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Anthracite Coals: An Overview

Prof. Dr J. Clifford Jones

PROF. DR J. CLIFFORD JONES

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CONTENTS

DEDICATION

The Mayor and Mayoress of Porthcawl.

PREFACE

This book follows naturally from ‘Sub-bituminous coals: An Overview’, which preceded it by a few months. Readers will have noted that the book is dedicated to the Mayor and Mayoress of Porthcawl, Robert and Ann Lee, to whom I am related. As Robert has pointed out to me, in the 19th and early 20th Centuries Porthcawl in South Wales was a centre for export of coal from the nearby coalfields, and these feature in this book. So the dedication has dual significance.

Clifford Jones.
Churchill, Victoria.

1 MAJOR DEPOSITS IN CURRENT OR RECENT USE

1.1 PREAMBLE

In the peat to anthracite series:

peat → lignite → sub-bituminous coal → bituminous coal → anthracite

anthracite is at the extreme, representing its high carbon content and other of its properties including its hardness. The approach taken in this book will be to discuss the properties as they arise in discussions of particular anthracites.

1.2 MAJOR RESERVES

Table 1.1 below gives these, with some details.

Location and reference(s).	Details.
Wales [1].	Aberpergwm mine. Treforgan mine. Nant y Mynydd mine.
Scotland [3].	Anthracite deposits in the Lothians and in the Border Counties.
Swaziland [7].	Maloma Colliery, operated by Xstrata South Africa.
South Africa [8].	Kiepersol mine, eastern Transvaal. Somkhele anthracite mine, Kwa-Zulu Natal. Zululand Anthracite Colliery.
Poland [12,13].	Zaklad Wydobywczo mine, Przetworczy Antracytu Walbrzych-Gaj mine, each in Lower Silesia.
Spain [14].	Anthracite produced in the Astur – Leonesa basin.
South Korea [15].	≈ 4 megatonne per year of anthracite.
North Korea [16].	Larger reserves than in South Korea.
China [18].	The world's largest producer of anthracite.
USA [19].	Production in Pennsylvania.

The Ukraine [23].	>200 million tonnes in the reserves operated by DTEK Sverdlovanthracite LLC.
Vietnam [25].	A major producer and exporter. See comments in the main text.
Russia [29].	Siberian Anthracite one of the major producers.
Germany [30].	Major production in the past but no hard coal mining in Germany beyond 2018.

Table 1.1. Anthracite producing countries.

With reference to the Welsh mines, Aberpergwm and Treforgan jointly constitute the largest anthracite deposits in Europe. Aberpergwm was closed in 1985 and reopened in 1996. There have been difficulties in making it viable, and a return to mothballed status began in 2012 [2]. Nant y Mynydd is open cast and in 2010 produced 1500 tonnes of anthracite per week.

Aberpergwm coal is partly destined for use at the Tata Steelworks in nearby Port Talbot. There it is used not in combustion but as a metallurgical reductant in a blast furnace. If bituminous coal is so used it first has to be carbonised in a coke oven, and there are two useable by-products: coke oven gas and tars. Anthracite for blast furnace use needs no such processing. This point is taken up in a subsequent chapter.

Anthracite from Scotland has been used as a smokeless fuel. There is an obvious common basis between that and the use of anthracite in place of coke in iron making: each is due to the paucity of volatiles[1]. Table 1.2 below gives volatiles contents for representatives of all of the ranks of coal.

Table 1.2 Representative volatiles contents across the range of coal rank.

Lignite	**Sub-bituminous**	**Bituminous**	**Anthracite**
Victoria, Australia: 47.2%[2].	Powder River Basin: 35.7% [4].	Pocahontas coal field, West Virginia: 21.0–29.6% [5].	Wales: 3–8% [6].

Welsh anthracites also find use as smokeless fuels. Below is an illustration of 'anthracite nuts' from Wales for such use.

Plate 1.1. 'Nuts' of Welsh anthracite for use as a smokeless fuel. Image taken from: https://www.google.com.au/search?q=anthracite+nuts+wales&biw=1779&bih=688&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjRxdHDnMfMAhWMI5QKHYeiADAQ_AUIBigB&dpr=1#imgrc=GBbgLjaB2f8WRM%3A

All of the anthracite from the Maloma Colliery is taken to South Africa, there being only a land border between the two countries. In South Africa herself (next row in the table) anthracite from the Kiepersol mine is metallurgical grade, that is, it can be used in a blast furnace. This leads to a point which complements that made in the discussion of such use of Welsh anthracite: not all coals corresponding to the classification anthracite according to criteria set by the standards bodies such as ASTM *are* suitable for such use. A particular anthracite is evaluated for metallurgical use according to certain properties as measured (e.g. [9]) and those selected as metallurgical anthracites sometimes have volatile contents as low as 2%. Anthracites not selected for such use are still very good coals, by reason of their high calorific values, for such applications as steam raising. Obviously, an anthracite falling short of metallurgical standard as mined can be beneficiated to bring it up to the standard.

The Somkhele anthracite mine produces upwards of a million tonnes a year of anthracite [10]. It is a mere 85 km from South Africa's major commercial port at Richard's Bay and anthracite from the mine is in fact exported through Richard's Bay. The anthracite produced there is metallurgical grade and finds application in metal extraction within South Africa. The Zululand anthracite colliery, which has been in operation much longer than Somkhele, produces around half a million tonnes of anthracite per year [11]. It is still known by that name since the reorganisation that led to the creation of the KwaZulu-Natal Province. These two major anthracite mines in KZN have different operators. Brazil imports anthracite from South Africa as does Morocco.

The Zaklad Wydobywczo and Przetworczy Antracytu mines in Poland produce about 200000 tonnes per year of anthracite [20] some of which is used in power generation at Kozienice Power Station, which receives more coverage later in this text. The Spanish anthracite referred to is to the north of the country and the anthracite co-exists with lower ranks of coal. The anthracite there is mined by Hullera Vasco Leonesa. Some of it is diverted to power generation, where it is blended with bituminous coal [14]. The anthracite produced in South Korea (following row) is used in power generation and in domestic heating (see also Chapter 13). Much of the anthracite in North Korea is exported to China (4.6 million tonnes in 2010). China is however a net exporter of anthracite [17] and, as noted in the table, is by far the world's largest producer of it; it has been so for at least a century. The 2011 production was 476 million tonnes [18].

Moving on to the USA, Pennsylvania is the only one of the lower 48 states with anthracite production. Its current production stands at ≈ 1.5 million tonnes per year: it was about five times this in the late 1990s [20]. Some is exported to Canada and some is used locally in heating. There are non-thermal applications of anthracites which will be dealt with in turn in later parts of the book. In anticipation we note that anthracite from Pennsylvania is used in water filtration. There is anthracite in Alaska although the small size of the resource precludes commercial production [21]. There is however development of an anthracite reserve at Mount Klappan in British Columbia, formerly referred to as the Arctos Anthracite Project [22] (see also Table 3.2).

Anthracite from the Ukrainian concern identified in the table is partly diverted to power generation. The total anthracite reserves of the country are 5.8 billion tonnes [24] and the Ukraine is third amongst the countries of the world in its anthracite reserves (see also section 4.3). The Donetsk Basin, which also features in the next chapter, is a major reserve. The Ukraine is also abundant in coals of other ranks; for example it produces bituminous coal, some for burning and some for coking. Anthracite from Vietnam is metallurgical grade and has been exported to Japan and to southern China for that application [26]. The anthracite deposit is in the Quang Ninh Province of Vietnam which is suitably located for exporting. Plate 1.2 below shows a monolith of anthracite from Quang Ninh which is now in a museum there. Its dimensions are given in [27] as being 3.6 m × 2.8 m × 2.2 m. In its own electricity production Vietnam mixes anthracite coal with bituminous [28]. Siberian Anthracite is one of the leading Russian producers of anthracite [29], as noted in the table, and its products are metallurgical grade. The target production figure for 2019 is 9.5 million tonnes.

Plate 1.2. Giant monolith of anthracite from Quang Ninh, Vietnam. Image taken from [27].

1.3 USE OF IMPORTED ANTHRACITE

Some countries, e.g. China as mentioned, both produce and import anthracite. It remains to be seen whether once Mount Klappan is productive of anthracite Canada will continue to import it from the USA[3]. In days gone by, long before the reform of the UK coal industry, Welsh anthracite was exported to countries including France, Switzerland, Italy, Egypt and Argentina [32]. Spain, additionally to her own production as noted, has imported anthracite from South Africa as has France.

1.4 ANTHRACITE CULM

This term refers to rejected anthracite from mining. It was once assembled into piles which, increasingly frequently, are being dismantled and put to fuel use. In general anthracite falling below the quality of the intended combustion or metallurgical use is classified as culm. It might well be suitable fuel use, for example in power plants, when it is sometimes simply referred to as 'high-ash anthracite'. This theme is developed in the next chapter.

1.5 PETROGRAPHIC ASPECTS

As a deposit advances along the coalification series the differences between the maceral groups become less marked. Even so vitrinite reflectance is of interest. Determination involves microscopic examination under plane polarised light and is the percentage of the incident light that is reflected by the vitrinite on to which the plane polarised light is focused. For lignites it is often less than 1%. Table 1.2 below gives examples of vitrinite reflectances of selected anthracites.

Origin of the anthracite and reference.	Vitrinite reflectance %.
'Mongolian raw anthracite' [33].	1.09.
Pennsylvania [34].	Up to 6.5.
Bramsche Massif, Germany [34].	Up to ≈ 7.
Chengzhuang, China [35].	3.21.
Spain, the Andes and Portugal [36].	2.62, 5.23, and 6.25 respectively.

Table 1.2. Vitrinite reflectances of anthracites.

It is clear then that high values of the vitrinite reflectance (usual symbol R_o) are expected from anthracites. There has been as assertion [37] based on the examination of large numbers of samples that 7–8% is never exceeded. (See also section 7.1.)

1.6 HARDNESS

In the Hardgrove index determination a known weight of the coal of interest is subjected to a known amount of energy by means of a ball mill. Size analysis of the particles so reduced in size is carried out, and the coal having been tested is placed on a scale from 30 (high resistance to grinding) to 100 (low resistance to grinding). In Table 1.3 below are examples of Hardgrove index values for anthracites.

Reference.	**Details.**
[38]	A value of 36 for a Pennsylvania anthracite.
[39]	Values in the range 21–63 for a large suite of Pennsylvania anthracites.
[40]	Welsh anthracites used to make water filters (see Chapter 6): Hardgrove indices in the range 50–70.
[41]	A range of 20 to 60 for anthracites generally.
[42]	A typical value of 35 given for anthracites.

Table 1.3. Hardgrove index values for anthracites.

The first two rows are both for Pennsylvania anthracites, and in the second row it is shown how wide a spread of Hardgrove indices there can be. The lowest values (representing those most difficult to grind) were for coals from Lackawanna County PA. The highest are for culm, low quality anthracite possibly having previously been discarded as waste (see section 2.2). The spread of possible values is confirmed in the next row.

1.7 HISTORICAL FACETS

The first recorded use of anthracite in Pennsylvania was in 1768 [43] and was on a limited, localised scale. Commercial mining of anthracite there began in 1775 [43], which is of course one year before Independence[4]. In the year 1900 there were 411 deaths and 1057 injuries in the anthracite mines of Pennsylvania [45]. At Cwmamman in South Wales there is anthracite which was dug out and used locally by the mid eighteenth Century. There was only small scale production of anthracite in Wales up to the introduction of the railways [46]. Anthracite was discovered on Rhode Island in 1808 [47] by which time there was established anthracite mining in PA. A constant preoccupation of the developers of the Rhode Island anthracite reserves was mining costs in relation to those of PA anthracites.

By the beginning of the 20th Century China was recognised as the country most abundant in anthracite, and an estimate of the known reserves at about the time of World War II is given in [48] as being 45870 million tonnes. Anthracite at Donetsk in the Ukraine (see section 2.2) was discovered in the first half of the eighteenth Century, but commercial production did not begin until 1876 [49]. Proliferation of anthracite in Russia in the 1880s was due to a paucity of wood which had been used excessively to make charcoal for iron smelting [50]. The anthracite at Mount Klappan previously referred to was discovered in 1899 [51].

1.8 SOME CURRENT EXPLORATION AND DEVELOPMENT PROJECTS

These include the Kangwane Anthracite Project in South Africa. The proposed mine there is adjacent to an existing one called the Nkomati anthracite mine, and in evaluation of Kangwane there has been some emphasis on comparisons of coal from the two [52]. Kangwane coal has calorific values in the range 27.8 to 28.1, very slightly down on the values for Nkomati anthracite. See section 5.3 for more on Kangwane. There is also development work at Panorama anthracite project in British Columbia [53]. Plate 1.3 below shows a scene from the Panorama development.

Plate 1.3. Scene from the Panorama anthracite project in British Columbia. Image taken from: http://www.abnnewswire.net/press/en/78600/Atrum-Coal-NL-(ASX-ATU)-High-Grade-Anthracite-Extension-Confirmed-at-Panorama-78600.html

Anticipating later parts of this book, one expects intuitively that attracting investors for anthracite mine development will be easier when the anthracite is of quality such that it can be used in metals extraction. There is also development of an anthracite reserve taking place in Peru [54] and it is noted that the project will benefit from infrastructure – power, roads, water – already in place.

1.9 FURTHER REMARKS

As applications of anthracites are discussed in subsequent chapters the information in this first chapter will be drawn on.

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2 USE IN POWER GENERATION

2.1 PREAMBLE

Selected power plants using anthracite as a fuel will be discussed in turn. There is a move towards anthracite from lower rank coals in some countries because of the lower volatiles and hence lower emissions of smoke. Hence several of the power stations discussed in this chapter are in 'proposed' status.

2.2 ANTHRACITE-USING POWER PLANTS

In spite of its own abundant reserves, the Ukraine has recently been importing anthracite from Russia and from South Africa for use in power generation, this of course being due to recent military activity. **Trypilska power station**, 45 km south of Kiev, [1] uses as fuel anthracite culm from Donetsk [2]. Plate 2.1 below shows Trypilska, which has been in service since 1969.

Plate 2.1. Trypilska power station, the Ukraine.
Image taken from
https://www.google.com.au/search?q=trypilska+power+plant&biw=1779&bih=716&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjy78i2kczMAhXiF6YKHdPbDmMQ AUIBygC#imgrc=BgcDXjmsdINJdM%3A

Trypilska produces power at 1800 MW, making it a sizeable facility. Its six 300 MW turbines use sub-critical steam. A Ukrainian power plant using 'highly non-premium' anthracite termed anthracite sludge, though also using some full quality anthracite, is **Donbasenergo power station**, at Starobeshevo in the Donetsk region [3]. It uses a circulating fluidised bed for combustion. In general low-quality fuels are suited to fluidised bed combustion. The sludge used there has a calorific value just under half that of the standard quality anthracite from the same mine, which is 25.1 MJ kg^{-1} on an as-received basis. Donbasenergo produces electricity at up to 210 MW, and the steam on turbine entry is in superheated (not supercritical) condition.

There are many power stations in Pennsylvania using anthracite culm partly because (as previously noted) stockpiles of culm having been in existence for over a century are being dismantled. As well as the benefit of clearing the land on which they stand, their removal eliminated spontaneous heating hazards. Plate 2.2 taken from a picture postcard dates 1908, shows a culm heap on fire in Scranton PA[5].

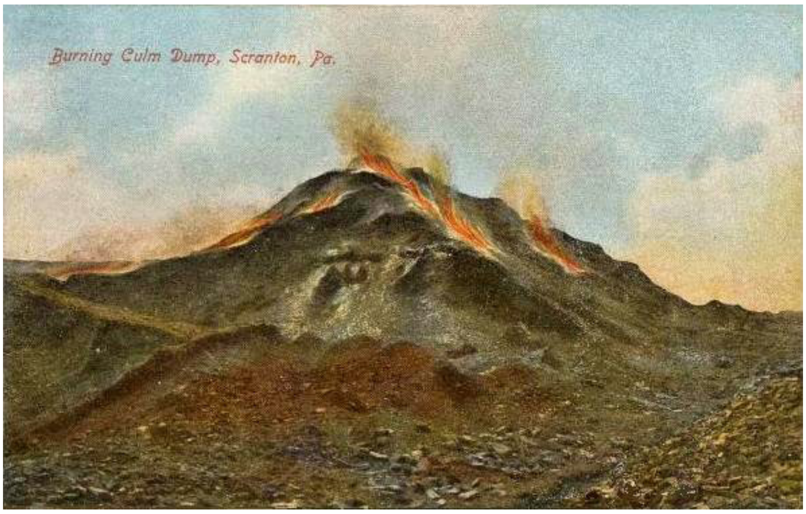

Plate 2.2. Culm stockpile displaying spontaneous combustion.
Image taken from:
http://carbonacea.blogspot.com.au/2015/03/pennsylvania-anthracite-culm-heaps.html

Wheelabrator Frackville [4] in Frackville PA uses anthracite culm for the express reason of land reclamation. It generates 40MW of electricity and also supplies steam to a local penitentiary. Where fuel is too heterogeneous or simply contaminated for its calorific value to be measured with a small laboratory sample, a 'boiler-as-calorimeter' method applies where measurements on the boiler can provide an indirect value of the calorific value. This is attempted for Wheelabrator Frackville in the boxed area below.

We are informed in [4] that the nameplate output of the facility is 48 MW, higher than the actual output given in the paragraph above. We are also informed that 500000 tons (453500 tonnes) of the anthracite waste are consumed in a year.

Now 48 MW round the clock represents:

$$48 \times 10^6 \text{ J s}^{-1} \times (24 \times 365 \times 3600) \text{ s of electrical energy} = 1.5 \times 10^{15} \text{ J of electrical energy.}$$

At a generating efficiency of say 35%, the heat energy required would be:

$$(1.5 \times 10^{15}/0.35) \text{ J} = 4.3 \times 10^{15} \text{ J} = \text{heat supplied in a year's supply of the fuel}$$

$$= 453500 \times 10^3 \text{ kg} \times Q \text{ J kg}^{-1} \text{ where } Q \text{ is the calorific value of the fuel}$$

$$\downarrow$$

$$Q = 9.5 \text{ MJ kg}^{-1}$$

This is a perfectly sensible result[6]. We note by way of comparison that the anthracite sludge used at Donbasenergo has a value of Q of 12.1 MJ kg^{-1} [3]. Note that the steam supplied did not have to be factored into the above. At the conclusion of the stage in the Rankine cycle where work is done the fluid can possess enough enthalpy for a subsequent heating application, and this is linked to the efficiency of conversion of heat to work.

More information on the Wheelabrator Frackville power station is given in [5]. The boiler uses particles of culm crushed to go through a 6.4 mm screen. The culm is burnt in a fluidised bed, being stockpiled in 5.5 tonne quantities prior to burner entry. The steam produced is at 90 bar, 513^{o}C. The saturation temperature of steam 90 bar is, from steam tables, just over 300^{o}C, so the extent of superheating is major.

Also in Frackville is a power plant operated by the **Gilberton Power Company** and it too uses anthracite culm as fuel. It produces electricity at 80MW as well as some steam for heating. It has a fluidised bed boiler and a single steam turbine [6]. **Schuylkill Energy Resources Inc**. operate a power plant at Shenandoah, PA. Fired by culm, it generates electricity at 80 MW [7].

Northeastern Power Company (NEPCO) at McAdoo PA use culm to make electricity at 550 MW, and steam is diverted to a horticultural use [8]. **Panther Creek Partners LP** use anthracite waste at their power facility in Nesquehoning PA. It produces at 94 MW [9]. The **Cogentrix Northampton Generating Company** in PA [10] produce from fuels including anthracite waste; they also use petroleum coke and residue from paper manufacture [11]. The **Mount Carmel** facility at Marion Heights PA uses culm to generate at 47.3 MW. It is clear then that in Pennsylvania there is major use of culm in power generation, and it is set to expand.

Aberthaw Power Station in Wales came into service fifty years ago and has used anthracite as well as other ranks of coal [12]. It has used local and Russian anthracite. It has expanded over the years and its nameplate capacity is now 1555 MW. If it is to continue at such a rate it needs to go to carbon mitigation procedures, either to partial or total replacement of the coal with biomass or CCS measures. Both of these are on the development agenda at Aberthaw.

In South Africa a new power station the **Colenso power station** is being planned [13]. There was a power station of the same name at the same location from 1926 to 1985. The new Colenso power station will use anthracite from Kwa-Zulu Natal, and the target power production is 1050 MW from three equivalent steam turbines. The **Kozienice Power Station** in Poland uses anthracite as fuel [14] and, very significantly, is being expanded so as to have more than one turbine using supercritical steam. In service since 1972, the power station currently produces 2840 MW. The **Vojany power plant** in Slovakia uses anthracite imported from Russia [15]. Since 2009 the coal has been co-fired with wood chips. The nameplate capacity is 220 MW from two turbines. The interesting point is made in [16] that in Russia and the Ukraine there is a move toward anthracite in power generation to free up natural gas for export. There are very many anthracite-utilising power stations in these are described in Table 2.1 below, most of the information in which is taken from [17].

Name of the power station location and year of commencement.	Details.
An Khan-I, Thai Nguyen, 2015.	Anthracite from Khanh Hoa coal mine burnt in two circulating fluidised bed (CFB) boilers. Current capacity 115 MW.
Cao Ngan, Thai Nguyen, 2006.	Anthracite from Khanh Hoa and Nui Hong mines. CFB boilers (supplied by Alstom). Current capacity 100 MW.
Cam Pha, Quang Ninh, 2011.	Anthracite and culm. CFB combustion. Current capacity 680 MW.
Duyen Hai-1, Tra Vinh, 2015.	Anthracite fuel. Nameplate capacity 1246 MW. 7 TWh per year expected when fully developed and commissioned.
Hai Phong-II, Hai Phong, commencement phased over 2011–2014.	Anthracite from Quang Ninh. Nameplate capacity 1200 MW. Four 300 MW turbines.
Mao Khe, Quang Ninh 2012.	Quang Ninh anthracite in a mine-mouth arrangement. Anthracite brought from a distance also used. CFB boilers. 440 MW.
Mong Duong-1, Quang Ninh, 2015.	Local anthracite. Nameplate capacity 1080 MW.
Nghi Son-1, Thanh Hoa, 2014.	Anthracite from Quang Ninh. Nameplate capacity 660 MW.
Ninh Binh, Ninh Binh , 1976.	Anthracite. 220 MW.
Nong Son, Quang Nam, 2014.	Anthracite. Power at 30 MW. A rural setting.
Pha Lai-2, Hai Duong, 2001.	Anthracite. 600 MW.
Uong Bi-7, Quang Ninh, 2007.	Anthracite from the Vang Danh mine. 300 MW.
Vinh Tan-2, Binh Thuan, 2014.	Anthracite. 1225 MW.

The Khanh Hoa coal mine (row 1) is a large one. There have however been spontaneous heating problems there in recent years, caused partly by unsettlement of the deposit by theft of the fuel [18]. Nui Hong anthracite for the Cao Ngan power plant is brought by rail to the power plant and stockpiled. At Cam Pha, local anthracite fines are used along with culm, a.k.a. 'slurry' [19], from Cua Ong. Cam Pha is a major reserve from which there have been exports [20]. Not that only the fines are used at the power plant, supplemented by culm from elsewhere.

In relation to the Duyen Hai-1 mine, round-the-clock operation would produce in a year:

$$1246\text{ MW} \times (365 \times 24)\text{ hour} \times 10^{-6}\text{ TWhMWh}^{-1} = 11\text{ TWh}$$

which means that the projected production is about 65% the maximum possible from the nameplate capacity on the assumption of no down time, a very sensible result. A photograph of the Hai Phong-II power station forms Plate 2.3 below. A calculation like the one for Duyen Hai-1 above gives a power production annually without lost time of:

$$1200\text{ MW} \times (365 \times 24)\text{ hour} \times 10^{-6}\text{ TWhMWh}^{-1} = 10.5\text{ TWh}$$

which is well below that presently aimed for which is 31 TWh. The obvious explanation is that all four turbines will be in use only at periods of high demand. It is also possible that allowance is being made for expansion of local industry (see also italicised quotation on the following page). Hai Phong (population > 2 million) is the third largest city of Vietnam and a major manufacturing base. To double that output of power in response to local growth would be straightforward.

Plate 2.3. Hai Phong-II power station, Vietnam.
Image from:
https://www.google.com.au/search?q=Hai+Phong-II+power+station&biw=1640&bih=716&source=lnms&tbm=isch&sa=X&ved=0ahUKEwi05YiU9NjMAhWBs5QKHS0yDVsQ_AUIBygC#imgrc=ZYzcbyIYDPyWBM%3A

Moving on to the Mao Khe power station, a relatively small one, there are residences only 500 m away and there have been complaints of vibrations and particle deposition. The Mong Duong-1 power station in the following row is expected to supply 5.8 TWh per year.

Before resuming discussion of these anthracite power stations in Vietnam, a point which will have become evident to a reader will be made. They are all of recent entry into service. The following quotation is taken from [21]:

Electricity demand in Vietnam is expected to see a remarkable increase of more than 10% per annum in the coming years due to rising population and economic growth. Southern Vietnam in particular, the country's largest economic block, faces a critical situation in relation to the current imbalance between existing supply and the increasing demand for electricity. There is therefore urgent need for the development of power generation infrastructure in the region.

It is reported in [22] that by 2025 sixty per cent of Vietnam's electricity will come from coal and accordingly carbon capture and sequestration (CCS) is being factored into the growth figures without yet being a reality. The piece in [22] concludes by saying that Vietnam will need international financial aid in implementing CCS. Of course, being a developing country Vietnam has a low carbon dioxide release, about 2 tonnes per capita annually [23] compared with 17 in the same units for the USA [23]. Added to this is the fact that about a third of Vietnam's electricity currently is hydro and this could expand.

Returning to the table, Nghi Son-1, the anthracite used there is from the Hon Gai and Cam Pha (see row three of the table) mines. All of the mines at Quang Ninh are susceptible to flooding. There was major stoppage during the second half of 2015 for this reason [24]. The Ninh Binh power station at a location of the same name is exceptional amongst those in Vietnam in that it has been producing for 40 years. The relatively very small Nong Son power station (next row) is expected to contribute 158 GW hour per year to the grid, converting to a rate of:

$$\boxed{158 \times 10^{9}\ \mathrm{J\ s^{-1}\ hour}/(365 \times 24)\ \mathrm{hour} = 18\ \mathrm{MW}}$$

a little over half the nameplate capacity. It is noted [17] that the anthracite used at Pha Lai-2 sometimes has an ash content as high as 33%. A scene from the Vang Danh mine (following row) forms Plate 2.4. At the Vinh Tan-2 power plant (next row) supercritical steam is used. This raises efficiency, an indirect way of reducing carbon dioxide emissions.

Moving from Vietnam to another Asian country, the Samcheok power station proposed for South Korea will use anthracite and, significantly, highly supercritical steam in its single turbine which will produce 100 MW. The Yangcheng International Power Company in the Shanxi Province of China uses anthracite coal to produce electricity at 21000 MW [25]. A point which will be reiterated early in the next chapter is that coal bed methane is of greater current interest than anthracite as a fuel for power production at this location.

Plate 2.4. Stockpiled anthracite coal at the Vang Danh mine, Vietnam.
Image from:
https://www.google.com.au/search?q=Vang+Danh+mine&biw=1640&bih=716&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjzxKLK_9rMAhVKHJQKHTQBAuw4ChD8BQgHKAI&dpr=1#imgrc=bH7uoKrLry2GOM%3A

In Portugal, power generation using anthracite from the Douro field ceased in 2004. This is discussed more fully in the final chapter in terms of the fly ash produced.

2.3 CONCLUDING REMARKS

The theme of the book will, in the next chapter, move on to the related topic of gasification.

2.4 REFERENCES

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3 GASIFICATION AND CARBONISATION

3.1 EXAMPLES OF PAST, PRESENT OR PROPOSED GASIFICATION OF ANTHRACITES

These are in Table 3.1 below, which is followed by comments.

Activity and reference.	Details.
Chinese anthracites [1] gasified in a fluidised bed.	Anthracites from Jincheng and Yangcheng examined on a test scale.
Pennsylvania anthracite [2] in a Wellman-Galusha gasifier.	Product a synthesis gas suitable for making methanol or a high-calorific value fuel gas.
Pennsylvania anthracite [3] in a Wellman-Galusha gasifier.	Fuel gas. See comments in the main text.
Mobile gas producer for vehicle propulsion, early 20th Century [4].	Welsh anthracite and German anthracite evaluated. See comments in the main text.
Gilberton PA [5][7].	Culm gasified to make synthesis gas then converted to liquid fuel in an integrated process which also produces electricity. See analysis below.
Vehicular use [7].	A typical yield of producer gas from anthracite given as 4.5 m^3 per kg of anthracite.
Early 20th Century US, gas producer using anthracite culm [8].	Electricity production from the gas at '1.5 mills per horsepower-hour'.
Underground gasification of Chinese anthracite to make synthesis gas [11].	Demonstration project.
Namhung Youth Chemical Complex, North Korea [12].	Anthracite gasification since 2006 (see Plate 3.1).
A Korean anthracite and a Chinese examined separately in the same gas producer using air/steam [13].	Significant difference in the calorific values of the gases from the two coals.

Ninh Binh Nitrogenous Fertiliser Plant, Vietnam [14].	Gasification of anthracite to make fertiliser.
USA circa 1835, retorting of anthracite [16].	See comments the main text.
Culm to synthesis gas followed by F-T [17].	Slag removal from the gasifier by use of a fluxant.
Comparison of syngas production from anthracite and from natural gas [18].	See comments in the main text.
Donetsk Basin, the Ukraine [19].	Gasification of anthracite with air.
US, early 1900s [20]	Rhode Island anthracite tested for gasification with steam.

The anthracite deposit at Jincheng is a large one and production for domestic use and export is major. One side of the deposit is particularly rich in coal bed methane and this is where the organisation's future lies in terms of power generation, as noted in the previous chapter. The Wellman-Galusha gasifier is for small scale production, service of a site rather than general reticulation. It can be supplied with oxygen (as in the work in row 2) or with air. Obviously when air is used the gas is producer gas. In the operation in the third row of the table the fuel gas had a calorific value of 140 BTU $ft^{-3} \equiv 5.3$ MJ m^{-3}. Such a gas will, on a suitable burner, melt steel. The 'maximum gasifier capacity' is given as 25 million BTU per hour. This value is examined in the boxed area below.

25 million BTU = 2.6×10^{10}J

Assigning a value of 25 MJ kg^{-1} to the anthracite, the amount required to produce this amount of heat is:

$2.6 \times 10^{10}J/25 \times 10^{6}J\ kg^{-1} = 1000$ kg approx.

So the gasifier – a small one as noted – is being fed with up to a tonne per hour of anthracite. This is an intuitively sensible result.

When a 'high-calorific value fuel gas' is obtained by oxygen blowing as in the previous row the product gas corresponds approximately to pure carbon monoxide, calorific value 11 MJ m^{-3}.

Reference [4] traces developments from about 1900, when Daimler-Benz was the only car manufacturer in the world: in addition to production of these vehicles within Germany there was some construction of them under licence in the US. Germany was therefore a centre of affairs for automobile R&D, and it should also be noted that the stationary gas producer was a German invention from about 35 years earlier. The flammable constituents in the gas from the mobile producer when supplied with anthracite were CO (29.3% molar basis), methane (3.3% molar basis) and hydrogen (7.9% molar basis). The hydrogen results from inclusion of water in the air supply, a common practice. The nitrogen content of the gas was 55.4% and this of course is a diluent. From the above it ought to be possible to calculate the calorific value of the gas and this is attempted in the boxed area below.

1 m^3 of any gas or gas mixture at 15°C, 1 bar pressure contains 42 moles.

Calorific value of methane = 889 kJ mol^{-1}

Calorific value of carbon monoxide = 282 kJ mol^{-1}

Calorific value of hydrogen = 285 kJ mol^{-1}

So 1 m^3 of the gas will release on burning:

$$42 \times [(0.293 \times 282) + (0.033 \times 889) + (0.079 \times 285)] \text{ kJ} = 5648 \text{ kJ } \mathbf{(5.65MJ)}$$

The result is the expected one. Whenever in gasification with air water is included it is with a view to enhancing the calorific value by creating some elemental hydrogen. The methane of course comes from pyrolysis of the anthracite.

The following data are given for the operation at Gilberton: 4700 US tons (4263 tonne) per day of culm; 3732 barrels per day of coal-to-liquid diesel; 1281 barrels per day of coal-to-liquid naphtha. The process is integrated and some of the syngas is used to make electricity for sale at a rate of 39 MW. It ought to be possible to glean more information from these figures, and this is attempted in the boxed area below.

The syngas is produced by:

$$C + H_2O \rightarrow CO + H_2$$

and this has a calorific value of 11 MJ m^{-3}.

39 MW of electricity requires about 110 MW of heat, so burning of the syngas is at a rate of:

$$[110 \times 10^6 \text{ J s}^{-1}/(11 \times 10^6 \text{ J m}^{-3})] = 10 \text{ m}^3\text{s}^{-1}$$

Now 1 m^3 of the equimolar syngas contains 20 mol of CO or 240 g of carbon, the source of which is the anthracite culm. So 10 m^3s^{-1}, the syngas required for the electricity, becomes 2.4 kg of carbon from the culm per second, 207 tonne of carbon per day. The culm is likely to be about 50% carbon so the quantity required per day is twice this or about 414 tonnes per day. This leaves 3849 tonnes per day of culm for gas for Fischer-Tropsch conversion to liquid. The liquid produced per day, diesel plus naphtha, is 5000 barrels, or just over one barrel per tonne of culm. From quality coal 3–4 barrels per tonne of the coal feedstock are available from F-T [6]. This low value reflects the inferior quality of the culm.

The numbers in the above calculation hang together; refinement would be possible if, for example, the carbon content of the culm was known precisely. The next entry in the table is concerned with mobile gasifiers, and it is interesting to note the date as 1983. That was at about the time when many projects in 'alternative' motor fuels, including those obtainable by flash pyrolysis of coals, were being reported.

Moving on to the next row of the table we first note that 'mill' as a unit of currency in the US denoted 1/1000th of a dollar. One US horse power is 0.75 kW, so the electricity was raised at a cost of 1.5 mills for 0.75 kW-hour or 2 mills per kW-hour. In the US at present the average price of electricity is 12 cents per kW hour [9]. Now the current US dollar has the value of about 2.5 cents in 1906 [10], so the current price extrapolated back to 1906 would be 0.3 cents per kW-hour, whereas 2 mills is 0.2 cents. The consistency is quite surprising!

The synthesis gas from Chinese anthracite in the next row is directed at ammonia production from the synthesis gas. The target ultimate production figure is 60000 tonnes per year of ammonia, and here again some simplified calculations based on mass balance will be helpful.

The sequence of reactions is:

$$C + H_2O \rightarrow CO + H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

Then CO_2 removal followed by:

$$0.5N_2 + 1.5\ H_2 \rightarrow NH_3$$

60000 tonnes of ammonia contains 10588 tonnes of H, or the equivalent of 5.294×10^9 moles of elemental hydrogen H_2. This was raised from an equivalent

molar quantity of carbon, so letting the anthracite be 95% in carbon the amount required is:

$$[(5.294 \times 10^9 \text{ mol} \times 0.012 \text{ kg mol}^{-1} \times 10^{-3} \text{ tonne kg}^{-1})/0.95] \text{ tonne anthracite}$$

Rounding gives:

Quantity of anthracite required = 67000 tonne and having regard to the approximations one might say that the anthracite yields *roughly* its own weight of ammonia when so processed. At the Namhung Youth Chemical Complex (next row) the gasifier plant is used to manufacture urea This is by production of ammonia and reaction of that with carbon monoxide. In the work in the following row, as is always true with producer gas the calorific value depended on the proportion of steam admitted to the gas producer with the air. The maximum calorific values obtainable with the Korean and Chinese anthracites respectively were 3.4 and 5.5 MJ m^{-3}.

Plate 3.1. Anthracite gasification plant at the Namhung Youth Chemical Complex, North Korea.
Image from:
https://www.google.com.au/search?q=anthracite+++gasification&biw=1640&bih=716&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjvwpSh89_MAhUE5KYKHbcgDP0Q_AUIBigB#imgrc=g41R1mnkxzl9hM%3A

Urea is also produced at the Ninh Binh Nitrogenous Fertiliser Plant (next row). There are three other urea plants in Vietnam. In relation to China a correlation coefficient of 0.85 between anthracite prices and urea prices, seen as also being applicable to Vietnam, has been noted [15]. The significance of the next entry, which is historic, is that the conclusion was drawn that anthracite without carbonising ('directly from the mine') is suitable for extraction of iron from its ore. This is relevant to a subsequent part of this book. There would have been small amounts of liquid and gaseous by-products from the retorting.

The next row of the table introduces a topic not previously considered: slag from gasification of culm, with its high proportion of inorganics and minerals. Returning to the activity at Gilberton in row five of the table, the slag there exits the base of the gasifier in molten form. In the work currently being considered it was found necessary to use a fluxant to keep the slag liquid and prevent fouling. Blast furnace slag is suitable for use as a fluxant in a gasifier, when close attention has to be paid to the particle size, which will be sub-millimetre to ensure good natural mixing. There in more on slag in the final chapter of this book.

Anthracite of low quality is frequently used to make syngas as is obvious from this chapter thus far. In next row of the table syngas made from anthracite is compared with syngas made from steam reforming of low-quality methane from mine drainage (heavily contaminated with air) by:

$$CH_4 + H_2O \rightarrow CO + 3H_2.$$

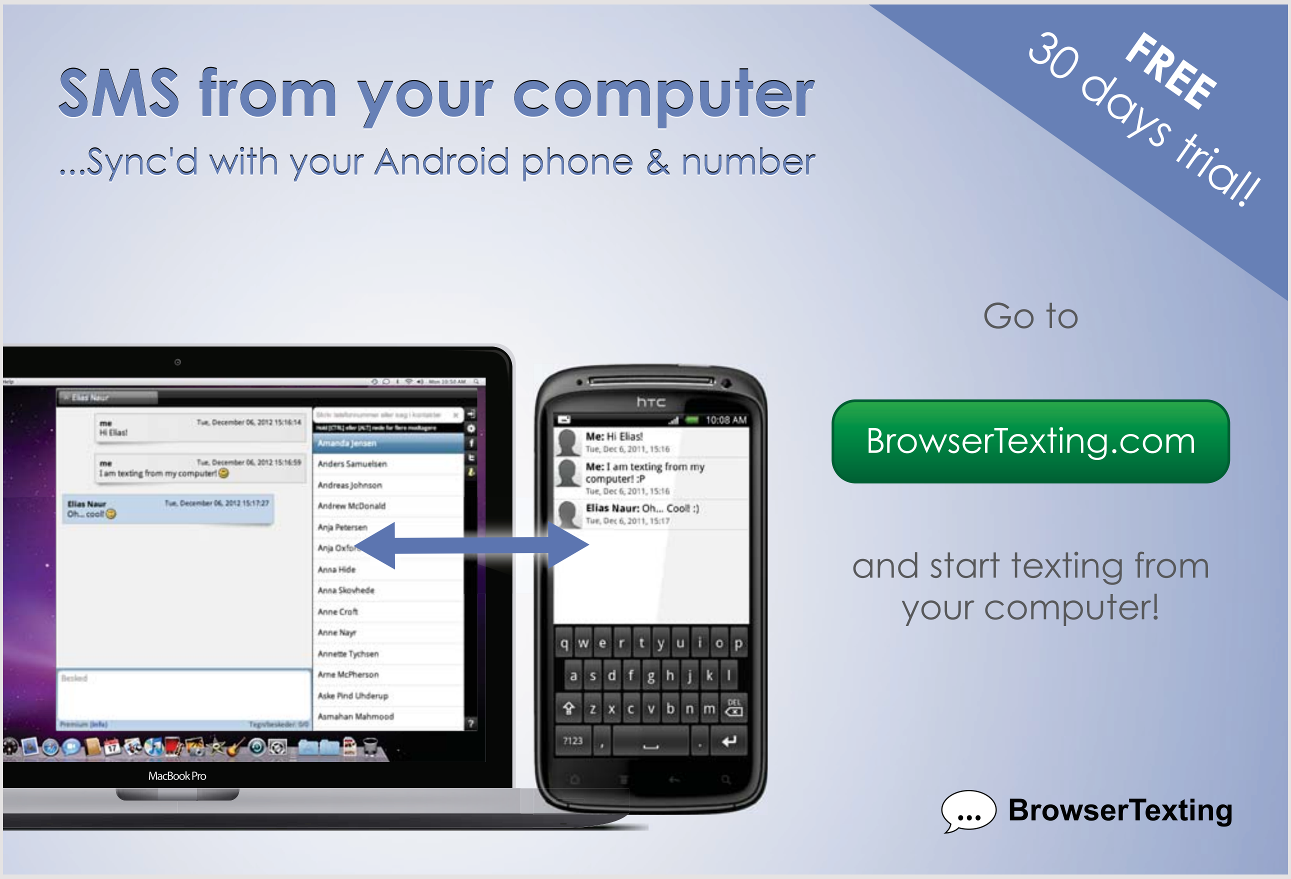
The ultimate aim of this work would be concurrent anthracite gasification and drainage gas reforming. The high hydrogen content of syngas from the mine drainage gas is noted in [18] and that this could be put to advantage if, for example, ammonia production from the syngas is aimed for. It is difficult to see how it would be advantageous in the production of syngas for fuel use. The gas made in the Donetsk Basin (next row) has a calorific value of 3.8 MJ m^{-3}, just a tenth that of methane. Even so, as previously noted such a gas could melt steel. Moving to the next row, Rhode Island anthracite mining ceased several decades ago. It was intended in the work referred to gas from steam gasification of the anthracite would be used to make electricity not only for RI but for Boston. The project was abandoned because of strong competition from bituminous coal from Pocahontas.

3.2 COAL BED METHANE (CBM) FROM ANTHRACITE

All ranks of coal yield CBM, an increasingly important resource in the 21st Century. There is a tendency for abundance of CBM to correlate positively with coal rank, therefore anthracite deposits are often productive of CBM. The low permeability and high degree of hardness of anthracites were once seen as precluding CBM production, and this was especially so in Russia [21] where instead CBM was obtained from the Kuzbass bituminous coal deposit. However in 1994 [22] successful operations at a Chinese anthracite mine to produce CBM commenced[8]. Production was 7 million cubic metres per day and (a very important point) produced water was moderate, 200 barrels per day. Amounts of this unwanted accompaniment to CBM production can make the difference between viability and non-viability of a CBM source. That achievement in China was followed by successful CBM production in Pennsylvania at just over 2 million cubic metres per day [22].

Currently the Shanxi Jincheng Anthracite Mining Group Co. produces coal bed methane from anthracite, sufficient to have generated 1.4 TW hour of electricity from in in 2015 [23]. Some of the CBM produced by the Shanxi Jincheng Anthracite Mining is converted to methanol and from that to gasoline at the plant shown in Plate 3.2 below. The plant produces 2500 barrels per day of gasoline.

Plate 3.2. Methanol-to-gasoline plant, Shanxi Jincheng Anthracite Mining Group Co. The methanol is made from coal bed methane from an anthracite deposit.
Image from:
http://corporate.exxonmobil.com/en/company/worldwide-operations/catalysts-and-licensing/synthetic-fuels



Note that conversion of coal to liquid fuels via methanol, as at the above plant, is an alternative to F-T which has featured previously in this chapter.

The Pennsylvania anthracite fields have been evaluated for CBM [24]. Gas-in-place estimates range from 0.2 $cm^3\ g^{-1}$ coal to 21.6 $cm^3\ g^{-1}$ coal for different sites at the anthracite fields. The middle of the range then is about 10 $cm^3\ g^{-1}$ of coal, and in a calculation which follows this will be transferred from the particular to the general.

The formation of methanol from CBM is by:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$\downarrow$$

$$CH_3OH$$

Mass balance need be performed only with respect to the carbon: the other elements in the methanol did not originate with the CBM. So we have 32 g of methanol from 16 g of methane or 2 g of methanol from 1 g of methane. Now 1 g of methane is 1/16th mol which, in volume terms, is

$$[(1/16) \div 40]\ m^3 = 1.6 \times 10^{-3}\ m^3 = 1.6 \times 10^3\ cm^3$$

Scaling up, 1 tonne of methanol comes from $1.6 \times 10^9\ cm^3$ which originates from:

$$1.6 \times 10^9\ cm^3/10\ cm^3\ g^{-1} = 1.6 \times 10^8\ g\text{, 160 tonne of coal.}$$

So on the basis of the figure used enough methane to make a tonne of methanol would originate with 160 tonne of the anthracite.

The discussion thus far has been about total gasification of the coal, the only residue being slag, and CBM. When any substance – coal or biomass – is pyrolysed there is a gaseous component to the products. Hence pyrolysis a.k.a. gasification is also partial gasification, so carbonisation of anthracites is the next and final topic to be covered in this chapter.

3.3 CARBONISATION

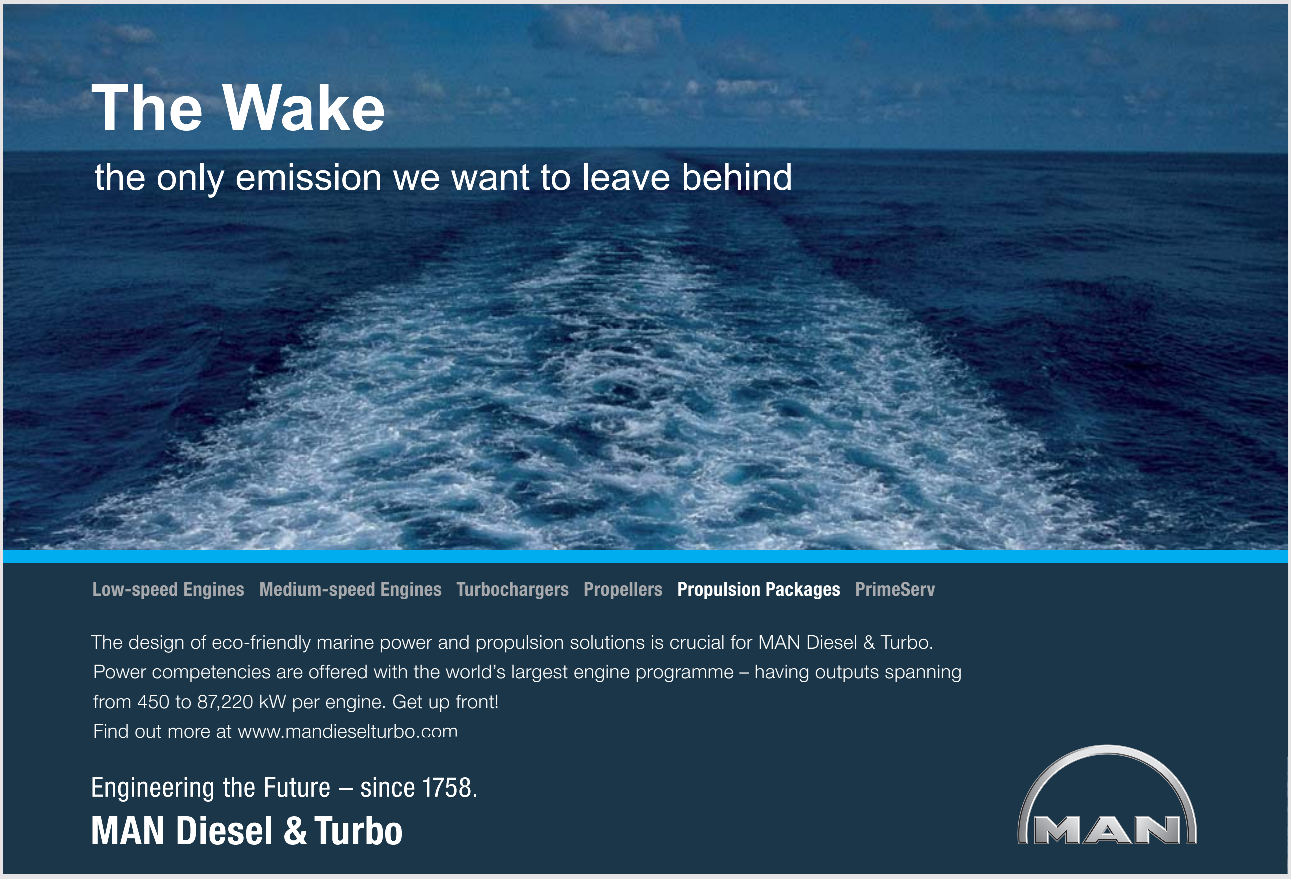
A distinguishing feature of anthracites from lower ranks of coal is paucity of volatiles, so the solid remaining when an anthracite is carbonised, known as anthracite char, has a mass not much below that of the parent coal. By contrast, when a lignite is pyrolysed the char will account only for 35% of the initial coal weight. In discussing this point we return to Table 3.1 and reference [15], where it was shown that there is no need to carbonise anthracite for many applications which would have required a carbonised bituminous coal: it will do the job of a char or coke without being converted to either. When a bituminous coal is pyrolysed ('retorted' if on a large scale) the primary product might be solid with gas as a by-product, in which case the gas is called coke oven gas. The primary product might be gas, known as retort coal gas, with solid as a by-product: there will be liquid by-products (tars and oils) in either case. The above is not true of anthracite coals, but carbonised forms of it do find application. Anthracite chars are sometimes themselves subsequently gasified. A discussion starts with Table 3.2 below.

Reference.	**Details.**
[25]	Pelletised adsorbent carbon made by carbonising anthracite.
[26]	Anthracite char from Mt. Klappan, Canada examined for gasification reactivity.
[27]	Anthracite char prepared by pyrolysis at 1000°C investigated for combustion behaviour across a range of pressures of oxygen.
[28]	Anthracite char as a removal agent for sulphur dioxide in flue gases.
[30]	CO_2 removal by carbonised Pennsylvania anthracite.

Table 3.2 Anthracite chars.

The product in the first row of the table is of a quality such that it can be used in food manufacture. A picture of this product forms Plate 3.3 below.

Plate 3.3. Activated carbon from carbonisation of anthracite. Image taken from [25].



In the work in the following row of the table the anthracite was carbonised at 1000°C. In thermogravimetric experiments on it gasification reactivity in air was investigated. Whether the coal had been demineralised before gasification had a measurable effect on this reactivity, that not having been demineralised being the more reactive. In the work in the following row of the table the effect of oxygen pressure on gasification rate was found to be quite strong. The time taken for gasification of half the initial mass of char ($t_{½}$ in the terminology of [27]) for the anthracite char at 575°C and 1 bar for oxygen was, for one of the size fractions, around 10^3 s rising an order of magnitude at 0.1 bar pressure of oxygen. Such information is the thrust of the paper [27] under review but what is perhaps more interesting is a point mentioned almost incidentally: the BET (Brunauer, Emmett and Teller) area of the char was 1.7 m^2g^{-1}, exceedingly small, and this obviously reflects the low volatiles and therefore low mass loss even at a carbonisation temperature as high as 1000°C. Reduction of sulphur dioxide by anthracite char features in the next row, and carbonaceous substances other than anthracite chars have found application to this including North Dakota lignite [29]. The process is believed to proceed via a C-S bond within the carbon which reacts with further SO_2 according to:

$$\text{'C-S'} + SO_2 \rightarrow CO_2 + 2S$$

and the sulphur dioxide is reduced all the way to elemental sulphur. The presence in the carbon substance of alkali metals as catalysts is a possible factor in the effectiveness of the sulphur dioxide removal. In the work in the final row of the table most of the surface area of the carbonised material was in the micropores. Adsorption of CO_2 was up to 65.7 mg CO_2 per g of carbonised anthracite.

3.4 FURTHER REMARKS

The theme of the book now passes on to anthracite briquettes and there will be some references to the material in the first three chapters in the coverage of them.

3.5 REFERENCES

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4 ANTHRACITE BRIQUETTES AND CALCINED ANTHRACITE

4.1 INTRODUCTION

Briquettes are of course made by moulding coal particles into a regular shape, often a brick-like shape or in an ovoid shape. There may or may not be a binder; if there is not natural cohesion is enough to retain the structure of the briquette for its expected shelf life. All ranks of coals have been briquetted for sale and distribution and this has perhaps been most true of lignites, where the compression required in the moulding has the bonus of removing some of the high inherent moisture. Peat has also been briquetted. The solid to be briquetted might have been carbonised, or the briquettes once moulded might be carbonised. This chapter is concerned with anthracite briquettes.

4.2 EXAMPLES

Anthracite coal fines from Pennsylvania were used to make briquettes, intended to replace coke in metallurgical use, in work described in [1]. The primary binder was lignin and there was also some gelatin and silicon metal powder (see following paragraph). They were closely examined for the mechanical strength that is needed for a metallurgical reductant. SUPAHEAT make available ovoids composed chiefly of Welsh anthracite. Their trade name is Multiheat®. Plate 4.1 below shows this product. At Boksberg in Gauteng Province, the Transvaal, South Africa, briquettes are made from anthracite blended with a lower rank coal [3].

Silicon powder is often added to briquettes for metallurgical use, to increase their ability to withstand the load by formation of silicon carbide. In a recent piece of work [4] rice hulls and ashes from their combustion, known to contain silica, were partially substituted for this in the production of briquettes from Pennsylvania anthracite fines. In [5] anthracite briquettes are evaluated for foundry use. They comprised fines from Pennsylvania anthracite plus collagen, a lignite binder and silicon. The briquettes were produced in two forms: pellets, 1.9 cm diameter by 1.9 cm height and cylinders, 2.54 cm diameter by 5.08 cm height. They were substituted to a degree of 25% for foundry grade coke[9] in a four-day demonstration trial, and the iron castings resulting were of sufficient quality for sale without distinction from those produced without such substitution. The point is made in [5] that coking requires energy for heating the coking coal and that in comparison briquetting is a simple process. These points are invoked in support of further investigation of anthracite briquettes for use in foundries. Reference [7] gives a brief accounts of briquette production from Chinese anthracite fines with a pitch binder at up to 20% of the weight.

Plate 4.1. Multiheat® ovoids, composed chiefly of anthracite. Image from [2].

Korea (N. and S.) have featured in this book as producers of anthracite and it is stated in [8] that briquette production began there in 1930. The composition is 90% Korean anthracite with 10% Chinese coking coal. Figures for Korean anthracite briquette production for 1955 (ten years after the partitioning) are given in [9] as < 1 million tons per annum. Thereafter in South Korea amounts rose steadily to 24.2 million tonnes in 1986, declining beyond then. The decline was due to a reduction in anthracite production, not to loss of demand for the briquettes. There was however an increase in 2003, and by 2008 54% of the South Korean anthracite utilised was in briquette form [10].

North Korean anthracite in as-mined form is of high quality, attracting higher prices on world markets than Vietnamese anthracites [11]. Some is briquetted and there has been export to China.

4.3 CALCINED ANTHRACITE

Anthracite, especially anthracite previously heated to high temperature ('calcined'), can be an ingredient of a carbon electrode. Anthracite heating for calcination can be by means of a gas furnace to give 'gas calcined anthracite' or by electrical heating to give 'electrically calcined anthracite'. Anthracite from the Horlivka (a.k.a. the Gorlovka coal field) in the Ukraine is amongst those having been so used [12], and gas calcination is at 1350°C. Purchasers of the calcined anthracite include the Novosibirsk Electrode Plant [13]. Details of other organisations either making or using calcined graphite are in Table 4.1 below.

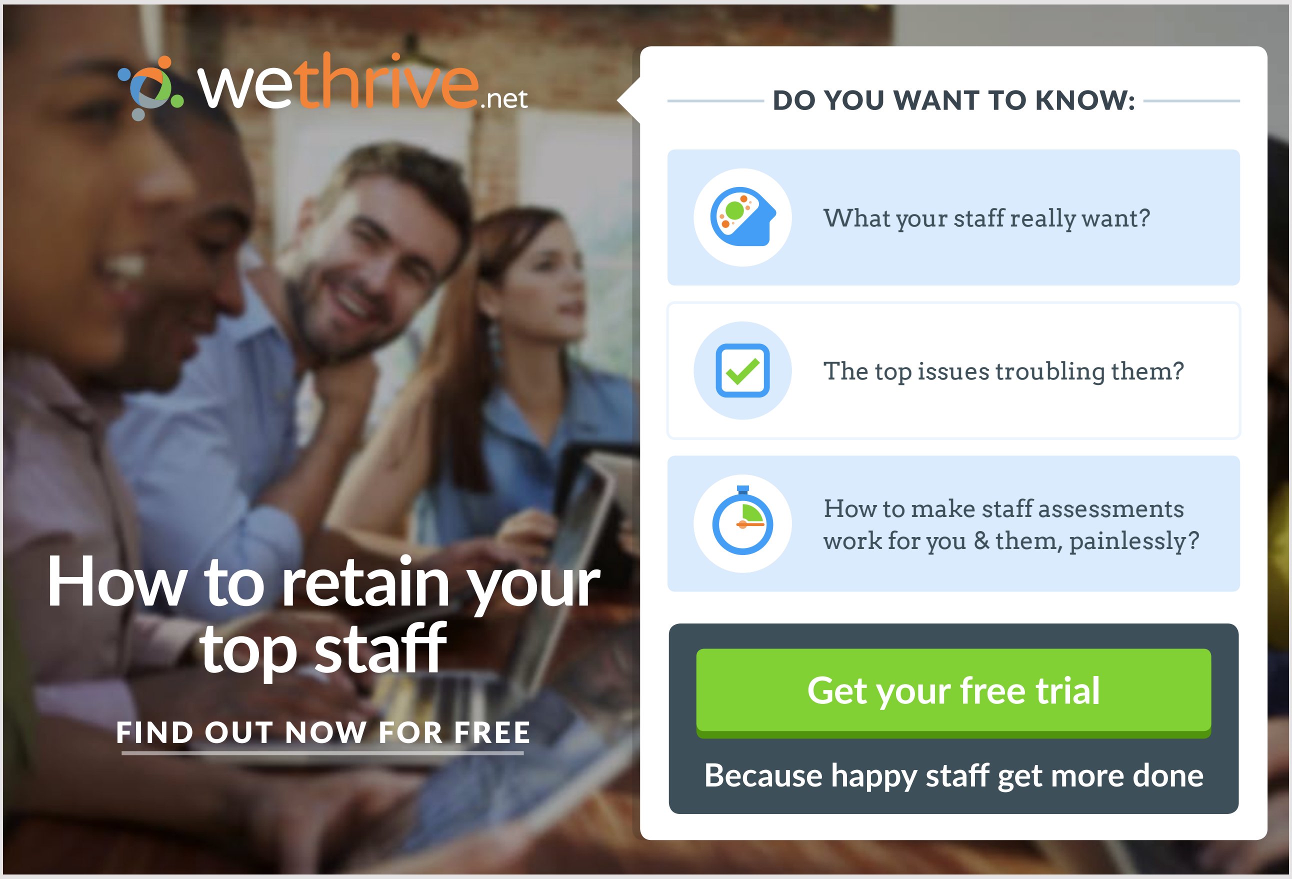
Country and reference.	Details.
Germany [14].	Aluminium Rheinfelden GmbH: anthracite calcined at 1200°C for incorporation into products including electrodes.
India [15].	DevEnergy: Offers both gas calcined and electrically calcined anthracite.
New Jersey, USA [16].	Asbury Carbons: Offers both gas calcined and electrically calcined anthracite.
China [17].	Ningxia Wanboda Carbons & Graphite Co., Ltd.: Offers both gas calcined and electrically calcined anthracite.
China [18].	Well United Resources Ltd. (Incorporated in HK): Electrically calcined anthracite for electrode use. Gas calcined anthracite for use as a coke.
India [19].	Maniyar Group: Electrically calcined anthracite or calcined petroleum coke used to make electrodes. Coal tar pitch a further ingredient.
India [20].	Carbon Resources: Carbon electrode paste, from electrically calcined anthracite or petroleum coke.
India [21].	Weston Electro and Carbon Products: see comments in the main text.
China [22].	Electrically calcined anthracite substituted for petroleum coke in electrode production.
South Africa [23].	Uncalcined and gas calcined anthracite and coal tar pitch used to make electrode paste.

Table 4.1. Calcined anthracite.

That in the first row of the table is gas calcined. With electrical calcining temperatures can be as high as 2000°C [15]. Plate 4.2 shows electrically calcined anthracite from this company.

Plate 4.2. Electrically calcined anthracite from DevEnergy. Image from [15].

The electrically calcined anthracite (ECA) in the illustration can be used as a foundry coke. Six ECA products are offered by DevEnergy, and that of highest volatile content has 1.3% of volatiles: the other five have <1%. The point is made in [16] that an ECA having experienced 2000°C will have some graphitic carbon in its structure. A general point will be added. In the power industry all sorts of low-grade anthracite (culm) can be profitably used. Not so in the chemical industry where anthracite is a raw material: the anthracite has to be of good quality.



The Chinese concern in the next row of the table produces 100000 tonnes per annum in total of calcined anthracite. The demarcation between the uses of the two types of calcined anthracite in the next row of the table is not general. With reference to the following row, it should be noted that the electrically calcined anthracite or petroleum coke when mixed with coal tar pitch is called ‘carbon electrode paste’. This product also features in the next row of the table. The Indian concern in the following row sometimes uses electrically calcined anthracite and electrically calcined petroleum coke together in the preparation of carbon electrode paste together with the coal tar pitch. When subjected to conventional proximate analysis this material has a volatile matter content of around 15% which, of course, originates with the pitch. In the research work described in the following row the anthracite was partly substituted for petroleum coke in an electrode for aluminium production. The substitution was satisfactory provided that regard was paid to the ash content of the anthracite. It is interesting to note that the motivation for this work was conservation of petroleum coke. The South African work in the following row was also on a laboratory scale, and a point of emphasis in the findings is that use of uncalcined anthracite causes electrode shrinkage at higher operating temperatures. There is a return to the process of calcining in section 10.3.

4.4 FURTHER REMARKS

It is clear then that calcined anthracite is an important product constituting a sector of the chemical industry. The book will now move on to the use of anthracite as a metallurgical reductant. Graphitisation can follow calcining, and this theme is taken up in Chapter 10.

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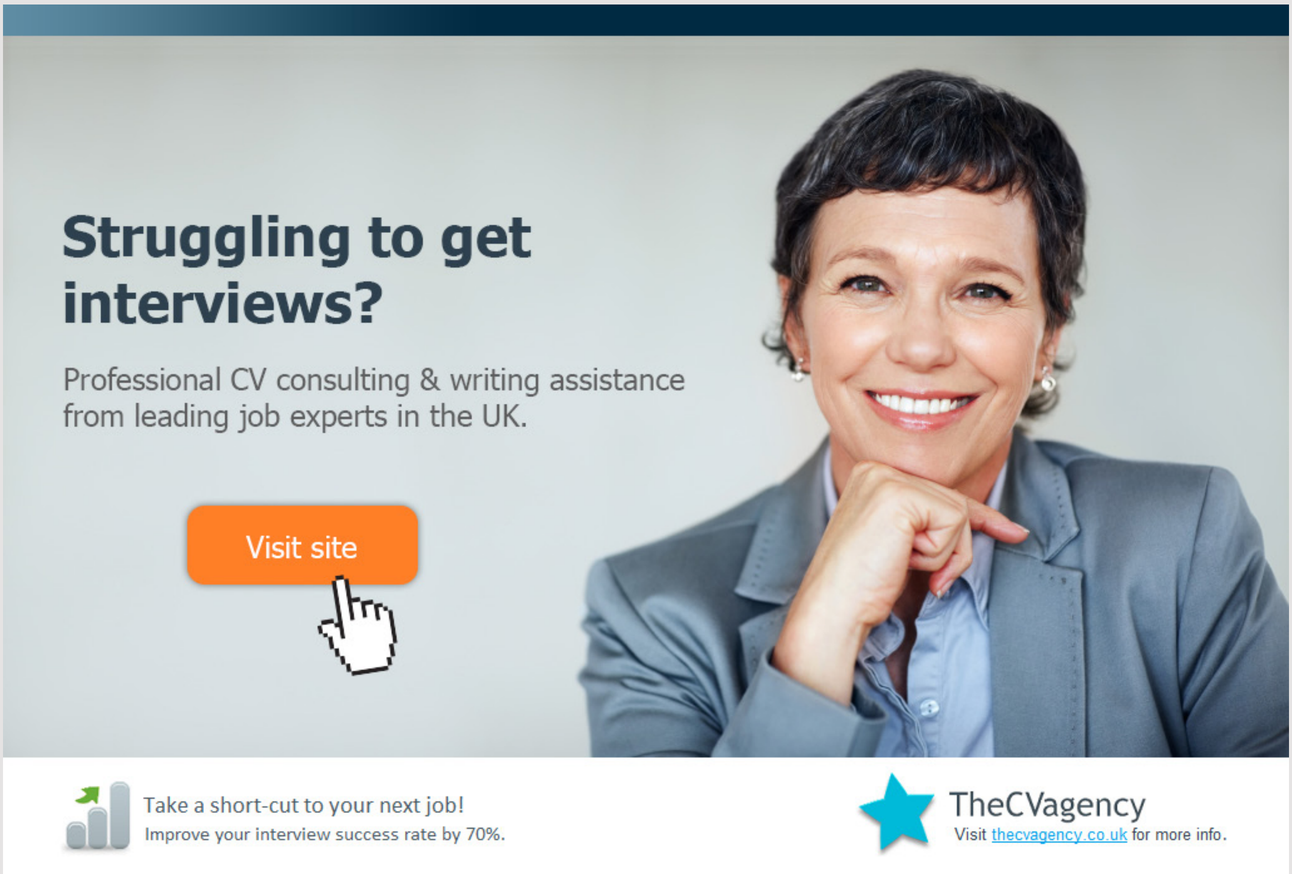
5 ANTHRACITE IN THE METALS INDUSTRY

5.1 INTRODUCTION

It is stated categorically in [1] that blast furnaces account for more coal than any other devices or operations in the steel industry, primarily because of the coke ovens. The point was made in an earlier chapter of this book that as far back as the 1830s it was noted that anthracite without prior retorting could be used in place of charcoal or bituminous coal coke in metal extraction. The term 'anthracite iron' was coined about then. This went into obscurity as more coking coal reserves were opened up, and the contemporary significance of anthracite in the iron and steel industry is that it can be admitted to a blast furnace operating on coke, either as lumps or as pulverised fuel (p.f.) [2]. Quality control in 21st Century iron and steel making is more stringent than it was for 'anthracite iron', and when anthracite is used in this way close attention is paid to two factors jointly and interactively: the quality of the ore and that of the product. When anthracite is so used coke (more expensive than anthracite) is saved. Lower ranks of coal than anthracite have also been applied to this purpose.



5.2 METALLURGICAL APPLICATIONS

An equally important use of anthracite in the iron and steel industry is in the electric arc furnace [3]. It is often used with ores, and can also take scrap metal which it heats to about 1650ºC[10], and typically [3] per 100 tonnes of scrap metal 3.3 tonnes of lime and 1.15 tonnes of anthracite. The purpose of the anthracite is to provide carbon to convert corroded metal to pure metal: the chemistry is quite analogous to a blast furnace. The lime is there to enable the impurities to form a slag from the process. Something carbonaceous (possibly coke) is injected into the slag to make it foam by releasing carbon dioxide, after which the slag on cooling becomes a by-product as a constituent of concrete. Table 5.1 below gives some examples of electric arc furnace use of anthracites.

Location and reference.	Details.
PA USA [4].	Atlantic Carbon Group: Suppliers of anthracite for electric arc furnaces.
USA [5].	Hickman, Williams and Co.: supply anthracite both as the reductant ('charge coal') and as the foaming agent ('injection coal') at electric arc furnaces.
Italy [6].	Carbones Italia: supply of anthracite both as charge coal and as injection coal for electric arc furnaces.
Canada [7].	QIT-Fer et Titane[11] Inc.: Pennsyvania anthracite used as the reductant in electric arc furnaces.

Table 5.1. Use of anthracites in electric arc furnaces.

Atlantic Carbon Group (row 1) also supply anthracite for use as p.f. in blast furnaces as described in the previous paragraph. It is noted in the second entry that this supplier makes anthracite available for the two purposes, and the same is true of the supplier in the following row.

5.3 FURTHER METALLURGICAL APPLICATIONS

The chemical formula of ilmenite is $FeTiO_3$ and there are major reserves of it in Australia as well as in Norway and in Canada. Anthracite can provide the carbon for the reaction, in an electric arc furnace:

$$FeTiO_3 + C = TiO_2 + Fe + CO$$

and the iron so produced is saleable pig iron. Sometimes it goes on to be processed into steel. The TiO_2 is formed as a slag [8] which undergoes further refining or processing. A major outlet for titanium oxide is pigments.

Plate 5.1 below shows such activity at the Rio Tinto Fer et Titane site in Quebec. This has nine electric arc furnaces for use with anthracite as reductant. Another such facility is in Richards Bay, KZN, South Africa [9]. Anthracite is used as reductant and it is noted in [10] that the fines are removed before admittance to an electric arc furnace. Part of the iron product goes to the automotive industry.

Plate 5.1. Ilmenite processing by Rio Tinto Fer et Titane in Quebec.
Image from:
http://qmp-powders.com/company/manufacturing-processes/

Table 5.2 below gives details of some other smelting processes which use anthracite as reductant. Some entries relate to particular scenes of such activity whilst others are general.

Metal and Reference.	**Details.**
Nickel [11].	Calcined[12] ore in an electric arc furnace with anthracite on a test scale in the 'ConRoast process' developed by Mintek in S. Africa.
Nickel [12].	Calcined nickel carbonate treated on a pilot scale in an electric arc furnace with anthracite as reductant.
Antimony[13] [13].	See comments in the main text.
Ferrochrome (iron-chromium alloy) [14].	Chromite (see main text) processed into ferrochrome in an electric arc furnace with anthracite reductant.
Nickel [15].	Colombia: > 50000 tonnes of nickel per year. Anthracite reductant.
Ferronickel alloy [15].	Compacted ore (sinter) which would otherwise have gone to a conventional blast furnace. Two electric arc furnaces with anthracite reductant. Dolomite also present.
Iron-manganese alloy [16].	Use of coke and anthracite in ratio 1:2 in a submerged arc furnace (see main text).

Zinc [17,18].	Zinc sulphide ore converted to zinc oxide which is treated with a reductant such as anthracite to obtain metallic zinc.
Lead [19].	Reduction of the prepared ore in a blast furnace with anthracite as a reductant.
Tin [21].	Reduction of the oxide by anthracite.
Vanadium [22].	Pig iron and/or scrap iron heated in a shaking ladle with possible inclusion of anthracite. Vanadium pentoxide in the slag used to produce metallic vanadium.
Copper-lead-iron alloy [24].	Slag from the smelting of copper heated in an electrical furnace with anthracite reductant.

Table 5.2. Smelting processes using anthracite.

It is stated in [11] that in the process in the first row of the table 250 kg of metal were produced per US ton of calcined anthracite. In the work in the following row the effectiveness of anthracite in the electric arc furnace was compared with that of a petroleum coke. The point of interest was completeness of the reaction, measurable as amounts of nickel in the slag, and the anthracite performed about equivalently to the petroleum coke in this regard.

Moving to the third row of the table, the extraction of antimony from its ore stibnite is by:

$$Sb_2S_3 + 3Fe = 2Sb + 3FeS$$

Although carbon does not appear in the above chemical equation it is standard practice to use anthracite also because some antimony oxide will co-exist with the stibnite, and the antimony from this is lost if there is no carbonaceous reactant present. Ferrochrome (next row) is made from the mineral chromite $FeCr_2O_4$. Ferrochrome is a generic term: the chromium can range from 50 to 70% in weight. The particular ferrochrome producing facility in [14] has four electric arc furnaces. Bentonite, a substance frequently used in drilling fluids, fulfils a binding role within the electric arc furnace where, in its role as a reductant, the anthracite is oxidised to carbon monoxide. This forms fuel for drying the furnace contents prior to admittance. The next row refers to the nickel mine and smelter at Cerro Matoso, and in contrast to the previous entries for nickel in the table relates to full-scale production. In the entry in the next row, a strong dependence of the nickel content of the product on the mass ratio of anthracite to sinter in the electric arc furnace was observed. The dolomite is there to help determine the slag composition (see previous section).

In any electric arc furnace the electrodes are contacting the furnace contents (they are not induction devices). Where such contact is by deep penetration the term submerged arc furnace (following row) applies. They are fairly widely applied to ferroalloys, but probably the most important application of the submerged arc furnace is in phosphorus production, dealt with separately later in this chapter. The point likely to be of most interest to a reader of this text is use of a coke/anthracite blend in [16]. The blend was used at 45% of the ore weight. In section 1.8 of this book the proposed Kangwane anthracite mine was discussed. It is expected that some of the product of that will be used to make ferroalloys.

The device in which zinc oxide is reduced by a carbonaceous substance (following row) is referred to as a retort, and producer gas has been used in the heating of these. The elemental zinc so produced is in vapour form and has to be condensed. The primary process occurring in a lead blast furnace (following row) is [20]:

$$PbO + C \rightarrow Pb + CO$$

and either anthracite or (more commonly) coke can provide the carbon. An analogous reaction occurs is tin smelting (following row):

$$SnO_2 + 2C \rightarrow Sn + 2CO$$

and the two have in common the fact that limestone is used to enhance the flow of the slag. In the process in the following row it is the slag that contains the primary product[14]. The motivation for the work in [24] was reduction in the expense of producing the alloy from the slag, and the performance of the anthracite was compared with that of two other reductants having regard to their respective costs. The anthracite in this application was in powdered form.

The value of anthracite as a metallurgical reductant is clear from the small number of examples in the table. The discussion concludes with a brief description of phosphorus production in an electric arc furnace. White phosphorous can be produced in a submerged arc furnace by reduction of minerals termed apatites, containing such salts as $Ca_5(PO_4)_3$, with anthracite in the presence of silica, which retains the calcium as a calcium silicate slag [25].

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6 FILTRATION AND ADSORPTION APPLICATIONS

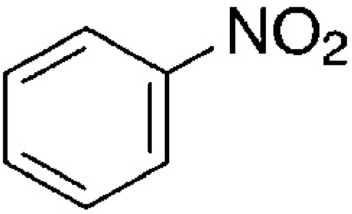
6.1 HOUSEHOLD WATER TREATMENT

The discussion will commence with a discussion of some research investigations, which will be followed by some coverage of some particular scenes of such usage of anthracite.

Reference.	**Details.**
[1]	Use of anthracite to remove three organic pollutants – nitrobenzene (NB), 1,3-dinitrobenzene (DNB) and 2,4-dichloronitrobenzene (DCNB), chemical structures below – from water.
[2]	Particle removal from wastewater using filter columns containing sand and anthracite ('dual media').
[3]	A commercial water filter using anthracite supported by sand.
[4]	Performance of an anthracite in water treatment compared with that of a granular activated carbon. Organic compound uptake stronger with the activated carbon.

Table 6.1. Research investigations of anthracites in cleansing water.

In the work in the first row of the table the anthracite had been milled down to particle sizes as small as 5 μm but had no pre-treatment beyond that.



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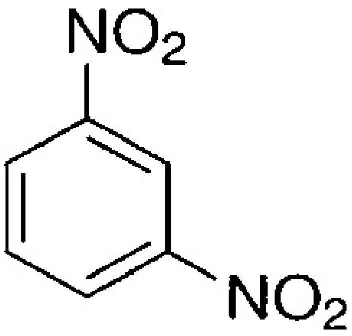
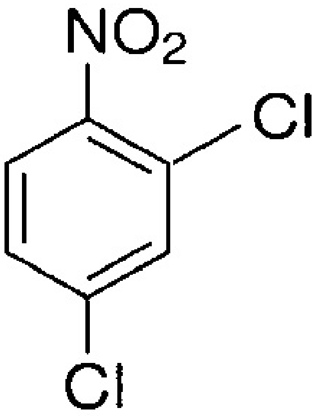


DNB



DCNB

25 ml liquid samples having each of the above substances present at 1 mg per litre were tested with 0.4 g of added anthracite, and each of them was removed to a degree of 98%. In the work in the second row of the table each filter column was filled with sand up to a height of 12 inches, and on top of the sand was the anthracite up to a column height of 60 inches. The anthracite particle size was of the order of a millimetre. Tests were carried out under a wide range including influx rate into the columns and in all cases the anthracite removed a greater mass than did the sand. This does not necessarily indicate superior performance of the anthracite however, as it is conjectured that the sand took up small particles accounting for less mass but requiring removal no less than the larger ones. The arrangement in the work in the next row of the table is also anthracite atop sand, and the sand is viewed as the secondary filter. The same configuration was used in the work in [4] and again the carbonaceous material was viewed as the primary filter.

Amongst the numerous scenes of water processing where anthracite is used as a filter is the **Wurdee Boluc water treatment plant** in Victoria, Australia [5]. The water there enters a triple medium device, encountering first of all anthracite[15], then sand and then gravel. 170 megalitres per day of water are so processed at the plant. Similarly the water treatment plant in service since 2004 in **Raymond New Hampshire** [6] uses anthracite in a dual medium arrangement with greensand. This is to meet the particular circumstances which prevail there. There are particles of manganese compounds in the water, only the larger of which are removed by the anthracite. The greensand, which itself contains manganese, removes the smaller ones. The two filters reduce the manganese content of the water from 1.3 to 0.03 mg litre^{-1}. **Hunter Water** in New South Wales use anthracite as a filter [7] as well as sand and gravel. **The Tarboro water treatment plant** in North Carolina, built in the late 1930s, uses anthracite in a dual media arrangement [8]. **East Bay Municipal Utility** in California supplies 375 million gallons per day of water and uses anthracite filters as sand and activated carbon [9]. These examples can of course be multiplied very many times and the aim of this paragraph is to make it plain that water treatment using anthracite is ubiquitous.

6.2 OTHER APPLICATIONS

Anthracites can also be used as decolouring agents for solutions, so that such solutions once evaporated yield a colourless product. This extends from aqueous applications to non-aqueous, for example to oils used in food. Table 6.2 below gives some examples of these and other uses of anthracites.

Reference.	Details.
[10]	Green glass. Anthracite used in the manufacture to adjust the colour.
[12]	Finely ground Chinese anthracite for a miscellany of uses including gas masks and BTX[16] removal from gas streams.
[13]	Anthracite filtration in the preparation of water for brewing.
[14]	Waste from edible oil production: filtration with anthracite.
[15]	Boiler condensate water filtration with anthracite.
[16]	Anthracite in the filtration of dairy processing waste.
[17]	Anthracite as a filter in a recirculating-water swimming pool.
[18]	Anthracite as a filter to remove water for irrigation of land.
[19]	Bentonite/anthracite together used to separate oil from oil-water emulsions.
[20]	Anthracite for air filtration and removal of exhaust fumes.

Table 6.2. Further uses of anthracites.

In the entry in the first row of the table the role of the anthracite is not as a filter or adsorbent but a reductant. If the iron chromite providing the green colour is present in manufacture to a degree that the glass will be too darkly coloured it can be reduced in quantity by reduction with anthracite. The principle (anthracite as a reductant in glass production) is applied more widely than just to the green tinting of glass with iron chromate [11]. The anthracite product in the next row of the table probably owes its effectiveness and versatility to the fine grinding. The entries in this table are all for anthracite, not anthracite chars. Of course, the chars do find such application (see section 3.3). In the next entry, it should be noted that filtration of water for brewing is necessitated by the likely presence in the water of solids from pipelines or of lime used in softening either of which can have an effect on the fermentation performance. In [14] it is noted that vis-à-vis aqueous applications, the higher viscosity of edible oils makes for difficulties with use of anthracite as a filter.

Removal of iron is one reason for the filtration of condensate water (following row). The application to swimming pools is of wider significance and has been taken further by NASA in its water reclamation program [17]. The entry in the next row is for water other than that from the municipal supply. Anthracite is effective at removing ferric oxide from such a water source. In the application in the following row oil removal by the bentonite-anthracite combination was up to 70%. In the following row air filtration by anthracite is introduced into the discussion.

6.3 FURTHER REMARKS

That anthracites as filter material find wide application is clear. That they have been evaluated for carbon sequestration is to be expected, and this is discussed in the next chapter.

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7 APPLICATION TO CARBON CAPTURE AND SEQUESTRATION

7.1 LITERATURE SURVEY

As in the previous chapter, the discussion will commence with examination of relevant research literature.

Reference.	Details.
[1]	Anthracite from Shanxi, China. Exposure to supercritical carbon dioxide and an examination for changes in coal structure.
[2]	Japan: noted in a study of possible carbon sequestration in disused coal mines that the anthracite seams in Honshu Island are too small to be of interest.
[4]	Anthracite from Paraná Basin, Brazil. See comments in the main text.
[5]	Quishui anthracite deposit, China: evaluated for possible future carbon sequestration.

Table 7.1. Research investigations on CCS with lignite.

For the work in the first row of the table a little background on carbon sequestration is necessary. In subsea burial of carbon dioxide, if the sea depth is sufficient for the pressure to correspond to the supercritical region on the CO_2 phase diagram at the prevailing temperature the CO_2 will remain in the supercritical state in which it was injected. If sequestration is into a coal mine injection is still likely to be of CO_2 in the supercritical state but retention will be by such phenomena as pore filling and adsorption. The finding in [1] was that the pore structure of the anthracite was increased by the injection of the supercritical fluid, increasing its sequestration capability to the advantage of the operation. Japan no longer mines coal of any rank (all of the mines there are 'disused'!), but when she did the Omine coalfield on Honshu Island (following row) was an important source of anthracite for local industry [3]. Moving on the next row, as is common on the scale of a 'basin' more than one rank of coal exists. Some of the coals at Paraná have vitrinite reflectances up to 2.6% which, by reference to Table 1.2 of this text, justifies classification as anthracite. Even so the part of the basin on which the work in [3] focused also contains coal lower than anthracite in rank. The operation considered was concurrent displacement of coal bed methane and sequestration of carbon dioxide, and a particular part of the basin of area 800 km^2 taking in a CBM well was deemed to be capable of sequestrating 15.4Gt (gigatonne) of carbon dioxide.

In assessment of the Quishi Basin the following points in favour of its use in carbon sequestration are noted: an area of 24000 km^2; thick and continuous coal seams at quite shallow depths; proximity to an existing pipeline structure; proximity to centres of population and activity; an existing detailed data base on the structure of the mine.

7.2 FURTHER COMMENTS

In Pennsylvania abandoned anthracite mines are being examined for their carbon sequestration potential [6] and comparisons being made with the carbon dioxide sequestration due to the State Forests. Of course, abandoned coal mines are a source of greenhouse gases as well as a potential site for sequestrating them. In the Shanxi Province of China, which features several times previously in this book, forty-four abandoned mines are believed to be releasing half a million cubic metres annually of methane [7]. Methane is of course a more powerful greenhouse gas than carbon dioxide.

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8 CO-COMBUSTION PROCESSES INVOLVING ANTHRACITE

8.1 INTRODUCTION

Examples of co-firing of anthracite with lower ranks of coal are many. This chapter will give examples of this, then move on to less conventional co-firing e.g. for carbon mitigation purposes. There are earlier parts of the book (see for example section 1.2) where co-firing of anthracite and bituminous coal features.

8.2 EXAMPLES

These are in Table 8.1 below, which is followed by comments.

Reference.	**Details.**
[1]	Tonghae thermal power plant, Korea (see Plate 8.1): Vietnamese anthracite and Australian bituminous coal in a fluidised bed. 200 MW of electricity.
[2]	660 MWe boiler fired with blended coals of varying anthracite proportions.
[3]	Korean anthracite co-fired with bituminous coal in a fluidised bed.
[5]	Co-firing of anthracite with petroleum coke.
[6]	Blend of petroleum coke and anthracite in steam raising.
[7]	Japan: fluidised bed using a blend of anthracite and bituminous coal and petroleum coke.

Plate 8.1: Tonghae thermal power plant, Korea.
Image from:
http://www.egcfe.ewg.apec.org/publications/proceedings/CoalFlow/10thCFS-11thCFET_2003/Session%2005/5-02%20Lee.pdf

Anthracite is the usual fuel at the 200 MW_e unit at Tonghae, which became the largest combustion unit for power generation to have utilised Korean anthracite. In [2] co-firing with an Australian bituminous coal is examined. The bituminous was tried in the weight range 40 to 100%, and even at the extreme of that scale there were no issues precluding bituminous coal use. The major difference was in the ash composition, there being a greater load on the electrostatic precipitator when bituminous coal was substituted for anthracite.

In the work in [2], when the unit was working at full capacity (660 MW) there was a drop in furnace temperature from 1339°C to 1150°C as the anthracite proportion was increased from 25 to 45%. Intuitively we should expect this to be due to the paucity of volatiles in the anthracite, 4.5% as compared to 12.1% for the bituminous. This is reflected by there being more carbon in the fly ash at higher anthracite proportions. There is a decline in NO_x with increasing anthracite proportion: the lower of the two temperatures above is at the lower limit for thermal (as opposed to fuel) NO_x production. Note (a point made by the authors of [2]) that 660 MW_e is a significant production level and in no way on a test scale. In the work in the following row of the table it was concluded that the volatiles from the bituminous coal brought about improved stability of combustion in comparison with anthracite only.

Korea has featured prominently in the table, and we note that some Korean electricity generators use both anthracite fired and bituminous coal fired plants. This is true of the Korea Midland Power Company, the varied output of which includes 3250 MW from bituminous coals and 400 MW from anthracite. Similarly, the Korea South East Power Company produces 6909 MW from bituminous coals and 325 MW from anthracite [4]. This is not of course co-firing but it is co-use within the same organisation to the same end. Each company also uses natural gas, having obtained it as LNG.

The next row of the table is concerned with co-firing of anthracite with petroleum coke. 2 million US tons of this blended fuel were burnt annually in Pennsylvania at the end of the 20th Century [5]. Such co-firing is the subject of [6], following row of the table. The interesting point is made that petroleum coke alone has a high fouling propensity because of the vanadium content, but that if it is co-fired with a coal the mineral constituents of that such as SiO_2 can absorb the vanadium pentoxide formed during combustion and prevent the fouling problem. The Japanese company using the triple blend (following row) has a wide range of products including textiles and cosmetics and one can imagine that the fluidised bed has a general-purpose role in heat supply. Japan has a very high oil refining capacity and petroleum coke as a 'supplemental fuel' makes every sense.

In addition to co-firing with bituminous coal, there is also co-firing of anthracite with such fuels as municipal wastes and with biomass. In the former case the motive is disposal, although there might be a carbon mitigation bonus, and in the second the sole motive is carbon mitigation. Tongahe, Korea has already featured in this chapter, and there has been activity at the Korean Electric Power Corporation (KEPCO) plant there into co-firing of coal and refuse-derived fuel (RDF) [8]. The RDF was in the form of pellets: this represents beneficiation of raw waste. These formed up to 5% of the anthracite weight at a generation rate across the composition range of 200 MW_e. This required up to about 5 tonne per hour of the RDF pellets. The primary interest in the investigation was post-combustion gas and solid residue, and in what looks like quite a positive result it was shown that the chlorine in the waste was fixed by the limestone in the bed. There was no more dioxin in the flue gases than when anthracite was used alone. Dioxins are have course been a difficulty in some examples of fuel use of wastes. Similarly NO_x emissions were not influenced by the incorporation of RDF into the fuel.

In work originating in China [9] municipal solid waste (MSW) was co-fired with anthracite in a fluidised bed. The bed operated at up to 0.22 MW of heat release. Emphasis was on production of oxides of nitrogen – NO and N_2O – from the combustion process. Anthracite coal and MSW were added separately to the fluidised bed: they were not blended beforehand. There was also co-firing of the MSW with a bituminous coal, and N_2O and NO were both higher with the bituminous coal/MSW blend than with the anthracite/MSW blend. With either coal increases in the proportion of MSW led to reductions in N_2O and increases in NO. Reference [10] describes a preliminary, lab-scale investigation of the possibility of concurrent use of anthracite and plastic waste as a fuel. (It is noted that plastic waste in combination with anthracite in blast furnace use is also of interest.) In [10] the observation is reported that the plastic waste brought down the combustion temperature when compared with anthracite only.

8.3 CO-FIRING WITH BIOMASS

There is interest in this in the Ukraine, where the benefits are seen as being twofold: carbon mitigation and a contribution to the country's energy mix, reducing dependence on natural gas [11][17]. Amongst the biomass that has been, on a test basis, co-fired with anthracite is alperujo, a waste from olive oil production [12]. In [13] tobacco residues and anthracite (each from China) were burnt together in a thermal analyser at temperatures up to 1273K. An important point emerges from the study which is likely to be of wide interest: abundance of volatiles in the biomass component and their virtual absence from the coal component strongly influences the combustion behaviour both at ignition and at later stages. This was not seen as precluding such co-combustion. Even so it is of obvious importance if plant for burning anthracite is subsequently to be used or adapted for co-firing with biomass.

Pyrolysis is of course coupled with combustion, and in conventional coal combustion how much of the volatiles burn as such and how much burn 'undevolatilised' is of interest and depends on conditions including particle heating rate. Reference [14] is concerned with co-pyrolysis of biomass and an anthracite coal is studied. The biomass took the form of torrefied wood, wood having been pre-heated at 250°C or at 300°C for one hour before combination with the anthracite for pyrolysis at much higher temperatures in a thermal analyser, and the same wood not so processed ('raw') was also used. Because of the very different abundances of volatiles in the anthracite and in the biomass and the different temperature patters of release, interactive effects are very small. The pyrolysis behaviour of the blends, from the thermogravimetric traces, was in either three or four distinct stages depending on whether the wood was raw, torrefied at 250°C or torrefied at 350°C. This indicates some potential for reaction control via the condition of the biomass in a scale-up. It is recorded that in China 50 MW of heat were produced by co-firing of anthracite with pelletised corn stalk [15]. Hoped for reductions in the NO_x were not realised. Co-firing of an anthracite with coffee grounds under oxy-fuel conditions features in the next chapter.

8.4 CONCLUDING REMARKS

As the world moves towards Kyoto targets the co-firing of anthracite with biomass will be given some consideration. A more important possibility is that some power stations now using anthracite blended with bituminous coals will go fully to biomass. In that event the other uses of anthracite – synthesis gas production, filtration, carbonisation products – will become more important. 'Chemicals from coal' is seen as being very much on the agenda as fuel use declines and the highest rank of coal is not excluded from such aspirations.

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9 ANTHRACITE IN OXY-FUEL COMBUSTION

9.1 EXAMPLES

By oxy-fuel combustion is meant combustion in oxygen and not air. The advantage is absence of significant amounts of nitrogen from the flue gas, making carbon capture easier. The term is sometimes broadened to include combustion in oxygen diluted with carbon dioxide. Examples of such combustion of anthracite are in the table below.

Reference.	Details.
[1]	Spanish anthracite in a fluidised bed releasing heat at 90 kW. Atmospheres ranging in composition from O_2:CO_2 23/77 to 60/40 as well as in air.
[2]	Blend of anthracite and spent coffee grounds[18] examined in a thermal analyser in an atmosphere of O_2 + CO_2 in a number of proportions.
[3]	Single p.f. sized particles of a Spanish anthracite in a drop tube furnace in an atmosphere of O_2 + CO_2 in a number of proportions. Photographic records of the burning.
[5]	Chinese anthracite of p.f. size. Thermal analysis under high pressure. An atmosphere of O_2 + CO_2 across a range of pressures.
[6]	Spanish anthracite in a fluidised bed releasing 3 kW of heat. Lime present to trap SO_2. O_2 at up to 35%, balance CO_2.
[7]	Anthracite burnt in the thermogravimetric unit under O_2/CO_2. Further experiments in a tube furnace.

Table 9.1. Oxy-fuel combustion of anthracite.

In the work in the first row of the table interest was in SO_2 and NO_x production. There was lime in the bed for sulphur dioxide capture, and the composition of the atmosphere influenced the effectiveness of this. At a bed temperature of 875°C and 40/60 O_2:CO_2, the sulphur dioxide emissions were about the same as with air. By contrast with 60/40 O_2:CO_2 the sulphur dioxide emissions were significantly reduced. This has to do with the fact that the lime can react with CO_2 as well as with SO_2 and this results in an interplay with a dependence on the carbon dioxide partial pressure. In the temperature range 800-850°C the nitric oxide (NO) yield decreased with increasing proportion of oxygen. In reviewing this result one must remember that it is fuel NO only which is being produced: the temperature is much too low for thermal NO. So again there are concurrent processes, and even in the case of an anthracite they include devolatilisation. The volatile matter content of the particular anthracite used in this work was 10.8%.

In the work in the following row, with 30% oxygen balance carbon dioxide the combustion behaviour of the blend was similar to that in air, but marked enhancement of rate was evident with 40% oxygen. The higher molar mass of CO_2 (0.044 kg) than air (0.028 kg) has an effect on devolatilisation, there being some restriction of diffusion of released material by the denser surrounding gas.

In the work in the third row of the table O_2:CO_2 ratios in the range 21:79 to 50:50 were used in the drop tube furnace. Maximum combustion development manifest as flame size and brightness was after 63 ms with the 21:79 mixture, and after 31 ms with the 50:50 mixture, where a visible emission greater than that with any of the other gas mixtures was observed. Tube furnaces and photography are a fairly classical means of investigating coal particle ignition (see [4]) and sometimes envelopment by volatiles is observed, in which case these burn ahead of the residual solid. It is noted in [3] that no such effect was observed in the anthracite studied. Two distinct temperatures were identified in the TG/DTG traces: the ignition temperature T_i and the burnout temperature T_b. For the Chinese anthracite in 21% oxygen balance carbon dioxide across the range of pressures 0.1 to 2 MPa, T_i ranged from 400 to > 500°C and T_b from ≈ 650 to ≈ 750°C. Several phenomena are invoked in reviewing these observations [5]. One is diffusion of oxygen to the coal and effects on that of increased pressure. Another is the envelopment effect referred to above, and a view that that might occur at the high end of the pressure range. In the work in the next row of the table, the focus was on SO_2 capture. The interesting point is made that in oxy-fuel combustion the flue gases can be 90% carbon dioxide, and that this by forming calcium carbonate with the lime influences the performance of that in SO_2 capture.

Fuel NO formation was also of interest in the work in the following row of the table. With temperature programmes in the TGA ascending to 1200K there was little difference between the temperature histories for atmospheres of O_2:20%N_2 and O_2:20%CO_2. Conversion of fuel nitrogen to NO was lower for the O_2:20%CO_2 atmospheres than for the O_2:20%N_2, indicating that NO_x suppression might be a bonus in the use of oxy-fuel for carbon mitigation.

9.2 FURTHER REMARKS

A reader is asked to note that in the work in the table both fluidised bed combustion and pulverised fuel combustion have featured, indicating that oxy-fuel might have a future with either or both of these combustion techniques.

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10 CARBON PRODUCTS FROM ANTHRACITES

10.1 GRAPHENE

The 2010 Nobel Prize in Physics went to Andre Geim and Konstantin Novoselov, both of the University of Manchester, not for the discovery of graphene – that had already taken place – but for their work on characterising its properties. Graphene has been described as a thin layer of carbon, equivalent to one layer from a three-dimensional graphite structure. It is the best conductor of electricity there is and consequently its applications include electrodes. There have (e.g. [1]) been successful attempts to make graphene from anthracite. In [1] the anthracite was from the Shanxi Province of China. After grinding the anthracite was subjected to catalytic graphitisation, that is, heating at 2400°C under argon with an iron-containing catalyst to yield coal-derived graphite oxide. Then followed hydrogen dielectric barrier discharge (DBD) treatment of the catalytically graphitised anthracite. Under the conditions of the DBD the hydrogen is able to remove the oxygen content of the graphite oxide to yield coal-derived graphene.

10.2 CARBON FIBRES

These can be made from anthracites via activated carbons. For example [2] use of such an activated carbon from a Spanish anthracite to make an electrode comprising polyaniline and a carbon fibre is described in [2]. 'Activation' of the anthracite was chemical, the activating agent being potassium hydroxide. The carbon so prepared was allowed to adsorb polymerised aniline. This protects the internal structure of the carbon from oxidation as well as eliminating side reactions. The capacitance of the final product was measured in an electrolyte solution as 200 Farads per gram (F g^{-1}). Reference [3] gives some background on such figures, and reports a value of 120 F g^{-1} for an electrode prepared from a petroleum coke and a values in the range 200 to 300 F g^{-1} for various coal- and pitch-derived electrodes[19].

10.3 GRAPHITISATION

This has in some degree been anticipated by the previous section. In work described in [4] a Pennsylvania anthracite was initially calcined at 1420°C then graphitized at 3000°C. The anthracite had a vitrinite reflectance as high as 5.19% and a carbon content of 90.3%. The ash content was 11.5%, and this leads to a point of some importance: demineralisation led to a higher degree of graphitization as determined by X-ray diffraction. There was considerable aluminium in the mineral and inorganic content of the anthracite but no evidence of a catalytic effect of this on graphitisation as has sometimes been observed. The motivation for the work was the hope that anthracite could replace petroleum coke as a basis for making such materials. A reader should note that this is the second time in this book (see section 4.3) that anthracite in place of petroleum coke to extend amounts of the latter has featured.

In a piece of work also involving anthracites from Pennsylvania [5] three petrographically distinct anthracites were treated at temperatures up to 2640°C. One particular sample (Jeddo, see section 10.4) reached a higher degree of graphitisation with the minerals present than with them removed. Furthermore, another of the samples (Summit) when treated without the minerals did not graphitise at all: an X-ray diffraction signal characteristic of graphitic structures was absent. That minerals participate in the graphitisation process is clear, and the view of the authors of [5] is that only certain of the minerals present do. Obviously control of the graphitisation and its extent could be attempted by introduction of selected minerals and inorganics.

10.4 SILICON CARBIDE NANOWIRES

Jeddo was also the origin of the anthracite used in an investigation of the production of carbon nanowires [6]. The procedure involved mixing 100 g of dried anthracite fines with silicon. This was added to a collagen-water sol. After mixing this preparation was placed into a mould in order to prepare pellets, which were pyrolysed at 1400°C under inert conditions. Scanning electron microscopy examination of the carbonised pellets followed, and silicon carbide nanowires were evident in abundance on the surface. There was discussion of whether the vapour-solid (VS) or vapour-liquid-solids (VLS) mechanism of nanowire formation had taken place, and the two following points of interest were made. VLS requires a metal catalyst: no such catalysts was employed in [6], but the natural inorganic and mineral content of the coal might have fulfilled this role. With the VLS mechanism intermediate existence of a liquid tends to lead to blobs at the ends of the fibres, and these were found not to occur in the work in [6]. Plate 10.1 shows a scene from the Jeddo mine, coal from which features in two sections of this chapter.

www.alamy.com - AFBGNF

Plate 10.1. Scene from the Jeddo mine, PA.
Image taken from:
https://www.google.com.au/search?q=jeddo+coal+field&biw=1637&bih=716&source=lnms&tbm=isch&sa=X&ved=0ahUKEwi_3LyHmpzNAhVLJpQKHUBNBnkQ_AUIBygC#imgrc=6LgT2EUg9rlJ-M%3A

10.5 MILITARY USE

Anthracite can be used in place of charcoal in gunpowder manufacture. There is a US patent for this dating from the mid 19th Century [7]. An indirect way in which anthracite influenced the Civil War is that prior to the War Virginia had obtained anthracite from Pennsylvania and this stopped as a result of the War [8]. The anthracite had been used in ironmaking, and production of weapons was jeopardised. Coking coals were obtained to supply a metallurgical reductant to replace the anthracite.

10.6 FURTHER REMARKS

Endeavours such as those described in this chapter are obviously consistent with intentions to use coals across the ranks more as sources of chemicals and less as fuels. One more such application will be mentioned: hydrotreating of anthracite, to make an organic binder such as might otherwise have come from a coking coal as a by-product [9].

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11 ANTHRACITE-WATER AND ANTHRACITE-OIL COMBINATIONS

11.1 ANTHRACITE-WATER

Table 11.1 below summarises some investigations into anthracite-water slurries.

Reference.	**Details.**
[1]	Anthracite-water slurry, 70% anthracite weight basis: stable combustion at a test-scale burner with little unburnt residue.
[2]	Yongcheng (China) anthracite slurried. See comments in the main text.
[4]	Guizhou (China) anthracite slurried and studied in a thermal analyser. Comparisons with a slurry of petroleum coke.
[5]	Korean anthracite slurried. Sodium naphthalene sulfonate, poly(methyl methacrylate), polypropylene and a polypropylene glycol based additive used to adjust the viscosity.
[6]	Anthracite coal slurried in water and in sewage sludge. Comparisons made in terms of viscosities.
[7]	Jingxi (China) anthracite treated with ultrasound before slurrying.

Table 11.1. Examples of anthracite-water slurries.

Notwithstanding the positive tone for the first entry in the table, it was concluded in [1] that the anthracite-water fuel could not be substituted for fuel oil in existing plant without major changes to the burner. If existing burners were to be used it would be necessary to use natural gas as a secondary fuel. In the work in the next row the slurry was across a range of coal-water proportion, and there was some emphasis in the variation of the dynamic viscosity with weight fraction of coal. At 68.9% coal it was almost exactly 1 Pa s, rising steeply to 1.4 Pa s at 71% coal loading and dropping steeply to 0.33 Pa s at 66.25% coal loading (measured at 25°C in each case). So that the viscosity has a strong dependence on the proportions of coal and water is clear. We note by way of comparison that 1 Pa s is the dynamic viscosity of glycerol at 20°C [3]. In the work in the next row it is recorded that both the ignition temperature and the burnout temperature were lower for the slurry made from petroleum coke. All of the additives identified in the following row had the effect of lowering the viscosity of the slurry from the Korean anthracite. This made higher loadings possible without a viscosity penalty.

In the work in the following row of the table emphasis was on viscosity, and at a shear rate of 100 s^{-1} the coal water slurry at a particular loading had a dynamic viscosity as < 0.5 Pa s. When the slurrying was in sewage sludge the viscosity (at the same shear rate) depending on the coal loading was up to ≈1.5 Pa s. There was a weak dependence of the viscosity on which of two additives – sodium naphthalene sulfonate formaldehyde condensate or sodium polycarboxylate – had been used. Each was at 1% weight basis. In the work in the following row, ultrasound was found to increase the slurryability up to a maximum then reduce it. The effect was not dramatic, and across a range of treatment times with ultrasound the maximum coal loading was always around 65%. Again, the effect on the amounts hydrophilic constituents is invoked as an explanation. The discussion now moves on to anthracite-oil fuels.

11.2 ANTHRACITE-OIL

Again a tabular approach will be taken. Production of such fuels provides a means of utilising fines, and this has been a factor in their development.

Reference.	**Details.**
[8]	Anthracite particle suspension in oil from pyrolysis of rice husk.
[9]	Anthracite in soybean oil.
[10]	See comments in the main text.
[11]	Discussions (in 1983) of the viability of slurried Pennsylvanian anthracite as a fuel.

Table 11.2. Examples of anthracite-oil fuels.

In the work in the first row of the table the coal loadings were significantly lower than in coal-water slurries, around 40%. Three anthracites were so treated, and the resulting blends had viscosities in the range 0.072 to 0.183 Pa s. Hydrophilicty of parts of the coal – a factor with coal-water slurries as noted – is also relevant to the coal/bio-oil mixture under discussion. Hydrophilic parts of the coal retain bio-oil by reason of the polarity of its constituents (petroleum materials lack such polarity), leaving less bio-oil in the liquid phase and so pushing up the viscosity. Emphasis was also on rheology in the work in the next row, and the viscosity increased sharply with coal loading, from < 1 Pa s at 20% loading to 60 Pa s at about 55% loading. Each of the fuels in the first two rows has the advantage of a degree of carbon neutrality so one might expect further R&D.

In reference [10] (next row) there is a summary of the conclusions of a group which met to discuss future thermal usage of anthracite in the US, and suggestions made included gasification, blending with bituminous coal (each of which has previously featured in this book) and use of anthracite-oil slurries. In [11] (next row of the table) it is the cost of such a slurry with that of oil that is the keynote of the discussions. The price of domestic oil in the US rose from $14.95 to $31.83 over the period 1978–1982, so projects into alternatives had instability in oil prices on their side. The viability of such fuels will always be affected by the price of oil. The oil used in making anthracite-oil mixtures is residual such as might have become heavy fuel oil.

11.3 FURTHER INFORMATION

The matter of the response of the surface of an anthracite to water has featured more than once in this chapter and is clearly an important issue in such applications. It is therefore of interest that the this response can be modified by pre-heating an anthracite [12]. Working with a Chinese anthracite, the authors of [12] observed that heating to 600°C reduced increased the hydrophilicity, and this is attributed to an increase in amounts of structures containing –C=O and –COOH functional groups. Carbons converted to these in the heating were previously –C-C- and –C-H which are hydrophobic so the statement above that the hydrophilicity is increased could equivalently have been re-expressed by saying that the hydrophobicity is reduced.

11.4 REFERENCES

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12 HAZARDS WITH ANTHRACITES

12.1 THE INTRINSIC REACTIVITY OF ANTHRACITE TOWARDS OXYGEN

Though it was known long before the work in [1] that anthracites are less reactive towards oxygen than lower ranks of coal, this was shown very directly by microcalorimetric measurement in [1]. An anthracite from the UK at 60°C released heat at a rate of 61 ± 20 mW kg^{-1}. An Australian brown coal at the same temperature in the same instrument released heat at 0.92 W kg^{-1} (920 mW kg^{-1}). The low heat-release rates of anthracite in air do not however preclude spontaneous heating.

12.2 SPONTANEOUS HEATING

Plate 2.2 shows a pile of culm on fire. With culm there might be the additional factor of catalysis by the mineral impurities as is known to happen with filter cake from lower ranks of coal [2]. In fact, anthracite culm fires in Pennsylvania are an all too common occurrence [3]. The image in Plate 2.2 is from 1908. Plate 12.1 below shows a fire at a culm heap in PA from 2014, over a century later.

Plate 12.1. Culm fire in PA, 2014.
Image from Reference [3].

Moving back again in time, ‘Popular Science Weekly’ for August 1916 has a black and white photograph of a culm heap in PA showing no smoke or other indications of fire even though it is burning at a considerable rate internally. A fire break was cut into the pile to prevent spread.

12.3 THE FIRE AT CENTRALIA PA

The best known example of a fire at an anthracite deposit is that at Centralia PA which began in 1962 and continues. Ignition was by a fire of trash lit at an abandoned coal pit which by then was the local landfill [4]. Whoever lit the fire was unaware that there was a layer of anthracite close enough to the wall of the landfill to be ignited by the fire within it. Flames at the surface were easily put out, but propagation into the anthracite layer had begun by then and was to continue until the present time! The result was that Centralia ceased to be inhabitable and the population moved to other locations with financial help from the federal government.

One can deliberate of the combustion behaviour at Centralia. The propagation rate would have been that characteristic of smouldering, not of flaming, although there would have been brief smouldering-to-flaming transitions when methane was released. Smouldering combustion will have a propagation rate < 1 mm s^{-1}. Volatiles are not plentiful in an anthracite, but such volatiles as there are would have led to smoke and polyaromatic hydrocarbons (PAH). Combustion of the coal carbon would have been much less than total.

Plate 12.2. Damage to a road surface near Centralia PA due to the anthracite fire.
Image taken from:
https://www.google.com.au/search?q=centralia&biw=1637&bih=716&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjX6uqUyaPNAhWDnZQKHcFsC68Q_AUIBigB#tbm=isch&q=centralia+sinkhole&imgdii=-ZrlPox2_LZtZM%3A%3B-ZrlPox2_LZtZM%3A%3BkuK5DdLBQUC5bM%3A&imgrc=-ZrlPox2_LZtZM%3A

Plate 12.2 above shows a road surface near Centralia fissured by the heat from the anthracite fire.

12.4 DUST EXPLOSIONS

The comment about low intrinsic reactivity of anthracites in comparison with lower rank coals is as relevant to dust explosions as it is to spontaneous heating, as is the low volatiles content. An important point in relation to explosions involving coal dust is that inside a mine the particles might be dispersed in methane, making the consequences of ignition all the more serious.

A US Bureau of Mines document from 1913 [5] (at which time the US was producing > 500 million tons per year of coal, about 60% of the 2015 production [6]) makes two points unequivocally and with emphasis. One is that in general coal dust in the total absence of methane can explode with fatal consequences. The other is that in an anthracite mine 'firedamp' – methane and possibly other flammable gases from the coal – is the cause of fatal explosions, and the dust alone not sufficient. The report states that in an anthracite mine an explosion of coal dust is 'not self-propagating'. That means that when in an anthracite mine there is a dust explosion it does not go beyond a flame kernel to a fully developed flame. This can of course be correlated with the low volatiles. The further point is made in [5] that a gas explosion at an anthracite mine is accompanied by the formation of 'afterdamp', a dominant constituent of which is carbon monoxide which is both flammable and poisonous.

The conclusion by the US Bureau of Mines that the susceptibility of anthracites to dust explosions is low is consistent with a statement in a very much more recent piece of work [7], which also informs a reader of the low explosion propensity of graphite[20]. That is not to say that anthracites do not display such combustion behaviour under any conditions, and there have been experimental investigations of anthracite dust explosions. A selection of such work is discussed in Table 12.1 below.

Reference.	**Details.**
[9]	Russian anthracite examined in a 20 litre metal sphere. Explosion across a range of oxygen concentrations and total pressures with an ignition source. Explosion overpressure of 5 bar.
[10]	Failure of anthracite dust to show flame propagation in air in a 1 m^3 vessel. Such propagation in a 20 litre vessel.
[11]	Failure to ignite anthracite dust in a 20 litre or a 1 m^3 sphere.
[13]	Explosion of anthracite dust at a concentration of 300 g m^{-3} in a semi-cylindrical vessel.

Table 12.1. Investigations of anthracite dust explosions.

With reference to the first row of the table, for a dust concentration of about 0.5 kg m^{-3} the overpressure was 5 bar. In an accidental explosion, an overpressure a tenth of that is lethal. In the work in the second row there is a link with restriction to kernel burning discussed earlier. Having happened in mines as reported it happens in a large vessel but not in a smaller one, consistently with the very widely observed fact that confinement accelerates combustion. In a mine a 1 m^3 cavity would be viewed as a confined space. In the work in the next row of the table, the authors tried a larger ignition energy to initiate an anthracite dust explosion, without success. An important point is that the minimum ignition energy of a gas-air or dust-air mixture is not a fundamental quantity: it depends on the time over which the energy is transferred [12]. The vessel in the work in the following row was also small, which probably accounts for the success of the trials.

12.5 CONCLUDING REMARKS

It suffices to reiterate the point made earlier that lower reactivity and small amounts of volatiles mitigate the hazards of anthracite in comparison with say a high-volatile bituminous coal or a lignite, but not to the total elimination of hazards. The text continues with a discussion of use of anthracite as a domestic fuel.

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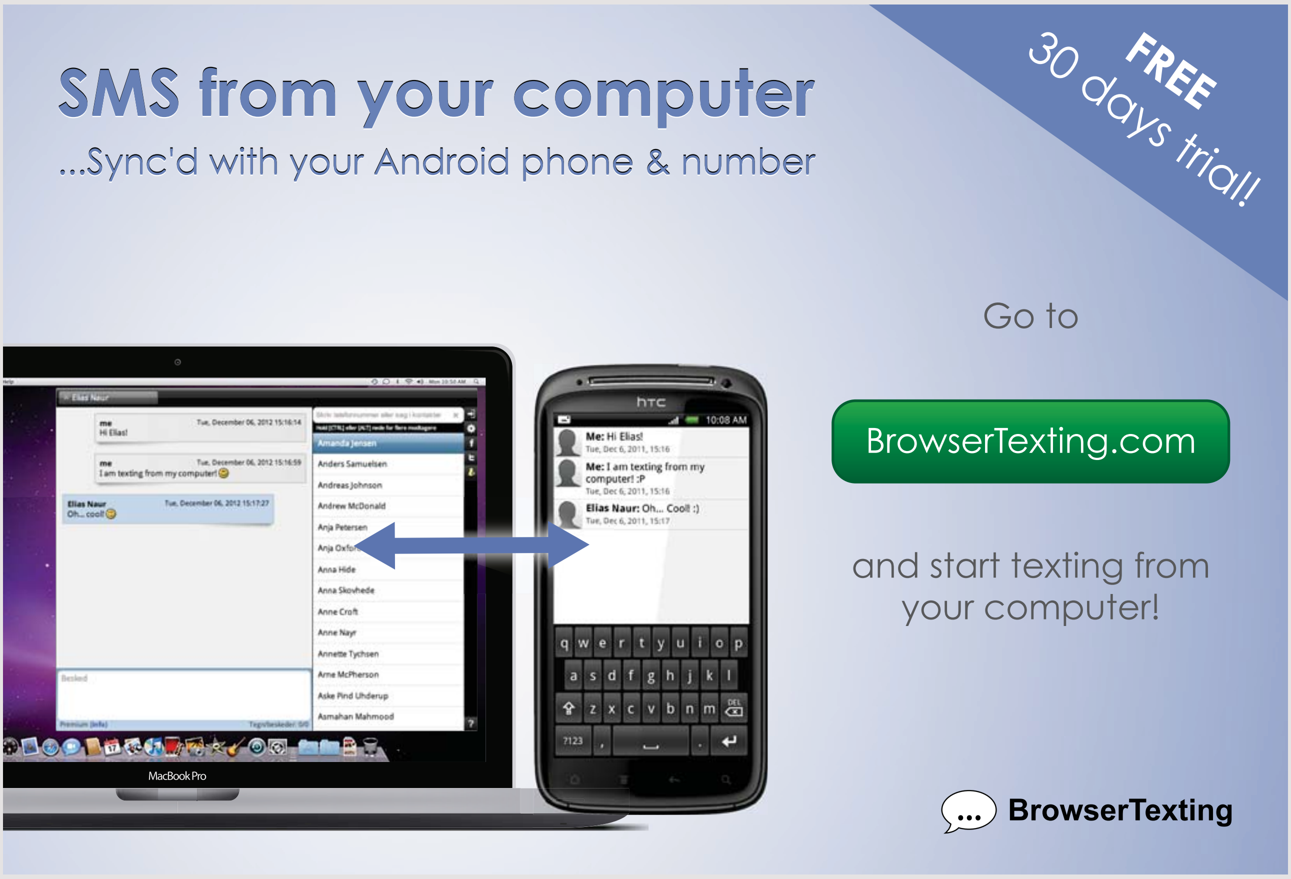
13 ANTHRACITE IN DOMESTIC FIREPLACES

13.1 INTRODUCTION

‘Scientific American’ for September 8th 1869 has an article entitled ‘Hints on the Burning of Anthracite Coal’ [1]. It states that kindling with wood or charcoal will usually be necessary, and that an appliance designed for bituminous coal will not be suitable. It recommends that when a fire has got low initially a small amount of coal should be placed on it initially to revive it. And the article has a good deal to say about clinker. Before returning the discussion to much more recent times we note that the advice to regenerate a dwindling fire with a single lump of anthracite obviously follows from the low volatile content, a factor exacerbated by the sluggish response of a lump of the anthracite to heat. Such a lump would of course be orders of magnitude heavier that a pulverised fuel particle or than a particle such as might enter a fluidised bed. In domestic use the low volatiles is a plus as it means little or no smoke.



13.2 CURRENT USAGE

In Pennsylvania there has for generations been home heating by anthracite [2][21]. It has been noted, in a document originating in Sugarloaf PA, that the amounts of coal from the region burnt in homes is increasing [3]. Plate 13.1 below shows an example of a modern domestic appliance for domestic heating with anthracite. It can use either 'anthracite rice' or 'buck coal'. By the former is meant anthracite at particle sizes in the range 5/16 down to 3/16 inch. By the latter is meant coal particles of size 5/16 to 9/16 inches [5][22]. The stove is rated at 85000 BTU per hour, a figure which is examined in the boxed area below.

85000 BTU per hour = 9×10^7 J per hour

Assigning the coal a calorific value of 30 MJ kg^{-1}, the rate of consumption of fuel is:

$$9 \times 10^7 \text{ J hour}^{-1}/(30 \times 10^6 \text{ J kg}^{-1}) = 3 \text{ kg hour}^{-1}$$

This can be supplied from a hopper which can contain up to 150 lb (68 kg) of coal, enough for a day's operation at rated capacity, longer at below rated capacity.

The stove is not intended to operate at its 'BTU rating' for anywhere near the whole time, so a full hopper would keep the appliance going for 2–3 days, perhaps longer.

Plate 13.1. The Allegheny RS-96S Model Coal Heating Stove, manufactured by Reading Stove Co., PA. Image taken from [4].

13.3 FURTHER INFORMATION

Wherever anthracites are used for domestic heating it is preferred that they be at the low end of the range of volatiles content for anthracites, to control the deposition of tarry substances [6]. Russian, Chinese, Korean and South African anthracites all find application *inter alia* to domestic heating [7].

13.4 REFERENCES

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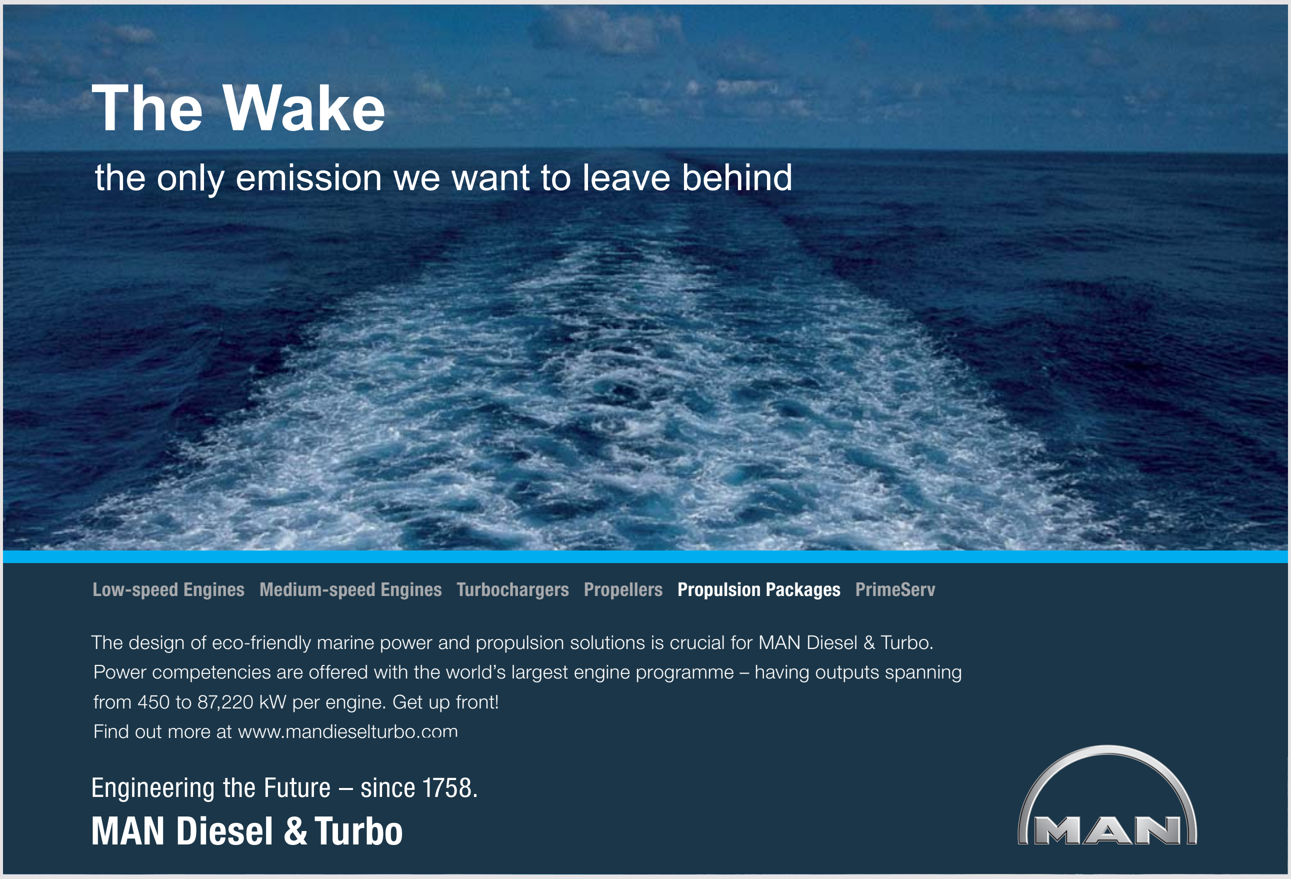
14 ANTHRACITE ASHES AND SLAGS

14.1 BLAST FURNACE SLAG AND ELECTRIC ARC FURNACE SLAG

Here again there is information from a US Bureau of Mines report [1] that is helpful. Many trials are reported, and we select one in which coke and anthracite on an approximately 50:50 basis were the metallurgical reductant. The ash content of the anthracite was 12.1% and that of the coke 7.2%. Per US ton of metal produced there were 1215 lb of slag. It is possible for incipient slag on its descent through the bed to collect carbon particles. The major contents of the slag include silicon oxide and aluminium oxide. Such slags can be used in applications including cement manufacture and are frequently made available for purchase in granulated form. There will be 80 to 200 kg of slag per tonne of metal product from an electric arc furnace using anthracite [2].

14.2 FLY ASH

The Douro anthracite field in Portugal featured in Chapter 2. There was anthracite production there from the late 18th century to the early 21st and consequently there are now waste heaps there as there are in Pennsylvania. Fly ash from Douro coal, produced in electricity generation, has been closely studied [3] and a precis follows.



It was stated in Chapter 2 that power generation ceased at Douro in 2004, and in this study which postdates the samples of fly ash were taken from a landfill. Dominant minerals in it included quartz and mullite (which contains aluminium and silicon oxides). However, more than half of the weight of each fly ash sample examined was not classifiable as any particular mineral structure but was amorphous. There was significant carbon retention in the fly ash: the samples had up to 10.9% fixed carbon and up to 2.3% volatile matter. The inorganic content never exceeded 90.6%. Clearly when the anthracite was fired this could have been avoided by using a higher degree of excess air. There was up to 0.29% sulphur in oxidation state +6 in the fly ash, leachates from which were acidic signifying organically bound sulphur in the coal structure. Trace elements included arsenic (up to 82.6 mg kg^{-1}), thorium (up to 13.8 mg kg^{-1}) and molybdenum (up to 4.0 mg kg^{-1}) amongst many others.

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[3] Ribeiro J., Valentim B., Ward C., Flores D. ‘Comprehensive characterization of anthracite fly ash from a thermo-electric power plant and its potential environmental impact’ International Journal of Coal Geology **86** 204–212 (2011).

POSTSCRIPT

Coals have for millennia (they were used in Roman times, and much further back than that) been utilised in the service of human beings. This book is concerned with one particular sort of coal, and whilst coverage is meant to be current there are a number of references to practices outside living memory. We can expect that as the 21st Century takes its course anthracites will continue to find both combustion applications and applications to chemical manufacture.

ENDNOTES

1. The illustration in the Appendix is relevant to this. The food is being cooked without a boundary between it and the fuel. Had for example low-rank coal briquettes been used as a fuel such a boundary, by means of a barbecue arrangement or whatever, would have been necessary to prevent contamination of the food originating with the volatiles.
2. ‘Brown coal’ in the terminology which applies in Victoria.
3. Probably it will, because Mount Klappan is very distant from Ontario where at present Canada’s steel industry is concentrated. That being said, Mount Klappan anthracite is metallurgical grade [31] which will make transporting costs easier to justify. A probable scenario is that a considerable proportion of Mount Kapplan anthracite will be exported to countries such as Japan for metallurgical use.
4. The issue of ‘Popular Science’ for November 1902 states: ‘The anthracite fields of Pennsylvania will be exhausted with 75 years…’. Happily this was unfulfilled: > 2 million tonnes were produced there in 2015 [44].
5. This theme is developed in section 12.2.
6. In [5] the ‘average’ calorific value of the culm used at Frackville, conventionally measured, is given as 8.2 MJ kg^{-1}. The plus-or-minus given encompasses the value from the rough calculation above.
7. Gilberton also featured in the previous chapter.
8. This was at Jincheng, which has featured several times previously in this book.

9. A distinction can be made between blast furnace and foundry grades of coke. The latter tends to be of lower reactivity than the former [6]. The origin of the difference is the coking coals or blends thereof used as starting material. Internationally, foundry coke is produced in much smaller amounts than blast furnace coke.
10. The arc itself is of course at a much higher temperature than this.
11. ‘Quebec Iron and Titanium’.
12. Not synonymous with ‘roasted’ in the metals industry.
13. A metalloid.
14. The term ‘shaking ladle’ is fairly self-explanatory. There is a critical shaking speed above which the degree of mixing declines [23].
15. An example of broadening of terminology. The coal used as a filter here is Australian bituminous with a high degree of hardness (Hardgrove index about 50: see Table 1.3). Description of such as an anthracite in a filtration application has become standard in the trade. The author owes the information in this endnote to James Cumming and Son, Auburn NSW, suppliers of such filters: http://jamescumming.com.au/cs-filter-coal-media/cs-brand-australian-filter-coal-media/
16. Benzene, Toluene, Xylenes.
17. See section 2.2.
18. Collected from a university cafeteria.
19. The precise value has a dependence on conditions including the electrolyte concentration.
20. Release into the atmosphere of dust from anthracite mining in Vietnam is a pressing health issue [8].
21. Interestingly, it is reported in [2] that the Amish people have a preference for anthracite as a domestic fuel.
22. These definitions vary.

APPENDIX

Anthracite being used to prepare a pizza, as reported in the Pittsburgh Gazette 25th September 2015.

Image from:
http://powersource.post-gazette.com/powersource/companies/2015/09/25/Pennsylvania-s-shrinking-anthracite-coal-industry-finds-a-specialty-pizza-oven-fuel/stories/201509240170