



STUDIECENTRUM VOOR ECONOMISCH EN SOCIAAL ONDERZOEK

FROM COAL TO ELECTRICITY
DESCRIPTION OF MAJOR SIDE-EFFECTS*

Guido ERREYGERS
Rapport 84/159

August 1984

*Thanks to Aviel Verbruggen for draft reading

Universitaire Faculteiten Sint-Ignatius
Prinsstraat 13 - 2000 Antwerpen
D/1984/1169/10

Abstract

The generation of electricity on the basis of coal engenders various side-effects. The paper describes the major ones. The description follows the fuel cycle, meaning that the examination begins with the mining of coal and ends with the conversion of coal to electricity. The stage of conversion to electricity appears to be most important with regard to side-effects. As a result, problems relating to plant construction, operation and maintenance, emission of particles, emission of oxides of sulfur, nitrogen and carbon, solid waste, and thermal pollution are thoroughly discussed. Special attention is paid to the problem of acid deposition: In the last section, we present some promising mitigation options, such as Fluidized Bed Combustion (FBC) and Flue Gas Desulfurisation (FGD). Completeness has not been aimed at.

§ 1. Introduction

In this paper we examine the most important side-effects of generating electricity from coal. The main part is devoted to conventional techniques. The final paragraphs deal with new developments.

Even a superficial examination of the problem learns that it would be heroic to assume that all side-effects are known, let alone quantifiable. Therefore, we do not aim at precise measurement, but rather at systematic description of side-effects. Our ultimate goal is a meaningful comparative evaluation of different electricity generating systems.

The structure of our analysis is based on the fuel cycle. We examine the major known side-effects, beginning with the mining of coal and ending with its conversion to electricity.

The quantitative estimates in Tables 1 to 8 always refer to a 1000 MWe coal-fired plant having a load-factor of 75 % (this is only a scaling convention). To account for uncertainties and variations, several hypotheses are put forward.

SECTION A : COAL MINING

§ 2. The amount of coal required to fuel a 1000 MWe plant for a year mainly depends on two elements : the heating value of the coal, and the thermal efficiency of the plant. On the basis of various assumptions, it is calculated that some 2 - 3 million tons of coal are needed (table 1).

TABLE 1 : Amount of coal required annually

case n° →	1	2	3	4	5	6
Heating value of coal (GJ/ton) →	23	23	26	26	29	29
Thermal efficiency (%) →	34	40	34	40	34	40
Amount of coal required (10 ³ tons) →	3025	2571	2676	2275	2399	2039

Coal is obtained in two ways : via surface (or strip) mining, and via underground mining. In general, surface mining is cheaper, safer and healthier than underground mining. However, it has catastrophic effects on the landscape, and it can only be practised where the overburden layer is less than 70 m. thick (1).

The major side-effects of coal mining are occupational diseases and deaths, and accidental injuries and deaths (2). Accumu-

lations of coal dust in the lungs cause pneumoconiosis ("black lung") and other respiratory diseases. Special hazards in the mines (explosions, cave-ins, etc.) lead to important rates of accidental injuries and deaths.

There is no agreement on the exact magnitude of these effects (table 2). This can be explained by the fact that figures from different countries, different periods and different practises have been lumped together.

TABLE 2 : Annual consequences of coal mining to fuel a 1000 MWe plant (range of estimates from the literature)

Pneumoconiosis (cases)	0.41 - 48
Pneumoconiosis (deaths)	0 - 7
Accidental injuries	24.6 1039
Accidental deaths	0.33 - 2.13

Source : COHEN & PRITCHARD (1980), p. 10

Other side-effects of coal mining include (3) :

- * risk of serious mine disaster
- * polluted watersheds, due to acid mine drainage
- * land disturbance, especially in the case of surface mining
- * aesthetic effects

§ 3. Mined coal is mixed with a lot of spoil material, resulting from sedimentary rocks and shale with which seams of coal

are deposited (4). This waste material in some cases amounts to 60 % of the coal extracted.

In theory, the spoil material could be recycled for use in building and construction. Mostly, it is piled up in giant waste tips. The land covered with this solid waste is almost certainly permanently lost. Accidents can happen as well : on October 21, 1966, in Aberfan (U.K.), a waste tip collapsed in rainy conditions, leading to many deaths in the nearby village (5).

SECTION B : COAL PROCESSING

- § 4. Various techniques are available to transform Run-Of-Mine (ROM) coal into a cleaner, and hence more efficient fuel. These techniques, either based on mechanical or chemical processes, aim at the removal of impurities such as sulfur and ash constituents.

It is obvious that processing will not only produce cleaner coal, but also large amounts of (solid) waste. This can cause new environmental problems, e.g. diffusion of dust, leaching of highly toxic trace materials, etc. (6).

To date, coal cleaning is not standard practise (7). The chemical techniques are only in the experimental stage. A more thorough discussion of coal cleaning can be found in the section dealing with mitigation (§ 20).

SECTION C : TRANSPORT AND STORAGE

- § 5. A special danger is associated with coal transportation : railway-crossing accidents between automobiles and trains carrying coal. This risk must not be dismissed as negligible; it has been estimated that a 1000 MWe plant in the U.S. is "responsible" for 1.5 railway-accident-deaths per year (8).

The problem seems to be linked to the absence of crossing gates, so mitigation could in principle be relatively easy. Other risks associated with railway-transport of coal have been identified : increased danger of train derailments followed by train collisions, increased danger of collisions with dangerous goods traffic, etc. (9).

Usually, the storage of coal does not present abnormal dangers. The storage of pulverized coal, however, requires special safety measures, since pulverized coal may form an explosive mixture with air (10). In any case, considerable storage capacity must be available in view of the quantities of coal involved.

SECTION D : CONVERSION TO ELECTRICITY

- § 6. The occupational and public health risks resulting from coal power plant construction seem fairly low (11). Risk estimates vary according to the activities that have been included. There is disagreement about the inclusion of so-called "pre-construction risks". E.g., power construction requires important amounts of iron and steel; should accidents in iron ore extraction be included in the calculations of construction risks ? (12) This explicitly raises the problem of system boundaries (discussed in the paper dealing with methodology of comparative assessment).
- § 7. The occupational risks from routine operation and maintenance of coal-fired power plants do not seem excessively high (table 3).

TABLE 3 : Annual occupation risks due to operation and maintenance of a 1000 MWe plant (range of estimates from the literature)

Accidental injuries	0.9 - 6.4
Accidental deaths	0.01 - 0.15
Cancer	(not available)

Source : COHEN & PRITCHARD (1980), p. 11

- § 8. The principle of coal-based power generation is the conversion of the chemical energy of coal to electricity via steam production. During combustion, the chemical energy of coal is

transformed into heat, used for steam production. When fed to a turbo-set, this steam generates electricity.

Combustion not only generates heat, but also transforms coal into a number of "new" solid and gaseous materials : bottom ash, fly ash, and flue gases. These residuals may cause a wide range of environmental and public health risks.

The main source of concern is undoubtedly atmospheric pollution. The air is being polluted by gases and particulates (among which metals and even radioactive isotopes) escaping through the stacks. Some of these materials fall down on earth after a relatively short time, without having been transformed. Other residuals undergo chemical or biological reactions in the atmosphere, and return to earth in another form. Yet others reside in the atmosphere for a very long time.

It has to be stressed that to date the chemical and biological mechanisms regulating this air pollution are not completely understood (13). In part this is due to a lack of adequate monitoring of air pollution in its various forms. The health effects caused by this air pollution are even less understood.

"There is no general acceptance of the magnitude - or even the reality - of these effects. However, if real, they are large because the number of persons exposed is large, and although proof of their reality is not available, and may never be, no one can disprove the existence of a large health effect of air pollution either."
(14)

Broadly, health effects can be distinguished in chronic and acute effects. Detailed case studies indicate that the following diseases could be related to coal-combustion-induced air pollution (15) :

- asthma
- bronchitis and emphysema

- pulmonary function diseases
- non-specific respiratory diseases
- cardiovascular diseases
- eye and throat irritations
- cancer.

We will now take a closer look at the problems caused by emissions of particles, oxides of sulphur, oxides of nitrogen, and oxides of carbon. Afterwards, we will pay some attention to the problems of solid waste and thermal pollution.

§ 9. Emission of particles (16)

A particle is "a small discrete mass of solid or liquid matter such as in aerosols, dusts, fumes, mists, smokes and sprays". (17). Coal-fired power stations emit particles in the fly ash that leaves the stack as smoke.

The amount of particles emitted depends on the ash content of coal; the combustion technique, the availability of particle removal systems, etc. On the basis of four different assumptions concerning the average ash content of coal, typical fly ash emissions from power plants without particle removal systems have been calculated (table 4). Emissions range from 150,000 to over 600,000 tons.

TABLE 4 : Annual fly ash emissions in the absence of particle removal systems (in 10³ tons)*

case n°**	→ 1	2	3	4	5	6
ash content of coal ↓						
10 %	248	211	219	187	197	167
15 %	369	314	326	278	293	249
20 %	490	417	434	369	389	330
25 %	611	519	541	460	485	412

* general assumptions : fly ash = 80 % of total ash
 sulfur content of coal = 2.5 %
 sulfur retained in the ashes = 10 % of total sulfur

** the assumptions underlying the 6 cases are found in table 1.

Particles remain suspended in the air until they are removed by gravitation or precipitation. The concentration of particles in the air is usually measured by the "Total Suspended Particulates" (TSP) concentration (expressed as $\mu\text{g}/\text{m}^3$ air), a rough measure in which particles of different size and different chemical structure are lumped together. Recently, more attention is being paid to size and chemical characteristics, since health effects seem to be dependent on them. A distinction is made between fine ($< 2 \mu\text{m}$) and coarse ($> 2 \mu\text{m}$) par-

ticles. The fine particles are in turn subdivided into very small primary ($< 0.1 \mu\text{m}$) and somewhat greater secondary particles. Primary particles (i.e. generated during combustion) enter the atmosphere directly from the stack. These fly-ash emissions contain a variety of trace metals (such as chromium, mercury, cadmium, beryllium, selenium) and other dangerous substances as toxic organic matter. Secondary particles arise from chemical reactions in the atmosphere : aggregation of primary particles, chemical conversion of emission gases (condensation, coagulation), etc. Noxious sulfate and nitrate compounds are among these secondary emission products (see also § 10 - 12).

Atmospheric dispersion of particulates is usually modeled in such a way that concentrations are thought to be distributed normally around a peak center-line concentration ("Gaussian plume dispersion"). In the Gaussian model, height of the plume, wind velocity, and quantity emitted per unit time by a chimney stack determine the average ground-level concentrations. This model of atmospheric dilution and dry disposition at ground-level predicts that higher stacks will lead to lower ground-level concentrations in the immediate neighbourhood of the stack - precisely what has happened in the last decades.

But the model proves inadequate for predictions of concentrations at distances beyond 30 km from the stack. Some processes of long-term transportation and dispersion are not captured by the model. The atmosphere eventually cleanses itself, by means of wet removal processes. Particles greater than $1 \mu\text{m}$ can be caught by raindrops falling through polluted layers under the clouds. This process known as "washout" can be the cause of acid rain. Smaller particles ($< 1 \mu\text{m}$) are subject to an incloud removal process called "rainout". These particles act as condensation-nuclei for cloud droplets; after condensation, they are eventually removed during precipitation. Since sulfates and nitrates turn out to be good condensation nuclei, acid rain can be the result. Knowledge about the processes of wet and dry deposition is still limited, however.

The health effects of increased concentrations of particulates have not been clearly demonstrated. There seems to be some evidence that especially small particles ($< 3 \mu\text{m}$) are dangerous because they penetrate deep in the lungs. Not only size, but also chemical and other physical properties determine the health effects. The most important health effects seem to be pulmonary function diseases and cancer.

§ 10 Emission of oxides of sulfur (18)

Residuals from coal combustion are not only discharged as particulates, but also as gases. The main primary gases released are : oxides of sulfur (SO_x), oxides of nitrogen (NO_x), and oxides of carbon (CO_x). Like particulates, primary gases participate in chemical interactions in the atmosphere. This leads to the formation of secondary emission products.

Almost every kind of ROM coal contains sulfur. The average content of sulfur varies, from a negligible weight fraction to as much as 7 %. Combustion of coal inevitably results in the formation of sulfur dioxide (SO_2), which is routinely released as a gas through the stack.

The amount of SO_2 released greatly depends on the sulfur content of the coal. We have estimated SO_2 -emissions using four different assumptions on the average sulfur content of coal (table 5). Emissions typically range from next to nothing to more than 200,000 tons.

TABLE 5 : Annual SO₂-emissions in the absence of SO₂ removal systems (in 10³ tons)*

case n° ** →	1	2	3	4	5	6
sulfur content of coal ↓						
1 %	54	46	48	41	43	37
2 %	109	93	96	82	86	73
3 %	163	139	145	123	129	110
4 %	218	185	193	164	173	147

* general assumptions :
sulfur retained in the ashes = 10 % of total sulfur

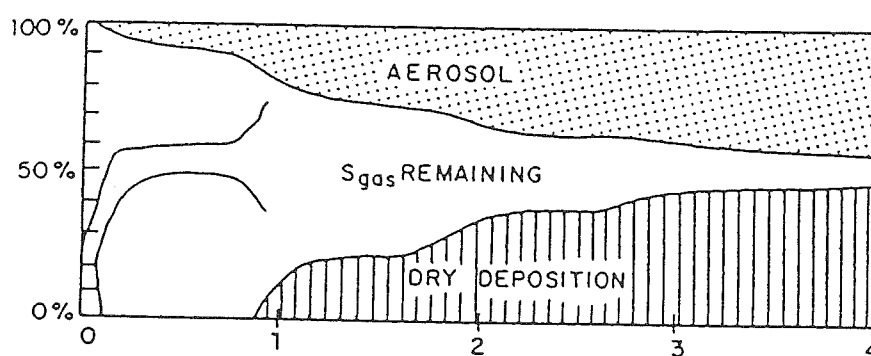
** the assumptions underlying the 6 cases are found in table 1.

It is now a well-known fact that short stacks lead to high SO₂-concentrations in the immediate neighbourhood of plants. In the past, levels of SO₂-concentrations in the vicinity of polluting sources have been very high. To counter this tendency, tall chimney stacks have been erected, successfully leading to wider dispersion and lower SO₂-concentrations.

But wider dispersion does not mean SO₂ has simply disappeared. In fact, SO₂ reacts chemically to sulfate (SO₄) particulates. Reductions of SO₂-concentrations at ground-level have not been accompanied by reductions in atmospheric

SO_4 -concentrations, rather on the contrary. Although the sulfur chemistry in the atmosphere is not yet completely understood, several possible mechanisms have been detected. Sulfate concentrations seem directly dependent upon SO_2 -concentrations in the atmosphere, the presence of air particulates that catalyze or provide a surface for reaction, atmospheric humidity, sunlight intensity, and the atmospheric residence time of SO_2 . Sulfate concentrations seem inversely related to wind velocity and precipitation. An example of typical power plant plume conversion is given in figure 1.

Figure 1. Estimated sulfur budget for a power plant plume over a 4-day period. The sulfur gas (SO_2) deposits or converts to an aerosol. (Adapted from R.B. Husar et al., "Sulfur budget of a power plant plume," *Atmos. Envir.* 12 (1978): 549-568.)



Source : WILSON e.a. (1980), 93

The effect of higher stacks on plume conversion can be described as follows. Higher stacks lead to a reduction of dry deposition, and hence result in decreased ground-level SO_2 -concentrations. Since more SO_2 remains in the atmosphere then (its atmospheric residence time increases), there is a fair chance that more of it converts to SO_4 . The crucial factor in this conversion process is of course

the conversion rate, which itself varies in relation to air pollution levels. The result of higher stacks is therefore increased SO_4 -formation. The removal of SO_4 , by means of rainout and washout (cfr. § 9), leads to acid precipitation.

The overall effect of higher stacks can now be assessed : local ground-level SO_2 -concentrations will decrease, but in a wider area atmospheric SO_4 -concentrations will increase, eventually leading to enhanced acid precipitation. The reductions of local ground-level SO_2 -concentrations, mainly in urban areas, have certainly added to the gradual disappearing of so-called "air pollution episodes". Such episodes, with severe acute health effects (increased morbidity and mortality) had been experienced in the Meuse Valley of Belgium (dec. 1930), and in greater London (several times in the 1950s). Chronic health effects due to long-term exposure to ambient SO_2 -levels seem to be less severe than chronic health effects due to long-term exposure to ambient SO_4 -levels. Various respiratory diseases have been mentioned to be among these chronic health effects. The possible overall result could be a shift of health effects, from acute (SO_2) to chronic (SO_4). However, the available evidence is insufficient to draw firm conclusions.

§ 11 Emission of oxides of nitrogen (19)

Combustion under high temperatures, as in power plants, leads to nitric oxide (NO) formation. Nitrogen and oxygen, both present in the air used for combustion, will only begin to react and form NO at high temperatures. The presence of organically bound nitrogen in coal additionally stimulates NO-production. In theory, NO-production could be prohibited by allowing no excess air (oxygen), i.e. just enough air as is needed for combustion. In practise, things are not that easy

The amount of NO_x (NO) emitted is dependent upon the combustion technique. NO_x emissions have been calculated on the basis of four different emission factors (table 6). Typically, NO_x -emissions range from 10,000 to 25,000 tons.

TABLE 6 : Annual NO_2 -emissions for conventional coal plants
(in 10^3 tons)

case no.* →	1,3,5 (thermal efficiency : 34 %)	2,4,6 (thermal efficiency : 40 %)
emission factors (kg/ GJ of coal burned) ↓		
0.20	14	12
0.25	17	15
0.30	21	18
0.35	24	21

* The assumptions underlying the 6 cases are found in table 1.

The problems with NO_x -emissions mainly result from the conversion products of NO , NO being a relatively harmless gas itself. High concentrations of NO and the presence of sunlight favor rapid oxidation of NO into NO_2 (nitrogen dioxide). NO_2 is a yellow-brown, toxic gas. Further action of sunlight on NO_2 sets in motion a chemical reaction leading to the formation of ozone, O_3 , which also has toxic effects. Other chains of reaction lead to the conversion of NO_2 into various

nitrites (NO_2 -compounds) and nitrates (NO_3 -compounds), both in particulate form. Wet removal processes, especially for HNO_3 , contribute to the acidification of rainfall.

The health effects of NO_x have not been established with full certainty. Long-term exposure to moderate doses of NO_2 ($< 200 \mu\text{g}/\text{m}^3$ air) could lead to deterioration of lung functions; short-term exposure to high doses could lead to airway irritation. Ozone possibly causes damage to respiratory mechanisms, the lung structure and eye functions. Nitrites and nitrates are believed to have carcinogenic and mutagenic effects.

§ 12. Acidification of the environment (20)

As mentioned (§ 9 - 11), several mechanisms lead from the combustion of coal for the production of electricity to the deposition of acid materials in the environment. In the absence of effective buffering capacity, this deposition causes acidification of the environment. To be complete one should add that not all observed acidification is related to the combustion of coal or fossil fuels in general, or to other anthropogenic activities, since there are natural phenomena involving emission and absorption of large amounts of acid material.

The man-made acidification processes can be distinguished by the means of deposition of the acid material. Dry deposition of particulates and gases occurs relatively quickly after emission, and includes direct absorption by trees and sedimentation on land and water surfaces. Wet deposition is the result from precipitation from clouds that have incorporated SO_x and NO_x in their droplets. Acid rain is the most important form of wet deposition.

Recently, the problem of acid rain has aroused a lot of excitement. A number of characteristics of acid rain can explain this:

- * acid rain causes exposures to relatively small, but nevertheless chronic levels of dangerous pollutants
- * the problem has been evolving slowly over the past decades
- * direct links to definite sources of emission cannot be made (travel distances of chemically transformed acid materials can be very large)
- * the damages are various and not yet completely known.

At least two important environmental problems have been related to acid deposition (wet and dry) : the disappearance of fish in lakes of the U.S., Norway, Sweden, and other countries, and the large-scale extinction of trees in forests of Central Europe. The main reason for the disappearance of fish seems to be the increased acidity of the lakes. A link between decreasing pH-levels and increasing acid deposition due to human activities cannot be denied. The extinction of trees seems to be more complex a problem. Apart from acid precipitation, other factors have been put forward as explanations :

- * climatological circumstances (e.g. the long hot summer of '76)
- * bad management of forests
- * infections.

A definite correlation between acid precipitation and large-scale extinction of trees has not yet been demonstrated.

§ 13. Emission of oxides of carbon (21)

Unpolluted atmospheric air contains a small portion of carbon dioxide (CO_2), some 315 ppm or 0.03 %. The combustion of carbon-based fuels adds enormous quantities of CO_2 to the atmosphere (table 7). If these quantities are not, or only partially, absorbed by the biosphere, then atmospheric CO_2 -levels will tend to rise.

TABLE 7 : Annual CO₂-emissions by conventional coal plants
(in 10³ tons)

case n° * → emission factor (kg/KWh of electricity produced)	1, 2, 3, 4, 5, 6
0.8	5,256
0.9	5,913
1.0	6,570
1.1	7,227

* The assumptions underlying the 6 cases can be found in table 1.

During the last decades, the CO₂-content of the atmosphere has in fact been rising steadily (by about 0.5 - 1.5 ppm per year). It is generally accepted that burning of fossil fuels is mainly responsible for this rise. However, since the precise mechanisms of the carbon cycle and its relation to the oxygen cycle are not fully known, caution is warranted. Not only man induces release of CO₂ to the atmosphere. Terrestrial and oceanic biota ("the biosphere") emit CO₂ in the atmosphere by means of respiration and decomposition. In normal conditions, the biosphere's emission is matched by absorption through photosynthesis. It is highly doubtful whether "normal conditions" still prevail in today's world. Land-clearing (deforestation) at alarming rates results in photosynthesis being reduced (= decreased ab-

sorption of CO_2), while at the same time enhancing decay of forest material (= increased release of CO_2). In addition, the effect of increasing CO_2 -concentrations on biological productivity is unknown. This and other unknowns make it difficult to determine whether today the biosphere is a source or a sink of CO_2 . It is nearly certain that the oceans are a sink of CO_2 , but then again it is uncertain how much CO_2 they absorb and at what rate.

Ambient atmospheric CO_2 -concentrations do not pose a threat to human health. The dangers of CO_2 reside in potential climatic (and related non-climatic) changes on a global scale. In spite of its limited occurrence, CO_2 has a major influence on the atmosphere's temperature (hence on the climate). CO_2 -molecules in the atmosphere are transparent to ultraviolet, but opaque to infrared radiation. The sun's radiation is thus partially absorbed (the infrared range), and partially not (the ultraviolet range). The earth's thermal reradiation, mainly confined to the infrared range, is equally absorbed by CO_2 in the atmosphere. It can easily be seen that an increase in atmospheric CO_2 -concentrations will lead to a warming of the atmosphere, since more heat, both from the sun and from the earth, will be captured ("the greenhouse effect").

"If the world continues its heavy reliance on carbon-based fuels, then we should expect during the middle of the twenty-first century a warming of $2^\circ - 3^\circ \text{C}$ accentuated by a factor of three or four at high-latitude regions. These average temperature changes are greater by a factor of three or four than those observed during abnormal historical weather conditions that prevailed, for example, during the "Little Ice Age" of the sixteenth and seventeenth centuries. The anticipated changes due to CO_2 , however, are smaller by about a factor of two than those experienced during the past million years in the glacial and interglacial periods." (22)

The details of this climatic change, and its related non-climatic effects (e.g. productivity of agriculture), are very

uncertain. On the one hand, the possibility that higher temperatures in the polar regions will cause melting of the ice caps cannot be ruled out. Pessimists estimate that this melting could occur during the next hundred years. On the other hand, some say that the warming of the atmosphere shall be moderated to a great extent by the increased concentration of particulates. This would lead to greater reflectivity of the lower atmosphere. Anyhow, research into the effects of the carbon cycle is urgently needed.

§ 14. Highly toxic waste (23)

Coal contains small amounts of harmful mineral elements and compounds such as arsenic, cadmium, lead, mercury, asbestos, etc. In addition, some species of coal contain very small amounts of the radionuclides uranium and thorium (and daughter products).

After combustion, these materials must have gone either into the air (as escaped fly ash) or into the ashes (as bottom ash or as captured fly ash). In both cases they can be dangerous. Dispersed into the atmosphere, they are respirable and could cause cancer and even genetic effects. Concentrated in the ashes, they can contaminate drinking water, and emit radioactivity comparable to routine radioactive releases from nuclear power plants.

Other highly toxic materials produced during coal combustion include polycyclic aromatic hydrocarbons (PAH), among which benzo(α)pyrene (BaP) is highly carcinogenic.

§ 15. Solid wastes (24)

Solid wastes are made up of bottom ash, and eventually recovered fly ash and sludge from emission control techniques.

Bottom ash production mainly depends on the ash content of coal. On the basis of four different assumptions, typical bottom ash productions have been calculated (table 8). They range between 40,000 and 160,000 tons.

TABLE 8 : Annual bottom ash production for conventional coal plants
(in 10³ tons)*

case no.** →	1	2	3	4	5	6
ash content of coal ↓						
10 % ash	62	53	55	47	49	42
15 % ash	92	78	82	69	73	62
20 % ash	123	104	108	92	97	83
25 % ash	153	130	135	115	121	103

* general assumptions : bottom ash = 20 % of total ash
sulfur content of coal = 2.5 %
sulfur retained in the ashes = 10 %

** the assumptions underlying the 6 cases are found in table 1.

Bottom ash is an inert and relatively stable form of waste, although not without dangers. Coal combustion has the effect of concentrating toxic trace elements of natural origin in the ashes (§ 14). It also favors formation of mutagenic and carcinogenic materials, which eventually, after removal from

flue gases, become part of the solid wastes. The behaviour of dangerous substances in deposits of ash is not completely understood. It surely depends on the way in which the ash is stored (waste tips, landfilling, ...), the characteristics of the soil, stabilizing agents added, etc. Potential damages include contamination of drinking water, and contamination of crops grown on infilled land.

Solid wastes can be re-used for cement-production, brick-making, etc.

§ 16 Thermal pollution (25)

Conventional coal plants have a thermal efficiency of 30 - 40 %. The remaining 60 - 70 % of produced heat is waste heat. If not used otherwise, it has to be dumped into the environment. About 10 % is lost through the stack (hot flue gases) and by means of radiation. The bulk is lost through heat removal systems, mainly by means of evaporation (transformation of a liquid into a gaseous state). Once-through cooling is a process in which cooling water from a river or from the sea flows in and out of the plant only once. Evaporation takes place downstream or in the sea. Cooling towers are equipped with recirculating cooling systems. Evaporation and condensation take place in situ inside the cooling tower. Air cooling systems dump waste heat by heating up air.

The disadvantage of once-through cooling is that it requires huge amounts of cooling water. Recirculating cooling systems require much less water, but necessitate the erection of large cooling towers.

Global climatic effects of thermal pollution, in the sense of heating the atmosphere, are negligible. Micro-climatological

impacts from large power stations, comprising several power plants with recirculating cooling systems ("heat islands"), cannot be excluded. Once-through cooling certainly causes changes in aquatic life.

- § 17. Decommissioning of coal-fired power plants does not present special problems.

SECTION D : MITIGATION POSSIBILITIES

§ 18. As the awareness has grown that coal-based power generation poses threats to human beings and the environment, environmental controls are being tightened, and more means are being devoted to research into possible mitigation techniques. As a result, several mitigation techniques available today have reached the stage of commercial feasibility.

In the following, we will briefly describe some of the most promising techniques. We have partitioned them into 5 main categories. The first category deals with coal mining, focusing on working conditions, management of derelict mines, and waste tip cultivation. The second category groups various coal-processing techniques, i.e. techniques turning coal into cleaner or better fuel before combustion (coal cleaning, coal gasification, coal liquefaction). Techniques improving combustion itself are the subject of category 3; Fluidized Bed Combustion is one of them. The fourth category deals with emission control techniques (Flue Gas Desulfurisation, Particulate Removal Systems, etc.). The last category describes remaining mitigation options.

§ 19. Mitigation and mining

Working conditions (26)

Hypothetically, a switch to more surface mining would lower occupational risks. In most areas of the world, however, such a switch is not practicable, at least not on a substantial scale.

Measures can be taken to decrease coal dust concentrations in underground mines to levels at which incidence of pneumoconiosis and other diseases is greatly reduced. This seems to

have happened in the U.K. It is sometimes claimed that adequate safety measures can lower the occurrence of occupational accidents as well. This is certainly true insofar as one looks at the rate "accidents/hours worked". But that is not all : one also has to take into account the possible effect of lower productivity, i.e. a decrease of the rate "coal produced/hours worked". One can easily see that the rate "accidents/coal produced" (and that is what matters) does not necessarily fall.

Land reclamation (27)

The catastrophic changes in the landscape brought about by strip mining can be mitigated by restoring the land to something approximating its original condition. This process is called "land reclamation". The effectiveness of reclamation depends, on the one hand, upon the site's geology and climate, and, on the other hand, upon the new soil material and the flora and fauna introduced on it. The costs of reclamation are estimated to be less than 10 % of the cost price of strip-mined coal.

Waste tip management (28)

Several solutions have been proposed for the problems caused by the giant waste tips in the neighbourhood of coal mines. These solutions include filling up derelict mines, filling up land, energetic exploitation, and biological exploitation.

§ 20. Mitigation and coal processing

Four kinds of technique will be discussed : coal cleaning, coal gasification, coal liquefaction, and underground coal gasification.

Coal cleaning

As mentioned (§ 4), coal cleaning can be based on physical or on chemical processes. Only the physical techniques are applied on a commercial scale. Several techniques exist; we describe only one of them (29).

The principle is that sulfur and ash constituents of coal are removed through selection based on size and weight of ROM coal components. First, ROM coal components are sorted out according to size, to obtain different size categories. Second, coal is eventually crushed and sorted out again, to obtain fine enough coal components. Finally, sulfur (only mineral sulfur) and ash constituents can be removed by means of gravitational separation, since mineral sulfur and ash have higher specific gravity than coal. Difficulties arise because of mixed coal-sulfur-ash components having specific gravities somewhere in between. Cleaner coal can only be obtained by losing some of the coal contained in these mixed components. As a result, clean coal quality and recovery of total heating value move in opposite direction. Usually, a minimum required recovery of total heating value is specified as a limit to the cleaning process (e.g. minimum 95 % of total heating value must be recovered).

Cleaned coal has a number of advantages over "raw" coal : lower sulfur and ash content, more homogeneity, upgraded heating value per ton, etc. This does not automatically mean that coal cleaning is cost effective in financial terms. Costs must be compared with benefits.

The main costs of coal cleaning :

- more raw coal required (in most cases)
- capital and operation costs for the cleaning facility
- costs for disposal of wastes at the cleaning facility

The main benefits of coal cleaning :

- reduced transportation costs if the cleaning facility is near the mine
- increased burner efficiency (lower coal burn rate)

- decreased disposal costs at the plant due to decreased bottom ash production
- decreased costs for particulates and SO₂ removal systems (if present).

The EPRI-study mentioned as a reference comes to the conclusion that for new power plants equipped with particulates and SO₂ removal systems, and obliged to meet stringent emission standards, coal cleaning is in general cost effective.

Coal gasification (30)

In the past, coal gasification has been developed as an alternative route to obtain gaseous (and liquid) fuels. The availability of cheap oil and gas, however, turned out to be a disincentive for large-scale research into coal gasification. Nowadays, there is renewed interest because it seems to offer possibilities for clean gas production. Coal gasification has indeed become defined as : "a process that removes sulfur and particulates before the fuel is burned, trace elements such as heavy metals also being removed in the gas cleanup process" (31).

Many coal gasification techniques have been demonstrated, the most well-known being the Lurgi-, Winkler-, and Koppers-Totzek-techniques. Basically, all techniques involve the heating of coal in the presence of steam. This leads to the formation of a primary fuel gas consisting mainly of a mixture of CO, CO₂, H₂, and CH₄ (methane). Three grades of gas may ultimately be produced :

- * a low-calorific-value gas (3.8 - 7.6 MJ/m³), when nitrogen (N₂) dilutes the gas
- * a medium-calorific-value gas (10 - 16 MJ/m³), when the gas is nitrogen-free
- * a high-calorific-value gas (> 21 MJ/m³), by means of methanation of medium-calorific-value gas.

During gasification, the sulfur in the coal reacts with hydrogen to form hydrogen sulfide (H_2S). It is standard industrial practice to recover elemental sulfur from H_2S . Ash is also removed during gasification.

To date, coal gasification is not a competitive alternative due to high costs.

Coal liquefaction (32)

Coal-based liquid fuels can be produced directly or indirectly. Well-known processes of direct liquefaction are pyrolysis (destructive distillation at high temperatures in the absence of air), and hydrogenation (reaction with H_2 and eventually a catalyst at high temperature and pressure). Indirect techniques require previous conversion of coal to a clean gas. The Fischer-Tropsch procedure, converting medium-calorific-value gas to clean liquid fuels, is being used in large-scale plants in Sasolburg, South Africa.

Underground coal gasification (33)

Underground coal gasification is as yet in an experimental stage. In principle, it consists of in situ conversion of coal to gaseous fuels using air, oxygen and steam or hydrogen as gasifying agents. The potential advantages of underground gasification include elimination of mining, reduction of ash disposal requirements, reduction of noxious emission, etc. Up to now, various difficulties have impeded major applications.

§ 21. Mitigation and coal combustion

Fluidized Bed Combustion (FBC) (34)

In general, a fluidized bed is a collection of solid particles through which a fluid is blown (from below) in such a manner

that the particles are held in suspension under a well defined limit.

Conventionally, coal combustion takes place in a fixed bed. The purpose of fluidized bed combustion (FBC) is to make combustion more efficient. Solid particles of coal, ash and a sorbent material make up the bed; the bed is fluidized by (hot) air. Coal burns inside the fluidized bed (and sometimes equally above it). Experiments have learned that under optimal conditions (bed temperature, availability of excess air, etc.) FBC can raise combustion efficiency to above 95 %.

Ashes are steadily removed from the bed during combustion. The sorbent material, usually limestone (CaCO_3) or dolomite ($\text{CaMg}(\text{CO}_3)_2$), reacts with the sulfur in the coal to form calcium sulfate (CaSO_4), which is then removed from the bed and recycled. Operation of experimental devices has shown that FBC can reduce SO_2 -emissions about 90 % with a twofold stoichiometric ratio.

The potential advantages of FBC can now be identified : increased burner efficiency, and reduced SO_2 -emission. In addition, it could be that NO_x -emissions diminish heavily because of lower combustion temperatures (but this is as yet not clearly demonstrated).

FBC is currently being tested in several pioneer projects in Europe and the U.S.A. The technique appears very promising.

§ 22 Mitigation and emission control

Flue gas desulfurisation (FGD) (35)

Systems aimed at the removal of SO_2 after combustion, i.e. from the flue gases, are termed Flue Gas Desulfurisation (FGD)

systems. Every FGD system is based on the contact between the flue gases and a substance that reacts chemically with SO_2 . Different types of FGD can be distinguished.

Non-regenerative wet scrubbing techniques, the most widely used, clean the flue gases by means of an aqueous solution (or slurry) of an alkaline absorbent. Usually the absorbent is lime (CaO) or limestone (CaCO_3), but other materials can be used as well. The solution or slurry is sprayed on the flue gases, and during the countercurrent contact the flue gases give off heat and sulfur, resulting in enormous amounts of waste (sludge). The amount of dewatered sludge produced equals about 5 - 6 times the amount of SO_2 removed, for a removal efficiency of 85 % (36). SO_2 -removal efficiency can reach 90 % or more.

Non-regenerative dry scrubbing consists of cleaning the flue gases by means of dry absorbents. Two main types have been developed. Dry sorbent injection systems involve contact between the flue gases and a powder such as nahcolite (NaHCO_3) or trona ($\text{Na}_2\text{CO}_3 + \text{NaHCO}_3$); the reaction products are collected in a baghouse. Spray-dry systems make use of a wet solution to scrub the flue gases; because of evaporation in the flue gases, reaction products are solid. Dry scrubbing systems are less developed than wet scrubbing systems, but SO_2 -removal efficiencies in the 80 - 90 % range seem possible.

Regenerative FGD systems are characterized by recycling of the absorbent on the one hand, and formation of a reusable, sulfur-based waste-product on the other hand. Absorbents used are sodium sulfite (Na_2SO_3), magnesium oxide (MgO), ammonia (NH_3), etc. Typical waste products are elemental sulfur and sulfuric acid (H_2SO_4). Experience with these types of FGD is limited, but the potential for SO_2 -removal appears to be as good as for the other FGD systems.

Flue gas desulfurisation creates problems of its own : considerable waste production (mainly for wet scrubbing systems),

corrosion of equipment (mainly for wet scrubbing systems), reliability (which can strongly influence the generation of electricity), etc. The main effect of FGD systems on power production is probably the decrease in thermal efficiency of the plant. Because they consume so much electricity, FGD systems can reduce energy output with as much as 5 % (37). Capital and operating costs could be high, especially when FGD is retrofitted to existing plants (38).

Particulate Removal Systems (39)

The dominant particulate removal device is the Electrostatic Precipitator (ESP). An ESP operates in two steps : first, it charges particulates; second, it collects the greatest part of the particulates by attracting them to the opposite pole. Efficiency can be very high, typically 99 %. An ESP system functions less efficiently when another type of coal is burned than the type for which the system has been designed.

An alternative device is the baghouse. A baghouse is a collection of fabric filters through which the flue gases are made to flow. Collection efficiency has been shown to be as high as 99.9 %, and seemingly insensitive to the type of coal burned. Large-scale baghouses for coal plants are in an experimental stage.

Nitrogen oxide Removal (40)

Two techniques seem promising : post-combustion selective catalytic reduction (SCR), based on ammonia, and retrofittable low-NO_x burners. Experience with both is very limited.

§ 23. Other mitigation techniques (41)

Preventive measures, such as adequate siting, can effectively reduce damage resulting from emission of pollutants. For

example, the presence of nearby downwind population concentration should be avoided.

In order to reduce acute high pollutant concentrations, intermittent control systems (ICS) have been developed for power stations that can not use tall chimney stacks. During weather conditions unfavourable to dispersion, either power generation is ceased, or a shift is made to low-sulfur coal (or even natural gas). In both cases, generating costs will inevitably rise.

Notes

- (1) ATWOOD (1975), 23-29
- (2) COHEN & PRITCHARD (1980), 10; INHABER (1978), Appendix A; RAMSAY (1979), 108 - 117
- (3) COHEN & PRITCHARD (1980), 17 - 18; ENVIRONMENTAL RESOURCES LIMITED (1980), 116; RAMSAY (1979), 95 - 103
- (4) ENVIRONMENTAL RESOURCES LIMITED (1980), 106; RAMSAY (1979), 98 - 99
- (5) COHEN & PRITCHARD (1980), 18
- (6) WILSON (1980), 140 - 141
- (7) In 1979, 30 % of U.S. domestic steam coal was cleaned; see EPRI (1981), 4.1
- (8) RAMSAY (1979), 106 - 107, 122 - 123, 170
- (9) COHEN & PRITCHARD (1980), 17
- (10) SEGERUD (1984), 4.2
- (11) COHEN & PRITCHARD (1980), 9; INHABER (1978), 25 - 28
- (12) COHEN & PRITCHARD (1980), 9
- (13) COHEN & PRITCHARD (1980), 21; RAMSAY (1979), 15; WILSON e.a. (1980), 29 - 37
- (14) WILSON e.a. (1980), 113
- (15) WILSON e.a. (1980), 116 - 127

- (16) mainly : WILSON e.a. (1980), 15 - 70, 113 - 148; also : COHEN & PRITCHARD (1980), 11 - 16; ENVIRONMENTAL RESOURCES LIMITED (1980), 108; RAMSAY (1979), 14 - 20
- (17) TVER (1981), 234
- (18) mainly : WILSON e.a. (1980), 63 - 141, 161 - 169; also : COHEN & PRITCHARD (1980), 11 - 16, DE BATIST (1981), 89 - 98; ENVIRONMENTAL RESOURCES LIMITED (1980), 108 - 113; HIGHTON & WEBB (1980), 61 - 76; RAMSAY (1979), 14 - 20; VAN GENECHTEN (1979), 117 - 127
- (19) mainly : WILSON e.a. (1980), 63 - 100, 113 - 159; also : COHEN & PRITCHARD (1980), 11 - 16; DE BATIST (1981); 89 - 98; ENVIRONMENTAL RESOURCES LIMITED (1980), 113 - 114; RAMSAY (1979), 20 - 21
- (20) COHEN & PRITCHARD (1980), 20; DE BATIST (1981), 89 - 98; DUA (1984), 1 - 14; RAMSAY (1979), 23; VANGENECHTEN (1979), 117 - 127; VAN GENECHTEN (1981), 1 - 13; WILSON e.a. (1980), 86 - 89
- (21) BERNARD (1980), 5 - 25, 127 - 170; MC DONALD (1982), 1 - 41; WILSON e.a. (1980), 101 - 107
- (22) MC DONALD, (1982), 11
- (23) COHEN & PRITCHARD (1980), 19; RAMSAY (1979) 21; WILSON e.a. (1980), 105 - 111, 182 - 185
- (24) COHEN & PRITCHARD (1980), 19; ENVIRONMENTAL RESOURCES LIMITED (1980), 115 - 116; RAMSAY (1979), 96 - 97
- (25) COHEN & PRITCHARD (1980), 20; ENVIRONMENTAL RESOURCES LIMITED (1980), 79 - 80, 123 - 125; RAMSAY (1979), 92 - 94
- (26) RAMSAY (1979), 108 - 118
- (27) ATWOOD (1975), 23 - 29; RAMSAY (1979), 96 - 103, 135, 145, 149, 172

- (28) COHEN & PRITCHARD (1980), 19 - 20; Anon. (1984a); Anon. (1984b); Anon. (1984c)
- (29) EPRI (1981), 4.I. - 4.II
- (30) INTERCOM (1983), 30 - 34; TVER (1981), 72 - 74; WILSON (1980), 187 - 193; WILSON e.a. (1980), 240 - 241
- (31) TVER (1981), 72
- (32) INTERCOM (1983), 36 - 37; TVER (1981), 72 - 74; WILSON (1980), 194 - 198; WILSON e.a. (1980), 240 - 241
- (33) INTERCOM (1983), 35 - 36; WILSON (1980), 193
- (34) SEGERUD (1984), 31 - 38; VEJTASA (1983), 121 - 127; WILSON, e.a. (1980), 229 - 232; Anon.(1982 b), 40 - 41; Anon.(1983 b), 21
- (35) HIGHTON & WEBB (1980), 61 - 76; MC ILVAINE & KAPLAN (1983), 23 - 25; NESBIT (1982), 7 - 15; PRESTON & MILLER (1982), 25 - 29; WILSON e.a. (1980), 225 - 230; Anon.(1983 a), 36 - 37
- (36) EPRI (1981), passim
- (37) HIGHTON & WEBB (1981), 55; HIGHTON & WEBB (1984), 73
- (38) HIGHTON & WEBB (1981), 50
- (39) PRESTON & MILLER (1982), 25 - 29; WILSON e.a. (1980), 232 - 239
- (40) PRESTON & MILLER (1982), 25 - 29; WILSON e.a. (1980), 239 - 240; Anon.(1982 b), 43 - 46
- (41) WILSON e.a. (1980), 245-269

BIBLIOGRAPHY

- ATWOOD, Geneviève (1975), "The strip mining of western coal",
Scientific American, vol. 233, nr. 6, p. 23 - 29
- BERNARD, Harold (1980), The greenhouse effect, New York, Harper
& Row
- COHEN, A.V. & D.K. PRITCHARD (1980), Comparative risks of electri-
city production systems : a critical survey of the literature
London, HMO Stationary Office, Health and Safety Executive
- DE BATIST, R. (1981), "Leefmilieu en energieproductie : kunnen
water en vuur verzoend worden ?", Consensus, nr. 3, p. 89 - 98
- DUA, Vera (1984), "Invloed van acidifikatie op het milieu, meer
specifiek op het bosekosysteem", BBL-Forum Zure Neerslag,
Brussel, 7 april
- ENVIRONMENTAL RESOURCES LIMITED (1980), Environmental impact of
energy strategies within the EEC, Oxford, Pergamom Press for
the Commission of the European Communities
- EPRI (1981), Impact of coal-cleaning on the cost of new coal-fired
power generation, Palo Alto, EPRI, CS - 1622
- HIGHTON, Nicolas H. & Michael G. WEBB (1980), "Sulphur dioxide from
electricity generation. Policy options for pollution control",
Energy policy, March, p. 61 - 76
- HIGHTON, Nicholas H. & Michael G. WEBB (1981), "Pollution abatement
costs in the electricity supply industry in England and Wales",
Journal of Industrial Economics, vol. 30, nr. 1 (sept.),
p. 49 - 65
- HIGHTON, Nicholas H. & Michael G. WEBB (1984), "The effects on
electricity prices in England and Wales of notional sulphur
dioxide emission standards for power stations", Journal of
environmental economics and management, vol. 11, p. 70 - 83

- INHABER, Herbert (1978), Risk of energy production, Ottawa, Ontario, Atomic Energy Control Board, AECB 1119/REV-1
- INTERCOM (1983), Steenkool-mogelijkheden en beperkingen, Brussel, Intercom
- MC DONALD, Gordon I. (Ed.) (1982), The long-term impact of increasing atmospheric carbon dioxide levels, Cambridge (Mass.), Ballinger
- MC ILVAINE, Robert W. & Marilyn KAPLAN (1983), "Flue gas desulphurisation - a status report", Modern Power Systems, sept., p. 23 - 25
- NESBIT, William (1982), "Scrubbers : the technology nobody wanted", EPRI-Journal, Oct., p. 7 - 15
- PRESTON, G.T. & M.J. MILLER (1982), "Environmental control technology advances for coal-fired power plants", Pollution Engineering, April, p. 25 - 29
- RAMSAY, William (1979), Unpaid costs of electrical energy-Health and environmental impacts from coal and nuclear power, Baltimore, John Hopkins University Press for Resources for the Future
- SEGERUD, K. (1984), Small size coal-fired hot water centrals - Technical Options Report, Energiplanerarna, 28-5
- TVER, David (1981), Dictionary of dangerous pollutants, ecology and environment, New York, Industrial Press
- VANGENECHTEN, I. (1979), "Biologische gevolgen van de verzuring van het milieu door verbranding van fossiele brandstoffen voor de energievoorziening", Consensus, nr. 3 - 4, p. 117 - 127
- VANGENECHTEN, I. (1984), "Verzuring van oppervlaktewateren in België door gebruik van fossiele brandstoffen voor energievoorziening", BBL - Forum Zure Neerslag, Brussel, April 7, 13 p.

- VEJTASA, S.A. (1983), "Comparison of alternative fossil fuel generating options", Second Symposium on Integrated Environmental Controls for Coal-Fired Power Plants, Colorado, Feb. 15 - 18, p. 121 - 127
- WILSON, Carol L. (1980), Coal-Bridge to the future. Report of the World Coal Study (WOCOL), Cambridge (Mass.), Ballinger
- WILSON, Richard e.a. (1980), Health effects of fossil fuel burning. Assessment and mitigation, Cambridge (Mass.), Ballinger
- Anon. (1982a), "AFBC Development", EPRI-Journal, March, p. 40 - 41
- Anon. (1982b), "Selective Catalytic Reduction", EPRI-Journal, Oct., p. 43 - 46
- Anon. (1983a), "SO₂-control by dry sorbent injection", EPRI-Journal, March, p. 36 - 37
- Anon. (1983b), "Emission laws push utilities into fluidized bed cogeneration contracts", Modern Power Systems, Sept., p. 21
- Anon. (1984a), "Bacteriën kunnen terrils nieuwe kansen geven", Het Volk, jan. 22
- Anon. (1984b), "Valorisation des terrils ", La Cité, féb. 20
- Anon. (1984c), "Comment 'exploiter' nos terrils ?", La Cité, March 3