVERKET	24.0	OPR	2012	OT/TS	WOOD			ACFB	KANIS	BT-40																			
SWEDEN	ABYVERKET 1	ABYVERKET	100	OPR	1999	OT/TS	WOOD	NONE	COAL/OL/PE	BOI				ITAL			17.0	80	SUBCR	520		ESP	ALSTOM	ACFB	N/A						
SWEDEN	BISTA 1	BISTA	40	OPR	1999	OT/TS	WOOD		PIRD	ACFB	ABBS	HP25	ABB					144	SUBCR	540					ACFB	N/A					
SWEDEN	DAVA 2	DAVA	49.4	OPR	2009	OT/TS	WOOD			AUSTENG	ACFB	SIEMENS		SIEMENS																P/N/Q/U	AIR
SWEDEN	GALLIVARE KVP1 NO 1	GALLIVARE	8.4	OPR	2010	OT/TS	PEAT		WOOD		ACFB																				
SWEDEN	HANDELO 11	HANDELO	80	OPR	1983	OT/TS	WOOD	COAL/REF	TAMPELLA	ACFB	STAL		ASEA				4	170	SUBCR	510	53	BH	ALSTOM	ACFB	N/A	SNCR	PET-MILI	SIEMENS	SIEMENS	OTF	
SWEDEN	HANDELO 12	HANDELO	10	OPR	1984	OT/TS	WOOD	COAL/REF	TAMPELLA	ACFB	STAL		ASEA				4	170	SUBCR	510	53	BH	ALSTOM	ACFB	N/A	SNCR	ROFARM	SIEMENS	SIEMENS	OTF	
SWEDEN	HANDELO 13	HANDELO	10	OPR	2010	OT/TS	REF	REF	NONE	PWED	ACFB	SIEMENS		SIEMENS				90	SUBCR	470				ACFB	N/A				FWEQ	FWEQ	
SWEDEN	HEDENBYN 1	HEDENBYN	30	OPR	1996	OT/TS	WOOD	PEAT	PIRD	ACFB	ABBS	HP16	ABB					140	SUBCR	540					ACFB	N/A					
SWEDEN	HEDENVERKET 11	HEDENVERKET	30	OPR	1990	OT	WOOD	COAL/GAS/PIR	ALSTROM	ACFB	ABBS						20	60	SUBCR	500		ESP		ACFB	N/A	SNCR					
SWEDEN	HELESTA 1	HELESTA	80	OPR	2009	OT/TS	REF	REF	WOOD	PW	ACFB	SIEMENS	SST-800	SIEMENS			80	90	SUBCR	540		BH		ACFB	N/A	SNCR		WSP	PW/YIT	OTB	
SWEDEN	KARLENSGA KRATFVARN 1	KARLENSGA KRATFVARN	10	OPR	2000	OT/TS	WOOD	NONE	PWED	ACFB	BHV	MARCC-CL1						4	SUBCR	400		BH		ACFB	N/A						
SWEDEN	KATRIKENS 1	KATRIKENS	9.0	OPR	2000	OT/TS	WOOD	PWST	PWED	ACFB	BHV	MARCC-CL1						80	SUBCR	480		BH		ACFB	N/A	SNCR		FWEQ	FWEQ		
SWEDEN	KRISTIANSTAD 1	KRISTIANSTAD ENERGI	10	OPR	1994	OT/TS	WOOD	PEAT	ALSTROM	ACFB	ABBS	MP100H					17.0	60	SUBCR	510				ACFB	N/A						
SWEDEN	KVV VARTAVERKET-III NO 1	KVV VARTAVERKET	130	CON	2010	OT/TS	WOOD	BIOMASS	ANDRITZ	ACFB	SKODA		SKODA					50	SUBCR												OTS
SWEDEN	LOMMA 1	LOMMA	3.0	OPR	1990	OT/TS	WOOD	PWST	ALSTROM	ACFB	ABB		ABB				5.1	60	SUBCR	510		BH		ACFB	N/A						
SWEDEN	LYCKLE 1	LYCKLE	10.0	OPR	2000	OT/TS	WOOD	NONE	PWED	ACFB	BHV	MARCC-HB4					17.0	60	SUBCR	520				ACFB	N/A						
SWEDEN	NASSO 1	NASSO	10	OPR	1980	OT/TS	WOOD	COAL/PEAT	KVAERNER	ACFB	ABBS						33.0	80	SUBCR	490		ESP		ACFB	N/A	SNCR		ABB	ABB	MDT	
SWEDEN	HYBRO PLANT 1	HYBRO PLANT	6	OPR		OT/TS	WOOD	NONE	BW/KVAER	ACFB								10	SUBCR	420					ACFB	N/A					
SWEDEN	ORTOFTA 1	ORTOFTA	30	CON	2014	OT/TS	BIOMASS	STRAW		PW	ACFB	SKODA		SKODA																	
SWEDEN	OSTERSUND 1	OSTERSUND	40.0	OPR	2002	OT/TS	WOOD	PEAT	PW	ACFB	SIEMENS		SIEMENS				50	140	SUBCR	540		ESP		ACFB	N/A	SNCR					
SWEDEN	SANDSVENVERKET 2	SANDSVENVERKET	30	OPR	1980	OT/TS	WOOD	PEAT	PW	ACFB	ABBS	HP16	ABB				4	140	SUBCR	540		ESP		ACFB	N/A	SNCR		FLAKT			MDT
SWEDEN	SCA MUNKSUND 1	SCA MUNKSUND	20	OPR	2000	OT/TS	WOOD	PWST	PW	ACFB	ABBS	HP25					38.0	60	SUBCR	480		ESP	ROTH	ACFB	N/A						
SWEDEN	SODERHAMN 1	SODERHAMN	9.30	OPR	2000	OT/TS	WOOD		AUSTENG	ACFB	MAN	MARCC-HB1	ELIN				11.0	60	SUBCR	500				ACFB	N/A	SNCR					
SWEDEN	VASTERMALMS 2	VASTERMALMS	8.70	OPR	2000	OT/TS	WOOD	PEAT	RPO	ACFB	MAN						10.0	70	SUBCR	500				ACFB	N/A						
SWITZERLAND	HRW AUBRUGG 1	HRW AUBRUGG	10.00	OPR	2010	OT/TS	WOOD	REF	BERTSCH	ACFB	MAN	MARCC-HB1	ELIN				10.0	80	SUBCR	500		ESP									
SWITZERLAND	HRW BASEL 1	HRW BASEL	10	OPR	2000	OT/TS	WOOD		BERTSCH	ACFB	MAN	MARCC-HB1	ELIN				9.0	4	SUBCR	400		BH		ACFB	N/A				TBU	TBU	
SWITZERLAND	NVA FORSTHAUS WEST 1	NVA FORSTHAUS WEST	10	OPR	2010	OT/TS	REF		MARTINER	ACFB	SIEMENS		SIEMENS					60	SUBCR	490		ESP			ACFB	N/A			ELECTRO	KAM	
SWITZERLAND	PERLEN MILL 1	PERLEN MILL	1.64	OPR	1990	OT/TS	PWST	WOOD	PW	ACFB	KKK			SIEMENS										ACFB	N/A	SNCR					
TAIWAN	MALIND RT-CFB 1	MALIND RT-CFB	148.264	OPR	2000	OT/TS	COKE	OIL	ALSTOM	ACFB	ABBT		ABB				138.0	130	SUBCR	400		BH	ALSTOM	NO	ALSTOM	SNCR	ALSTOM	ALSTOM	ALSTOM	ALSTOM	ALSTOM
TAIWAN	MALIND RT-CFB 2	MALIND RT-CFB	148.264	OPR	2000	OT/TS	COKE	OIL	ALSTOM	ACFB	ABBT		ABB				138.0	130	SUBCR	400		BH	ALSTOM	NO	ALSTOM	SNCR	ALSTOM	ALSTOM	ALSTOM	ALSTOM	ALSTOM
THAILAND	CHANG MAI WTE 1	CHANG MAI WTE	25	OPR	1990	OT	REF	COAL	KVAERNER	ACFB	ABBT		ABB																		
TURKEY	ULOP PARK 1	ULOP PARK	130	OPR	2000	OT	BITUMEN		DONGFANG	ACFB	SHANGHAI		SHANGHAI											ACFB	N/A				CSEPI	CMEC	MDT
USA	ALPENA 1	ALPENA	10	OPR		OT	WOOD	SAW	NONE		ACFB											BH		ACFB	N/A						
USA	ARCHBOLD 1	ARCHBOLD	20	OPR	1987	OT	GAS	LGAS	YKW	ACFB	DRESSER		DRESSER											ACFB	N/A				RS		
USA	ATHERTON 1	ATHERTON	0.70	OPR	1980	OT/TS	WSTWSL	COAL	ZIMP	ACFB								4	400	SUBCR			VENT		FGD				ETA		
USA	AUBURN 1	AUBURN	7.0	OPR	1980	OT/TS	WOOD	NONE		ACFB																					
USA	DAY SHORE REPOWER 1	DAY SHORE	350	OPR	2000	OT	COKE	NONE	PW	ACFB	WH	TC1F	WH				1000	2000	SUBCR		100R	BH	BRANDT	ACFB	N/A			PW	PW	OTF	
USA	BILLINGS REFINERY 1	BILLINGS REFINERY	60	OPR	1990	OT/TS	COKE	COG	TAMPELLA	ACFB	MHI	EX					600	1200	SUBCR					ACFB	N/A				WALSH	WALSH	AIR
USA	BRAME ENERGY 3 MADISON	BRAME ENERGY	700.8	OPR	2010	OT	COKE	COAL	PW	ACFB	HITACHI	TC4F	HITACHI				4240	2400	SUBCR		100R	BH	ALLIED	WLSST	HITACHI	SNCR	PW	SHAW	SHAW	CL	
USA	BUENA VISTA BIOMASS 1	BUENA VISTA BIOMASS	20.0	OPR	1987	OT/TS	WOOD	GAS	LURGI	ACFB	SIEMENS		SIEMENS				150	1200	SUBCR			BH		ACFB	N/A				CE/LUR	TIC	
USA	CFB FORMOSA 1	CFB FORMOSA	100	OPR	2010	OT	COKE	COAL/GAS	ALSTOM	ACFB																					
USA	CFB FORMOSA 2	CFB FORMOSA	100	OPR	2010	OT	COKE	COAL/GAS	ALSTOM	ACFB																					
USA	CHINESE STATION 1	CHINESE STATION	20	OPR	1980	OT	WOOD	AGWST	EPI	ACFB	DRESSER		EMC				200	1200	SUBCR			ESP		ACFB	N/A	NH3 II		ULTRA	ULTRA	AIR	
USA	CHOWCHILLA 1	CHOWCHILLA	12.0	OPR	1987	OT	BIOMASS	AGWST	WOOD	EPI	ACFB	GE	GE				120	600	SUBCR			BH</									