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Proceedings of the
9th INTERNATIONAL CONFERENCE ON COAL RESEARCH

OCTOBER 13-16, 1991

WASHINGTON, DC

ICCR'91

Balancing Global Needs Through Technology

COMPILED BY

OFFICE OF TECHNOLOGY TRANSFER

U.S. DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

Proceedings of the 9th INTERNATIONAL CONFERENCE ON COAL RESEARCH

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CONTENTS

Coal and the Economy

UNIT OF MEASURE ABBREVIATIONS USED IN THE PAPERS IN THIS PROCEEDINGS

Ah	ampere hour	lb	pound
bps	bits per second	m	meter
C, °C	degree Celsius	m^3	cubic meter
cfm	cubic foot per minute	MBq	megabecquerel
cm	centimeter	mCi	millicurie
cm^3	cubic centimeter	meq	milliequivalent
d	day	mg	milligram
deg	degree	MHz	megahertz
g	gram	min	minute
GBq	gigabecquerel	MJ	megajoule
gpm	gallon per minute	mm	millimeter
Gt	gigaton	μm	micrometer
GW	gigawatt	mPa	millipascal
h, hr	hour	MPa	megapascal
K	kelvin	ms, msec	millisecond
kg	kilogram	Mt, Mtonne	megaton
kHz	kilohertz	mV	millivolt
km	kilometer	MW	megawatt
kPa	kilopascal	nm	nanometer
kV	kilovolt	Nm	newton meter
kW	kilowatt	pct	percent
kWh	kilowatt hour	ppm	part per million
l	liter	psi	pound per square inch

UNIT OF MEASURE ABBREVIATIONS USED IN THE PAPERS IN THIS PROCEEDINGS—Continued

s, sec	second
t	ton (tonne)
t/a	ton per annm
t/d, tpd	ton per day
t/h, tph	ton per hour
tps	ton per second
TWh	terawatt hour
TWy	terawatt year
V	volt
wt%	weight percent
yr	year
DM	Deutsche Mark (FRG)
p	penny (UK)
Pfg.	Pfennig (FRG)
R	rand (South Africa)
$	dollar (U.S.)
£	pound (UK)

OTHER ABBREVIATIONS AND ACRONYMS USED IN THE PAPERS IN THIS PROCEEDINGS

BCC	British Coal Corporation
BCURA	British Coal Utilisation Research Association
BERG	Building Effects Review Group (UK)
BGL	British Gas and Lurgi
CEC	Commission of the European Communities
CEGB	Central Electricity Generating Board (UK)
CEPCEO	Comite d'Etude des Producteurs de Charbon d'Europe Occidentale (Association of Coal Producers of the European Community)
CFBC	circulating fluidised bed combustion
CFC	chlorofluorocarbon
CIAB	Coal Industry Advisory Board
CID	coal interface detection
CRE	Coal Research Establishment (UK)
CSIR	Council for Scientific and Industrial Research (South Africa)
CSIRO	Commonwealth Scientific Industrial Research Organisation (Australia)
CURL	Coal Utilisation Research Laboratories (UK)
CWM	coal water mix

OTHER ABBREVIATIONS AND ACRONYMS USED IN THE PAPERS IN THIS PROCEEDINGS—Continued

DOS	disk operating system
EC	European Community
ECE	European Commission for Europe
ECSC	European Coal and Steel Community
EEC	Council of the European Communities
EERC	Energy and Environmental Research Center (U.S.)
EFTA	European Free Trade Association
EPRI	Electric Power Research Institute
ETH	Eastern Transvaal Highveld (South Africa)
FBC	fluidised bed combustion
FEP	front-end processor
FGD	flue gas desulphurisation
GDP	gross domestic product
HD	hydrothermal dewatering
HHV	high heating value
HTW	high-temperature Winkler (gasification process)
IEA	International Energy Agency
IGCC	integrated gasification combined cycles
I/O	input/output
IPCC	Intergovernmental Panel on Climate Change
LDC	less developed country
LHV	low heating value
LPG	liquid propane gas
LSE	liquid solvent extraction
MRC	microwave resonant cavity
MRDE	Mining Research and Development Establishment (UK)
MSHA	Mine Safety and Health Administration (U.S.)
NCA	National Coal Association (U.S.)
NCB	National Coal Board (UK)
NEC	National Energy Council (South Africa)
NGCC	natural combined gas cycles
NIOSH	National Institute for Occupational Safety and Health (U.S.)
NMEP	National Materials Exposure Programme (UK)
OECD	Organization for Economic Cooperation and Development

OTHER ABBREVIATIONS AND ACRONYMS USED IN THE PAPERS IN THIS PROCEEDINGS—Continued

OFS	Orange Free State (South Africa)
OMS	output per man shift
PC	personal computer
PCB	polychlorobenzene
PDU	process demonstration unit
PF	pulverised fuel (combustion)
PFBC	pressurised fluidised bed combustion
R&D	research and development
RD&D	research, development, and demonstration
ROM	run-of-mine
SCR	selective catalytic reduction
SCSR	self-contained self-rescuer
UMWA	United Mine Workers of America
UNEP	United Nations Environment Programme
WMO	World Meteorolgical Organization

PROCEEDINGS OF THE 9TH INTERNATIONAL CONFERENCE ON COAL RESEARCH
October 13-16, 1991
Washington, DC

ABSTRACT

This U.S. Bureau of Mines publication contains papers given at the 9th International Conference on Coal Research (ICCR '91). Topics include environmental concerns in coal mining, beneficiation, and power generation; the health and safety of the mining workforce; and the use of computer technology for increased productivity and safety. The authors of these papers are representatives of Government and industry in Australia, Canada, France, Germany, the Republic of South Africa, the United Kingdom, and the United States.

INTRODUCTION

The International Committee for Coal Research (ICCR) is an organization of world coal representatives joined in simulating scientific studies on technologies for extraction and utilization of coal as an economic, secure, and environmentally acceptable fuel across the globe. Members include representatives of private industry and Governments from Australia, Belgium, Canada, France, Germany, Japan, the Republic of South Africa, Spain, the United Kingdom, and the United States.

Nearly 20 years ago, the ICCR sponsored the first International Conference on Coal Research, in Washington, DC, as the world stood on the brink of an energy crisis. Oil was suddenly unavailable, and coal could not quickly fill the breach because production capacity was at the lowest levels in decades. The conference provided a forum for the coal leaders of the work to exchange information on the best ways to increase coal production to meet rapidly increasing new demands.

The 9th International Conference on Coal Research returns to Washington, DC, as coal faces a challenge of a difference type. Because coal is the world's largest energy resource, it will be called upon to meet an every increasing share of tomorrow's energy needs and to meet these needs while simultaneously sustaining and improving the environment.

The 9th International Conference on Coal Research provides an opportunity for the coal industry leaders of the world—Government and private industry alike—to exchange views on the best ways that coal can meet the challenges of the 1990's. This conference is sponsored by

National Coal Association
U.S. Bureau of Mines
U.S. Department of Energy
U.S. Department of Commerce
U.S. Department of State
International Committee for Coal Research

AN INTERNATIONAL VIEW OF ATMOSPHERIC ENVIRONMENTAL PROTECTION MEASURES

BY G. ZIMMERMEYER, J. ENGELHARD

Abstract

After a period of discussion about local and regional environmental impacts of air pollution, which resulted in limiting emissions like SO_2 and NO_x - at least in some countries -, the problem of global impact on climate and the environment due to emissions from energy use has come into focus now.

Targets and policies to limit or reduce CO_2 from energy use are presented and discussed. As future energy needs have to be met with fossil fuels, mainly the most abundant coal, it is shown that this can be done in an environmentally benign way. Increasing the efficiency of coal use is the key instrument. A global strategy from the coal industry's point of view is developed.

Introduction

Legislation and the implementation of measures and technical installations to reduce emissions into the atmosphere has to be based on valid scientific findings regarding the effects of the emissions avoided and on cost / benefit evaluations. Hardly any of the subjects in the environmental debate has been brought to a final scientific assessment. Therefore, it is necessary to evaluate the risks involved and to develop a prudent risk management strategy.

One of the most important scientific debates in the 80s was about the problem of forest decline as well as lake and groundwater acidification. Even though many uncertainties, open questions and doubts remain in this debate, it seems to be an appropriate precautionary measure to reduce SO_2, NO_x and particulate emissions by a significant amount. Technologies to achieve such an objective are available. They should be applied as far as emission reduction is proportional to the risks reduced.

Some industrialised countries - especially in the western world - have already reduced or at least stabilized the emissions of pollutants like SO_2, NO_x and particulates because of their possible harmful effects on a local or regional scale. Many developed countries and even some of the centrally planned economies have agreed to implement action plans to reduce emissions. It goes without saying that there still remains a deficit in many countries to meet their liability within the forseeable future.

Compared to those emissions, the recent debate on global problems, mainly possible climate changes due to the emission of climatically relevant trace gases, has a completely different dimension, quality and character.

In contrast to the observed forest decline or lake acidification, there is no evidence on direct climatic effects. However, there is a possibility that future generations may suffer from a changing climate if we continue to increase our emissions. Therefore, climatologists demand reductions in the emission of climatically relevant trace gases. But on the other hand, we should all agree: It can't be tolerated that in our present generation billions of people suffer and millions of people die, because of lack of food and drinking water. To make those people survive, we are forced to use more energy for food production and walter cleaning. Increase in food production, however, will result in an increase in emissions like CH_4 and N_2O. Increase in energy use might result in an increase of CO_2-emissions (fig. 1), provided that no further development in technology occurs. Securing future energy supply must be seen as a strategic task. Consequently, future energy needs and a perceived necessity to reduce CO_2-emissions for climatic reasons present conflicting policy objectives to society. It will be a difficult task to resolve both of those problems satisfactorily (fig. 1).

The key answer to this antagonistic conflict is to increase efficiency by developing new technologies.

International bodies like IPCC, WMO, UNEP and several national bodies claim or apprehend that this is not sufficient. Other international organizations like OECD, IEA and ECE however have adopted such an efficiency strategy as a first step in the short or medium term.

National and international policies to reduce climate risks

After adopting and even tightening the Montreal Protocol to reduce CFC production to protect the ozone layer, CO_2 assumes a central role when coping with climate risks. At present emission rates, CO_2 is estimated to contribute about one half to the additional radiative forcing resulting from human activities (fig. 2). As a result, efforts aimed at restraining radiatively active trace gas emissions are centered on CO_2. As man made CO_2-emissions mainly come from fossil fuel use and biomass burning, the CO_2 issue is increasingly influencing energy policy.

There seems to be a "public view" supported by politicians that the greenhouse effect is synonymous with coal fired power plants. This view, however, does not agree with reality. Globally, CO_2 from coal combustion is estimated to contribute 15 % to the global greenhouse effect. Overall, about half the world's coal is used to produce electricity and hence in total only about 7,5 % of the calculated greenhouse effect is due to coal fired electricity generation which in turn produces 40 % of the worlds electricity (CEPCEO study on European Coal and The Greenhouse Effect, 1989). This gives an estimate to what is achievable in focussing political objectives to (only) that issue.

The 1988 Toronto conference on "The changing atmosphere" has presented general guidelines as to how much worldwide CO_2 emissions should be reduced in the next decades. Leaving aside basic scientific uncertainties the Toronto conference demands a 20% reduction by the year 2005 to avert disastrous global warming. This demand has assumed a benchmark character in the political debate and international as well as national reduction strategies are built around it.

By early 1991, a number of countries had announced either reduction or stabilization targets (table 1) although most of these countries have not yet identified the policy measures they want to employ to meet those goals.

As a matter of fact, almost the entire OECD region has made some sort of a pledge on climatically relevant trace gases. Nevertheless, as recent studies by e. g. Grubb suggest, "global carbon emissions will continue to rise even if there are considerable abatement efforts". Similar conclusions are also reached in econometric studies on the impact of tradable CO_2 emission permits (e. g. DRI / Mac Graw Hill, 1991). This assessment is generally supported by a variety of studies on future global energy requirements.

Given the uncertainties associated with climate model forecasts on the one side and possible economic disruption caused by adopting overly stringent reduction measures on the other, the strategy of employing no-regret-measures emerges. Those are measures which have overall benefits which seem to fit ideally to the idea of a "sustainable development". Sustainable development means to meet the demand of present generations without compromising the ability of future generations to meet their own needs. It cannot simply be defined as trying to avert a risk to climate.

Some studies claim that reductions of energy use in industrial countries (and attendant CO_2 emissions) might be cost neutral or even cost negative for the first few percent of reduction. Even if such a technology existed, it remains to be seen if it would penetrate the market. Other studies have concluded (e. g. DRI/Mac Graw Hill) that even relatively modest reductions might not be achievable cost-effectively, but may rather lead to noticeable reductions in Gross Domestic Product (GDP).
Above all, it is essential to realize that global warming is a problem of global dimensions. Changing the trend in global CO_2-emissions can only be achieved in close international co-operation. No national government or economic entity would be able to solve that problem in a go-it-alone fashion. As an example, even if all EC countries ceased to emit CO_2 - which of course is not possible - this would only lead to a 14 per cent reduction of world wide CO_2 emissions (their share) and thus only to a seven per cent reduction in the additional greenhouse effect.

As another example, if the Federal Republic of Germany - after all the fifth largest CO_2-emitter in the world - would cease to emit CO_2, it would only take a few years for additional emissions to reach the previous global emission level. E. g. China's 5-year-plan aims to reach an increase in coal production which is of the same order as the total present CO_2-emission in West Germany. Therefore international efforts should be made to help getting those economies more efficient rather than to exaggerate national strategies in already efficient economies.

As an example for an industrialised country the situation in Germany shall be highlighted in the following. This is a very important and impressive example because it demonstrates the futility of a go-it-alone strategy - or a leadership role - very illustratively.

THE CO_2-DISCUSSION IN GERMANY

The unified Germany contributes about 4,7 % to global emissions from energy use (fig. 3). In West Germany (former FRG) the share of oil is the biggest with 312 Mio t CO_2 followed by hard coal with 211 Mio t of CO_2 and lignite with 102 Mio t CO_2. In East Germany the share of lignite was 274 Mio t CO_2 in 1987 corresponding to 70 % of the energy consumption. After the reunification lignite's share has already decreased and will further decline (fig. 4).

34 % of the CO2 in West Germany originates from industry, 20 % from transport and 28 % from residential use and 18 % from small business (fig. 5).

Electricity generation in the unified Germany contributes 357 Mio t CO_2 i.e. nearly 33 % (fig. 6).

Total CO_2-emissions in FRG went up by more than a factor of 2 between the 50s and the second half of the 70s but declined afterwards as in most other western industrialized countries (fig. 7).

Among those countries who have announced to reduce greenhouse gas emissions, the Federal Republic of Germany (FRG) has paid particular attention to CO_2 emissions associated with energy use. The German cabinet announced its objective to reduce CO_2 emissions by 25 per cent from 1987 levels by the year 2005 on 13 June 1990 and appointed an interministerial working group (IMA) to conduct feasibility studies into how the proposed reduction target might be achieved. Within four months the IMA has presented an interim report to the German cabinet which formed the basis of its decision on 7 Nov. 1990 that an even larger reduction was thought achievable in the former East Germany.

In order to achieve this reduction it proposes to rely primarily on:

Fiscal measures and additionally on
Regulatory measures

As far as fiscal measures are concerned, there is still an ongoing debate whether a CO_2 tax or a CO_2 levy should be imposed. The main difference between both is that taxes would flow into the general revenue bag, whereas a levy would be used for specific purposes to reduce CO_2-emissions only, as e.g. financing investments into energy efficient technology. Therefore a levy has a much stronger steering effect than a tax.

The amount of the levy that has been debated last year was around 10 DM per t of CO_2. In the electricity sector (coal fired power stations), this would translate into about 1 Pfg. per kWh, raising the price of electricity by roughly 5 per cent.

The concrete structure of a possible carbon levy is not known presently. If it will be imposed on CO_2 emissions, it might result in efforts to substitute coal by gas, nuclear or renewables. Switching to gas would not be a prudent strategy in view of the short and long term availability, the market situation and environmental problems e. g. the methane-problem. This problem has to be taken into account since the leakage and the loss of this climatically relevant gas - with its much bigger importance than CO_2 -, might be unexpectedly high. Switching to nuclear energy seems not possible because of an ongoing lack of public acceptance. Switching to renewables is in fact a political objective. However, the supply situation for renewables argues strongly against a premature and expanded reliance on them. Therefore, a levy on CO_2-emission would be the wrong signal. If a levy is imposed anyway, it should not be on CO_2 emissions but on energy itself or on the efficiency of energy supply systems. This would directly aim at energy conservation and would therefore be in line with the global task of securing long term energy supply.

A second alternative could be a modest and early announced increase in general energy prices.

Anyway, the economic and social results of such strategies have to be studied. It is clear from reasons of competitiveness that such measures should only be implemented globally.

Regional and global strategies.

The European Commission is just developing a strategy to meet its commitment to stabilize CO_2-emissions by the year 2000 at the level of 1990. They give preference to a tax that is 75 % energy based and 25 % on CO_2. A decision is announced for July 1992.

A global arrangement might be the result of the UNCED conference 1992 in Brasil. But even if the assembled statesmen agree to a target for reduction or stabilisation the question of political instruments will presumably remain open.

For an international agreement it has to be taken into account, that

- sinks for CO_2 play an important role and have to be developed (afforestation, oceanic biota)
- the costs for different CO_2 reduction measures differ substantially
- the potentials for CO_2 reduction should be exhausted - where achievable - at the lowest costs
- industrialised countries have the responsibility to provide money, research and development, technology,

and technical education for the LDCs to help them limiting their CO_2 emissions.

- a least- cost strategy should be developed maintening energy supply and increasing energy security by lowering environmental risks.

ECE has calculated that central and eastern European energy economies are half efficient as those of market economies. Reducing this gap by half would reduce CO_2-emissions by 20 - 25 per cent in comparison with continuing trends in the ECE regions. This would translate into a 10 per cent reduction of global CO_2 emission-levels.

In a study for IEA, CIAB has calculated that a reduction of CO_2 emissions by 31 % should be possible by implementing the best available technology for power plants (efficiency 37 %) to replace the existing ones (efficiency 25 %).

One further step - implementable in the middle of the 90s - will be the Integrated Gasification Combined Cycle system (IGCC). This technology is able to convert any type of coal and can increase efficiency at least up to 45 % and possibly even more. IGCC is an example of applying modern technology to coal burning processes. The aim is to increase energy efficiency while decreasing emissions of air pollutants. IGCC can therefore be perceived as a prime example to employ clean coal technologies. An example of this technology is the 300 MW KoBra demonstration plant (KoBra= lignite-based combined cycle power plant). RWE Energie AG and Rheinbraun are jointly constructing this plant at a site near Cologne. The plant uses the Rheinbraun High Temperature Winkler gasification process (HTW), which has been tested on a commercial scale and can be applied to a large variety of coal grades. The KoBra-plant will go on stream arount the end of 1995; it will have a power generation efficiency of about 45 % and permits a corresponding reduction of Co_2.

Another way to increase the efficiency of energy use is the combined heat and power generation system. For district heating and industrial applications this is already a state-of-the-art technology. This approach allows to increase the useful energy output to 80 % and more. In the future this technology should be increasingly used - particularly in the developed countries - wherever technically applicable and economically feasible.

Lessons from the past

The energy crises of the 1970s have forced the major world economies to reduce their dependence on insecure supplies of foreign energy. This drive has resulted if not in actual reductions of fossil energy use then in a decisive increase of energy efficiency measured as energy used per unit of GDP. Most of the OECD countries presently emit little more CO_2 or even less than they did 18 years ago while their GDP has drastically risen. This is due not only to efficiency increases but also to structural shifts in the economy and to shifts in the energy supply. In fact, the largest efficiency increases in the utilities and in the manufacturing sector in Germany did not occur in the 70s and 80s (under the impact of much higher energy prices) but in the 50s and 60s, when energy was still cheap (fig. 8). This is leading some analysts to suspect that efficiency increases will be implemented anyway if they're technologically possible and economically sensible. Some conclude it would be harmful to direct financial resources away from industry - by means of either a CO_2 tax or levy - and opt for leaving those resources with industry to be used more efficiently by them - providing a better climate and more solid framework for innovation and investment.

THE IMPACT OF CO_2 REDUCTION TARGETS ON GLOBAL WARMING

The impact of CO_2 reduction targets on global warming as proposed by the OECD countries has been analyzed by a group of scientists from the climate research unit of the University of East Anglia. They conclude that if all OECD countries went ahead with their trace gas reduction plans as announced by late 1990, the resultant global warming would, by the year 2100, be only .45° C less than the IPCC "Business as usual" estimate of 3.2°C (fig. 9) and entirely insignificant in the next five decades. Compared to the herculian task of reducing trace gas emissions even by the relatively small amount proposed within the OECD that figure seems almost abysmally small.
This once again underlines that it is futile if individual countries put particular ardour into trace gas reduction strategies if their zeal is not met solidarily by most of the other major trace gas emitters. Consequently, governments might find themselves in a precarious position when putting an extra burden on their economies and citizens to stave off global warming if it becomes apparent later on that the concern over climate was either not justified or that their national efforts alone were meaningless. Therefore, any of the proposed solutions should - as the basic premise itself that global warming will entail disaster - be thoroughly scrutinized.

CONCLUSION for a global strategy from the coal's view

- Globally, future energy needs and the alleged necessity to reduce energy use in order to ward off deleterious climate changes present conflicting policy objectives to the world community which it must resolve.
- Given the uncertainties associated with the scientific assessment of future climate changes as projected by model calculations, the setting of specific reduction targets does not appear to be justified at this time.
- If held necessary, a significant CO_2 reduction can only be initiated globally - or at least among the majority of CO_2 emitters with solidarity and not in a national go-it-alone strategy.
- R and D in energy technology should be enhanced especially in clean-coal technologies to improve efficiency because this is the only medium-term strategy able to meet all the necessary targets.
- Incentives should be given to encourage the implementation and operation of clean and efficient technologies.
- If a strategy is to be implemented to discourage energy use and increase efficiency by higher energy prices (taxes or levies) studies have to be made to elucidate the economic impacts of those strategies.
- A comprehensive concept has to be developed not only by taking into account all anthropogenic climatically relevant activities but also including possible sinks of greenhouse gases with the aim to enhance the effectiveness of such sinks. Such actions would create additional advantages, for instance in maintaining or gaining a better local environment (afforestation).
- The International coal community should agree upon a Code of Conduct concerning the behaviour and objectives of coal within the framework of the need for a secure energy supply and the protection of environment and atmosphere.

Main items of such a Code of Conduct should be:

- Supporting R and D
- Commitment to an early implementation of efficient clean coal technologies.
- Developing strategies for implementing appropriate technologies in the LDC.
- Advise the Coal Community in the LDCs on how to use coal more efficiently rather than extracting it from the ground.
- Using waste energy

- Increasing use of mine gas for energetic purpose
- Reducing waste production
- Developing and offering the technical Know-How to meet other environmental objectives of society (e. g. waste disposal in underground mines).
- Afforestation (domestic and abroad).

CO2 EMISSION BETWEEN ASPIRATION AND REALITY

Fig. 1

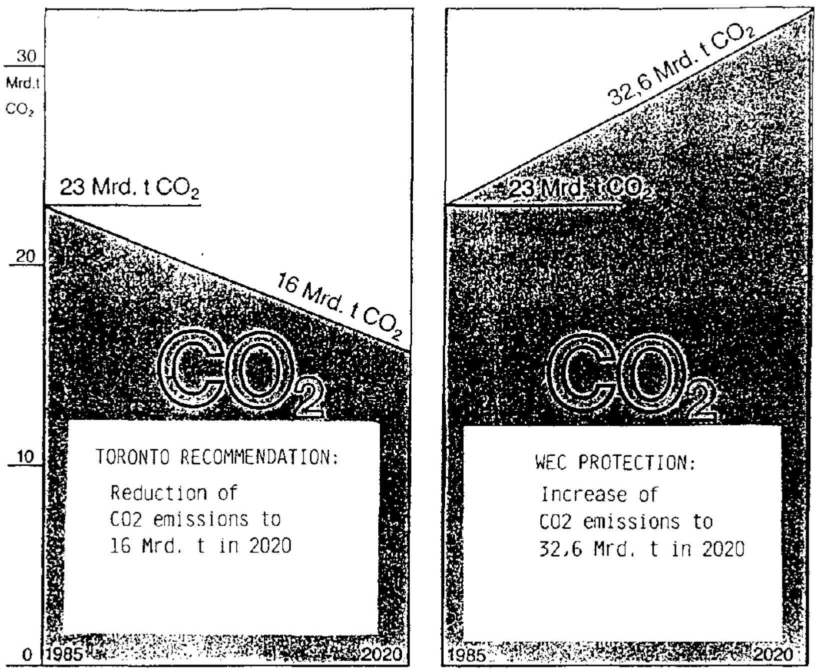
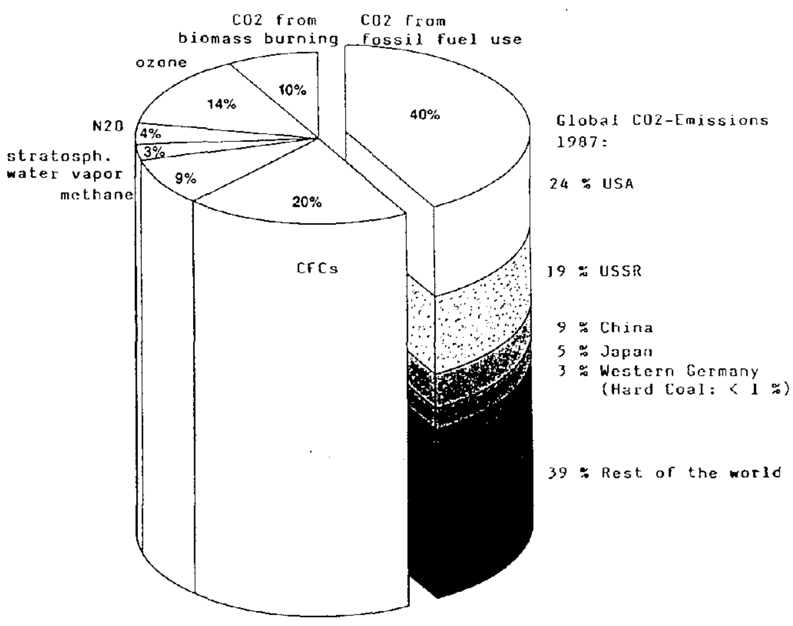


Fig. 2

CONTRIBUTION TO ADDITIONAL RADIATIVE FORCING



Source: 3rd Interim Report of the Enquete-Comission of the German Bundestag "Protecting the earth's atmosphere"

Table 1

Unilateral Efforts to Reduce Greenhouse Gases

AUSTRALIA	in October 1990, agreed to a 20 % cut in gases not controlled by the Montreal Protocol from 1988 levels by 2005
AUSTRIA	agreed to a 20 % cut in CO_2 from 1990 levels by 2005
DENMARK	agreed to a 20 % cut in CO_2 from 1990 levels by 2000
GERMANY	in June 1990, agreed to a 25-30 % cut in CO_2 from 1987 levels by 2005; in October 1990, the Bundestag released a report outlining specific programs in each sector to curb greenhouse emissions
ITALY	Environment Minister Giorgio Ruffulo committed to a 20 % cut in CO_2 by 2005
LUXEMBOURG	agreed to a 20 % cut in CO_2 from 1990 levels by 2005
NETHERLANDS	in May 1990, agreed to a 3-5 % annual cut in CO_2 from 1989-90 levels by 2000
NEW ZEALAND	in October 1990, announced a five-year acceleration of previous government's commitment to CO_2 reductions, agreeing to a 20 % cut from 1990 levels by 2000; a list of specific proposals is to be sent to the Cabinet by mid-1991
NORWAY	the Parliament approved a carbon tax effective January 1, 1991 (oil is taxed at US $ .05/liter; gasoline at $ .10/liter; natural gas at $ .10/cubic meter; coal is exempt)

Unilateral Efforts to Stabilize Greenhouse Gases

AUSTRALIA	in October 1990, agreed to stabilize gases not controlled by the Montreal Protocol, at 1988 levels by 2000
BELGIUM	agreed to a 5 % cut in CO_2 by 2000, and "substantial reductions" thereafter
CANADA	in December 1990, agreed to stabilize CO_2 and other greenhouse gases at 1990 levels by 2000
EC	in October 1990, energy and environment ministers agreed to a community-wide stabilization of CO_2 at 1990 levels by 2000; the Council of Ministers is currently considering policies to achieve cuts
EFTA	in November 1990, agreed to adopt the same overall CO_2 target as the European Community
JAPAN	in June 1990, agreed to stabilize CO_2 on a per capita basis at 1990 levels by 2000; in October 1990, agreed to stabilize all greenhouse gases at 1990 levels by 2000
NETHERLANDS	agreed to stabilize CO_2 at 1988-89 levels by 1994-95, as part of a national environmental policy plan
UK	called for a stabilization of CO_2 at 1990 levels by 2005

Fig. 3

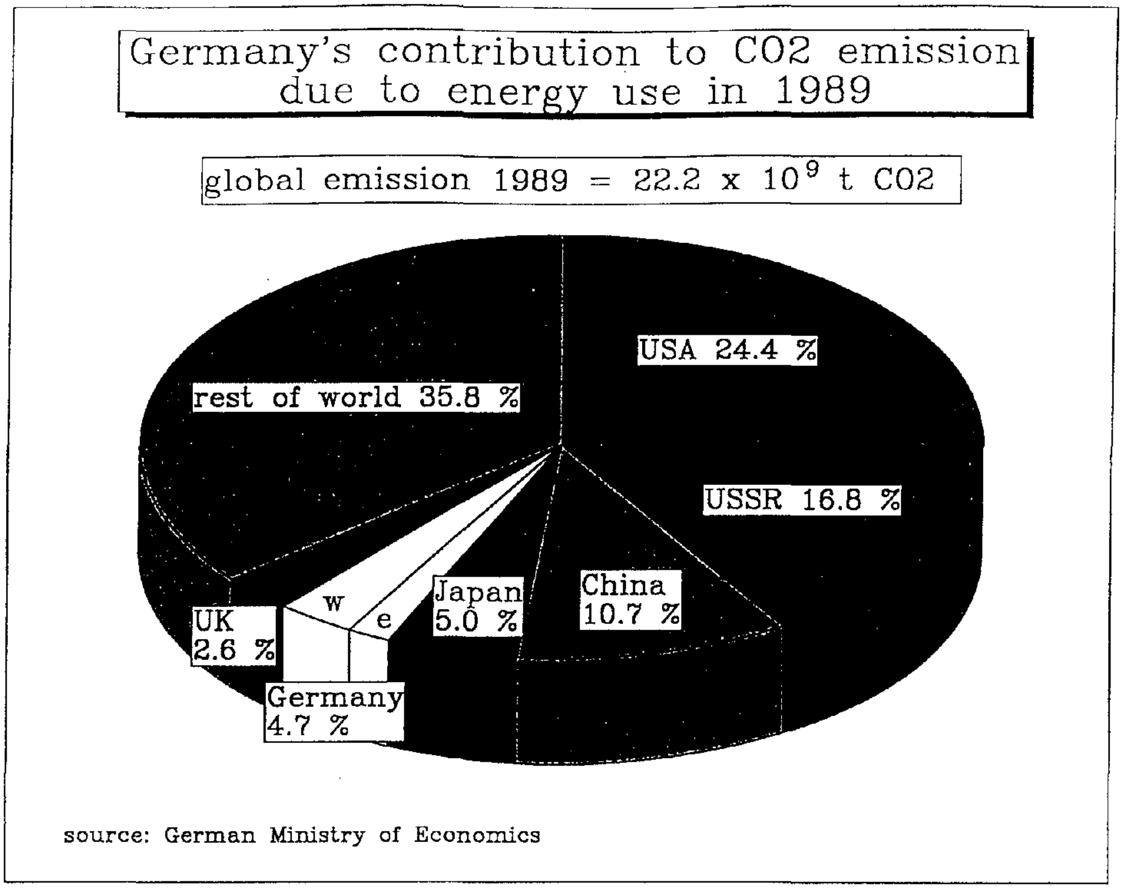
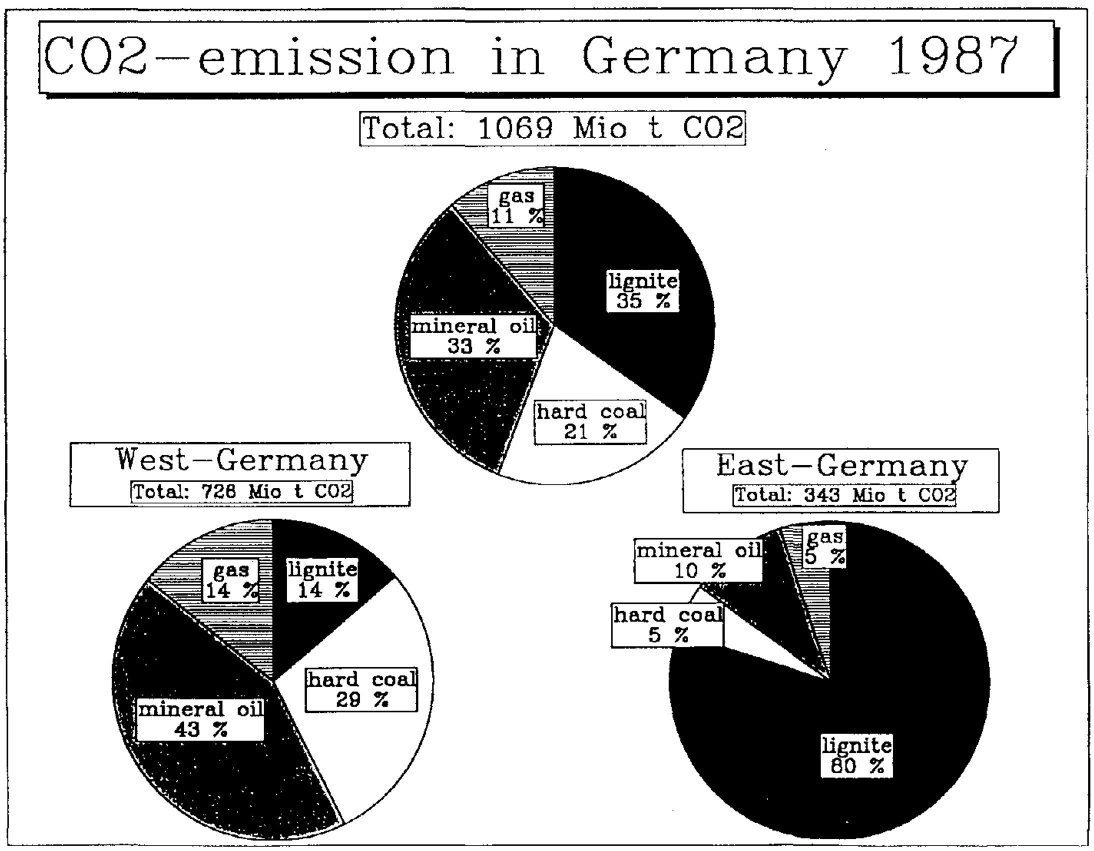

Germany's contribution to CO2 emission due to energy use in 1989
global emission 1989 = 22.2 x 10⁹ t CO2
USA 24.4 %
rest of world 35.8 %
USSR 16.8 %
Japan 5.0 %
China 10.7 %
UK 2.6 %
w
e
Germany 4.7 %
source: German Ministry of Economics

Fig. 4


CO2-emission in Germany 1987
Total: 1069 Mio t CO2
gas 11 %
lignite 35 %
mineral oil 33 %
hard coal 21 %
West-Germany
Total: 726 Mio t CO2
gas 14 %
lignite 14 %
hard coal 29 %
mineral oil 43 %
East-Germany
Total: 343 Mio t CO2
mineral oil 10 %
gas 5 %
hard coal 5 %
lignite 80 %

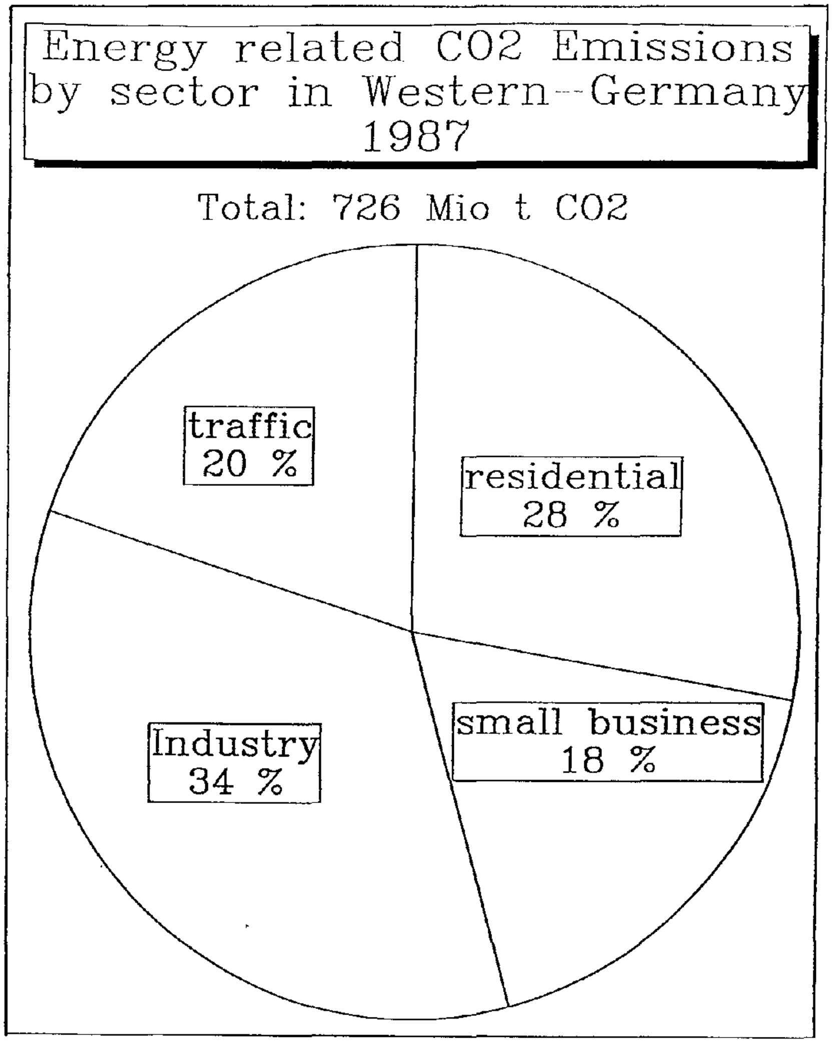

Energy related CO2 Emissions
by sector in Western-Germany
1987
Total: 726 Mio t CO2
traffic
20 %
residential
28 %
Industry
34 %
small business
18 %

Fig. 5

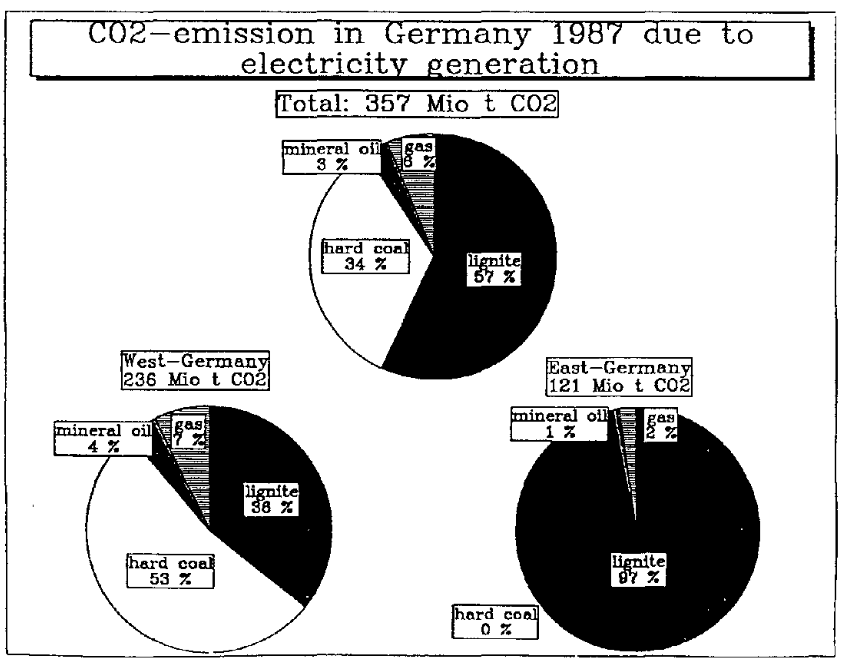

CO2-emission in Germany 1987 due to
electricity generation
Total: 357 Mio t CO2
mineral oil
3 %
gas
6 %
hard coal
34 %
lignite
57 %
West-Germany
236 Mio t CO2
mineral oil
4 %
gas
7 %
lignite
36 %
hard coal
53 %
East-Germany
121 Mio t CO2
mineral oil
1 %
gas
2 %
lignite
97 %
hard coal
0 %

Fig. 6

Fig. 7

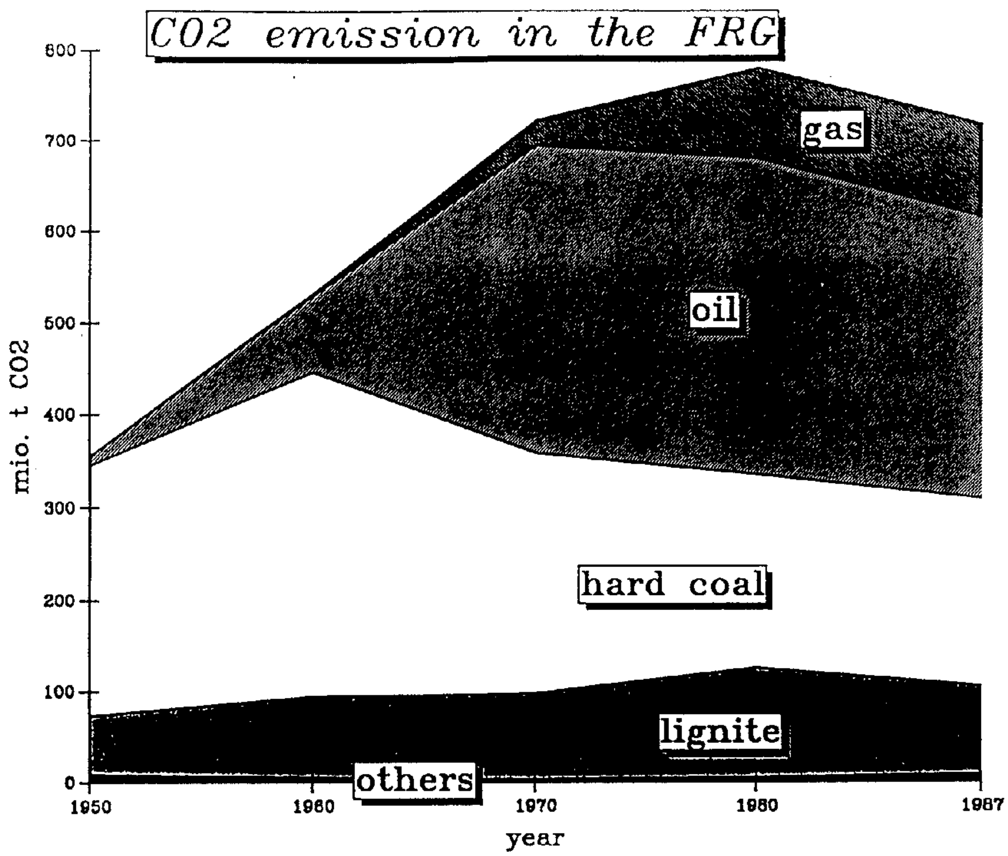


Fig. 8

Energy efficiency of the German manufacturing sector (kg of ce per 1000 DM of goods produced) and crude oil prices (DM per t) in constant 1980 prices.

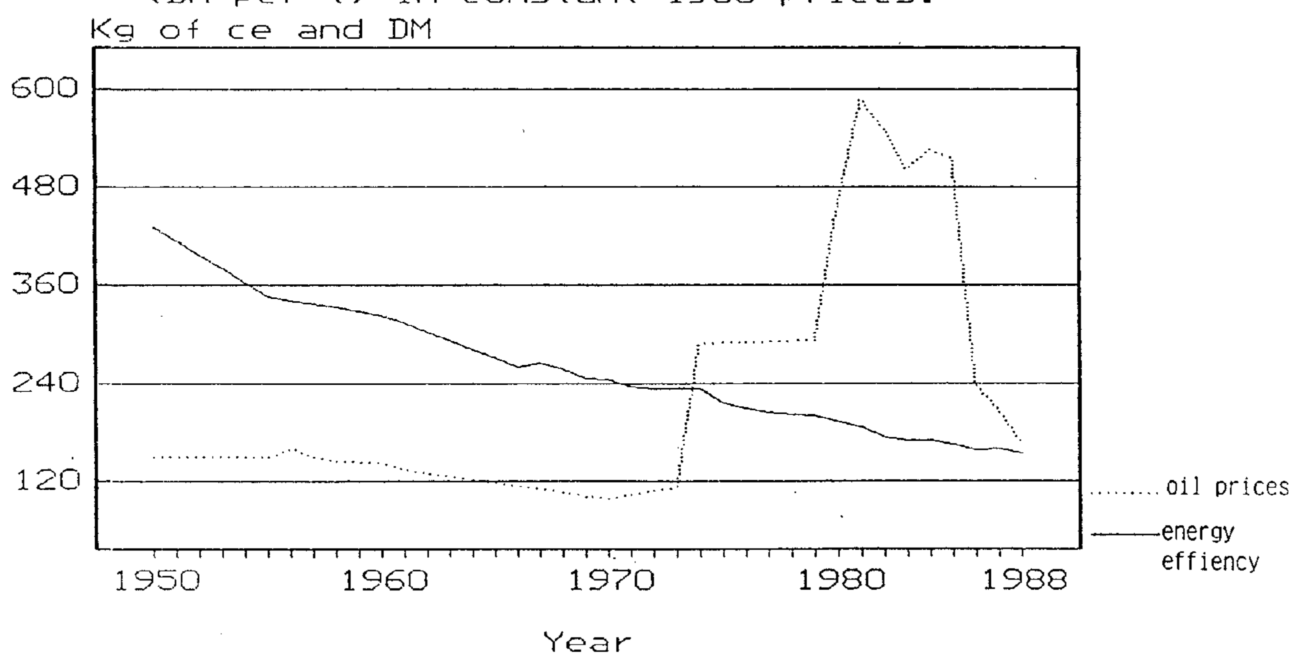
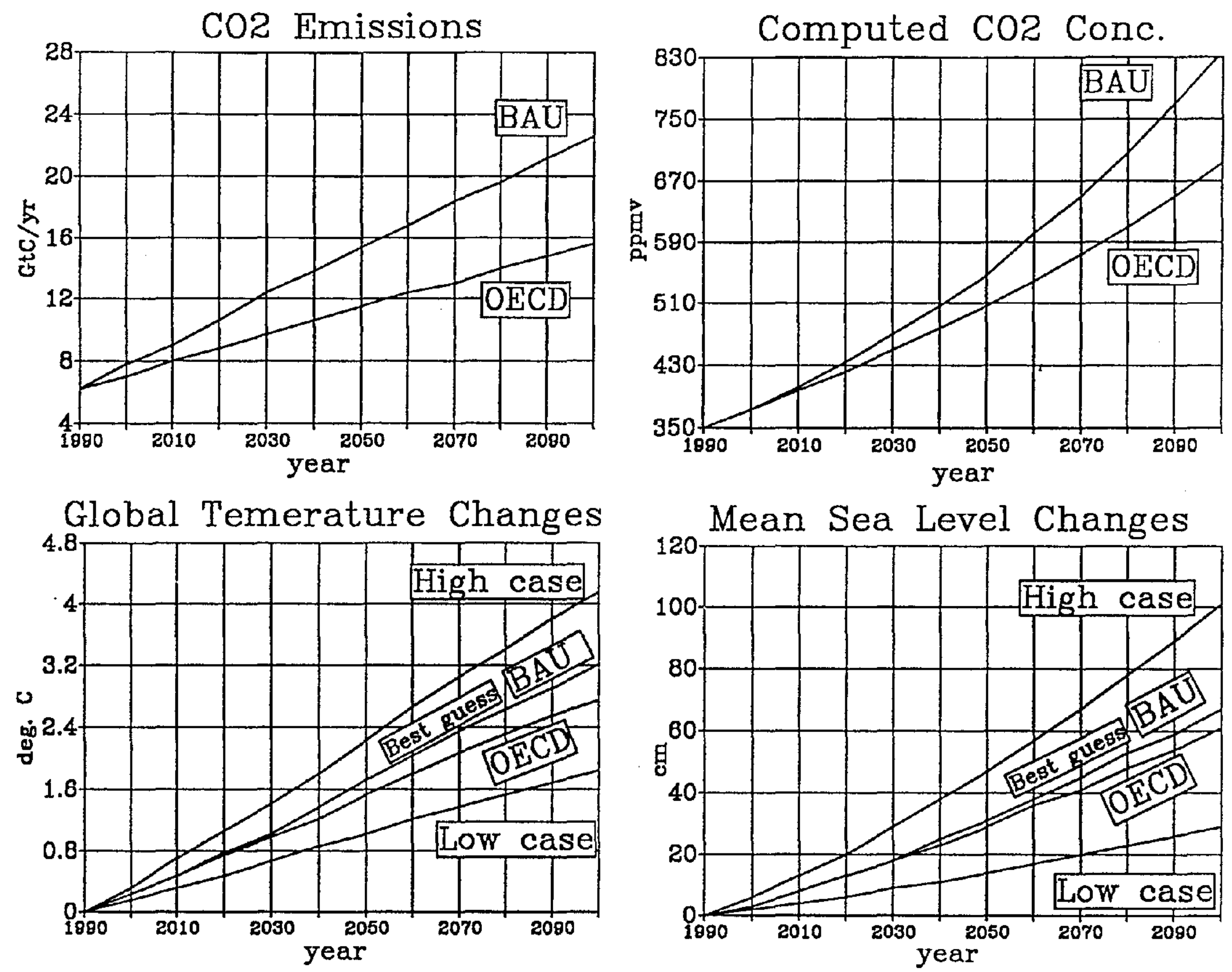


Fig. 9


CO2 Emissions
GtC/yr
28
24
20
16
12
8
4
1990
2010
2030
2050
2070
2090
year
BAU
OECD
Computed CO2 Conc.
ppmv
830
750
670
590
510
430
350
1990
2010
2030
2050
2070
2090
year
BAU
OECD
Global Temerature Changes
deg. C
4.8
4
3.2
2.4
1.6
0.8
0
1990
2010
2030
2050
2070
2090
year
High case
BAU
Best guess
OECD
Low case
Mean Sea Level Changes
cm
120
100
80
60
40
20
0
1990
2010
2030
2050
2070
2090
year
High case
BAU
Best guess
OECD
Low case

MANAGING THE INTERFACE BETWEEN COAL AND THE ENVIRONMENT IN THE REPUBLIC OF SOUTH AFRICA

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ABSTRACT

South Africa has committed itself to strive for a balanced exploitation policy in respect of the optimum development and utilisation of energy resources, and the demands imposed by the need to preserve the human and natural environment. Within this broad framework, various R&D, economic-incentive and legislative strategies have been implemented across the total coal cycle, ranging from mining through beneficiation to eventual utilisation. These strategies have been tailored to suit South African conditions, particularly with regard to the dominant role of coal in the national energy economy, the privatised nature of the coal industry, and the nature and geographic distribution of the country's coal deposits. Key elements in the successes achieved to date have been the South African Government's endorsement of the free enterprise system and the coal industry's voluntary responsible attitude towards environmental protection.

INTRODUCTION

The interface between the exploitation of natural resources and the environment has been part of human existence since prehistoric times. Over the last century, however, the dimensions of this interface have changed dramatically, mostly as a result of the growth in world population which, together with the introduction of new technologies, have led to an unprecedented increase in the demand for energy. Modern society has in fact now reached the point where responsible management of the inevitable interaction between energy and the environment has become essential to ensure quality of life, maintenance of living standards, or even mere survival.

In a sense it is ironical that man's quest to improve his standard of living now seems to threaten this very objective. Fortunately, unlike other creatures, man has the ability to consciously shape his own future by taking timely actions to safeguard his own interests as well as those of the environment of which he forms an integral part. Such actions are largely determined by the nature, intensity and consequences of the energy/environment interface and are strongly moderated by affordability and need (Venter and Bredell, 1991)

The reality therefore needs to be accepted that, although the environmental challenge is very much a global responsibility, the actual management of the energy/environment interface will largely be dictated by local circumstances in individual countries.

In South Africa for example, coal features so strongly in the energy requirements and the general economy of the country that it naturally forms the focal point of most environmental strategies and strategies aimed at ensuring the well-being of present and future generations. This paper will attempt to illustrate how such strategies have been tailored to meet South African requirements in a globally acceptable manner. The basic point of departure is that no society can be expected to care about the environment from a position of poverty or mere survival. Quality of life is therefore considered the primary issue and sustained economic growth is regarded as the only sensible way to prevent environmental degradation.

THE ROLE OF COAL IN THE SOUTH AFRICAN ECONOMY

South Africa has a large coal reserve base amounting to some 55 billion tons of bituminous and anthracitic coal (Bredell, 1987). In the absence of significant petroleum and natural gas resources and the limited hydropower potential, coal has become the cornerstone of the country's energy industry and is currently providing 82 per cent of the primary energy requirements (Fig.1)

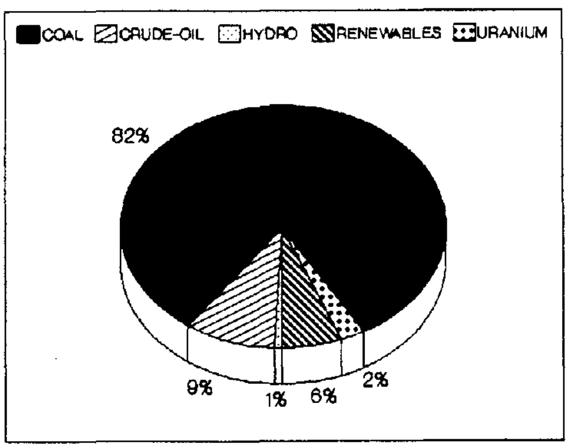

Figure 1: Primary energy use in South Africa

During 1990 South Africa produced 185 million tons of saleable coal which, according to recent information supplied by Daniel (1991) amounts to about 93 per cent of Africa's coal production.

The value of local coal sales (R4,12 billion for 1990) amounts to about 50 per cent of all local mineral sales, while coal exports have since 1979 been the biggest contributor to foreign exchange earnings after gold. During 1990 49,6 million tons of predominantly steam coal valued at R4,02 billion were shipped to foreign consumers. This means that South Africa currently supplies almost 28 per cent of internationally traded steam coal, competing with Australia as the world's leading steam coal exporter.

Some 90 per cent of South Africa's electricity generating capacity lies in coal-fired power stations, and almost 43 per cent of the country's total saleable coal production is used for this purpose (Fig. 2).

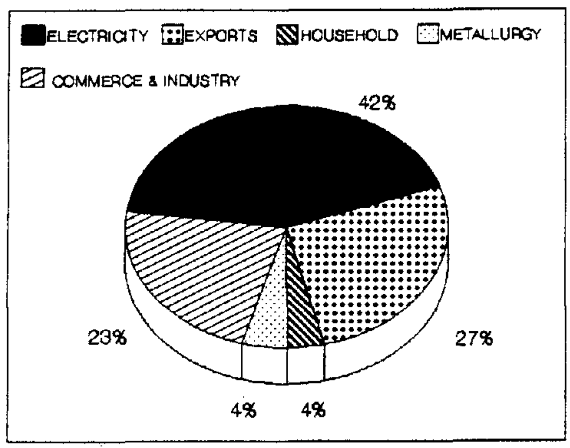

Figure 2: Coal sales per consuming sector (1990)

Local industry, including the synthetic fuel industry, consume approximately 27 per cent of the coal produced. Less well known is the fact that South African coal also forms the feedstock for a wide range of petrochemical commodities which have become an indispensable part of modern society. These include explosives, plastics, fertilisers, pharmaceutical products, tar, liquid petroleum gas, wax, kerosene and synthetic rubber. Coal also plays a vital role in the local metallurgical industry, and last but not least, coal still serves as the most important household fuel for a large part of the community.

There can be no doubt that coal has had an overwhelmingly positive impact on the human environment in South Africa. The country's coal mining industry alone employs about 90 000 people, approximately 87 per cent of whom are unskilled or semi-skilled workers who are estimated to support at least 470 000 dependants (Management Committee, Department of Agriculture, 1990).

Virtually impossible to quantify, however, is the vast indirect socio-economic impact of coal on secondary and tertiary industries and the accompanying products, services, job opportunities and regional development.

Coal will undoubtedly continue to dominate the South African energy scene for many years to come. Other energy carriers are bound to play an increasing role in the quest to provide appropriate and affordable energy to all, but it is generally accepted that for large-scale power generation, as a petrochemical feedstock, as a metallurgical reductant, as a catalyst for industrial growth, and as a major force in the country's economy, South Africa's reliance on coal is not going to decrease materially.

The South African Government and the local coal industry are, however, accutely aware of the fact that the coal industry's economic sustainability and its international competitiveness will in future be strongly influenced by the ability to effectively mitigate negative environmental impacts (Louw *et al*, 1990).

THE INTERFACE BETWEEN COAL AND THE ENVIRONMENT

Fundamental issues influencing the coal/environment interface

The nature and intensity of the coal/environment interface is to a large extent determined by a few basic, immutable factors which form an inherent part of South Africa's coal make-up. These are -

- the geographic distribution of the coal reserves;
- the composition of the coal reserve base; and
- the mineability of the coal.

Analysis of these factors shows that, together with the economic dependence on coal as described above, they form a rather unique combination which dictates most strategies aimed at the management of the coal/environment interface.

As illustrated in Figs. 3,4 and 5, South Africa's coal resources are for all practical purposes located in two geographic areas, namely the Eastern Transvaal Highveld (ETH) and the Waterberg coalfield. Due to its remoteness and unique character of the deposits, the latter coalfield is still largely intact. The ETH on the other hand, is located close to the Pretoria-Johannesburg metropolitan areas and has attracted a high concentration of coal mining activity and coal-based industries. More than 80 per cent of South Africa's coal production currently comes from this area and about 74 per cent of the country's coal-based electricity is generated here, amounting to 40 % of Africa's electricity generating capacity. In addition, South Africa's biggest synfuel and petrochemical plants are located in the ETH, together with a whole range of secondary and tertiary industries. To have all of this contained in an area of approximately 100 by 100 kilometres inevitably results in a highly concentrated interaction with the environment. Considering the vast reserves in the area (about 29 billion tons) this concentration is unlikely to decrease in the foreseeable future. In the long term, however, a gradual shift of coal activities to the Waterberg coalfield is expected where a similar or even higher concentration is bound to develop eventually.

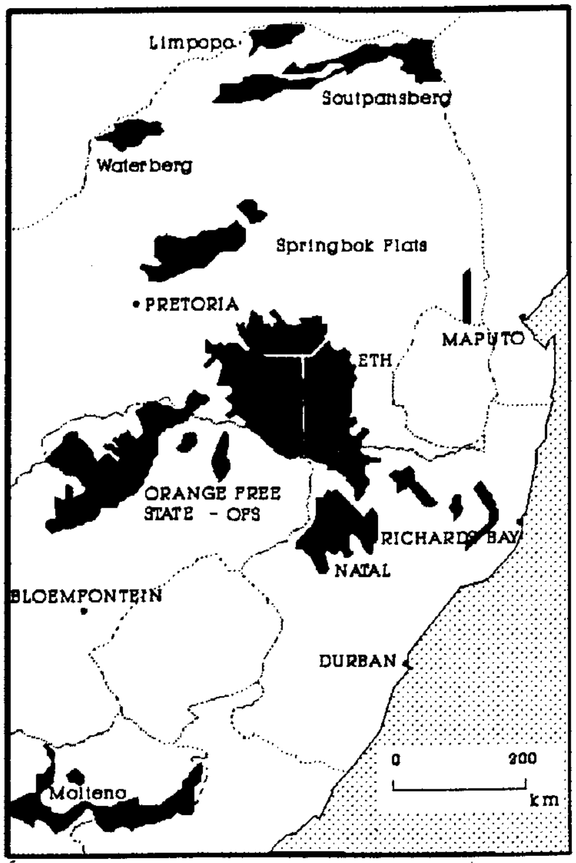

Figure 3: Location of South African coalfields

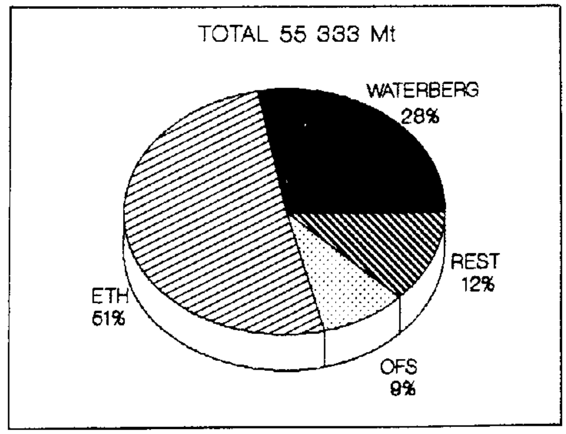

Figure 5: Geographic distribution of recoverable reserves

The composition of the South African coal reserve base (Fig. 6) not only determines its suitability for various applications and the technologies required to achieve this, but it also has a marked effect on the nature and intensity of the coal/environment interface. Of particular relevance is the generally high inorganic content of the run-of-mine coal which results in a bigger environmental impact due to -

- larger volumes which need to be mined for a particular energy requirement;
- more discards being generated during beneficiation; and
- more solid residue (ash) being formed during utilization.

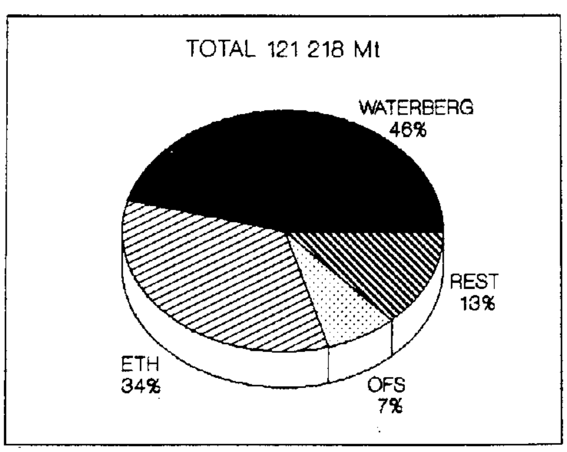

Figure 4: Geographic distribution of in situ resources

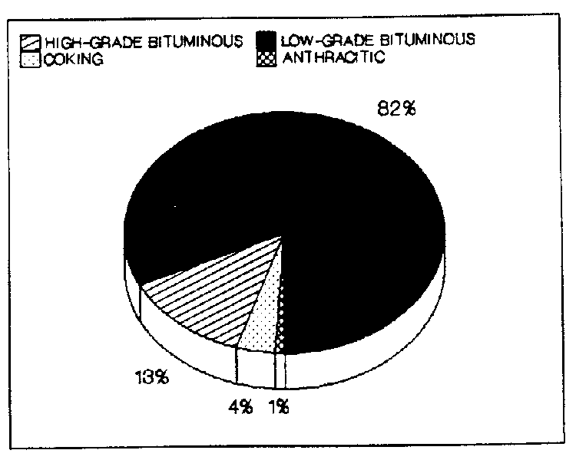

Figure 6: Composition of the South African coal reserve base

Comparing the composition of current national production (Fig. 7) with the composition of the reserve base clearly indicates that the reserves of high-grade bituminous coal are being depleted at a faster rate than those of low-grade bituminous coal (Bredell, 1987). In the long term the environmental challenges described above can therefore be expected to intensify.

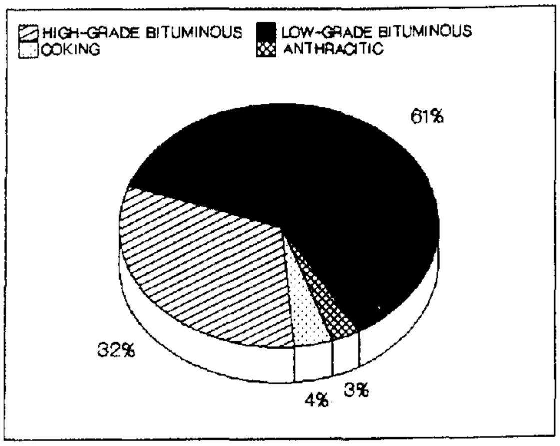

Figure 7: Composition of current national production

On the positive side, however, South African coal has a characteristically low sulphur content which reduces its contribution to atmospheric pollution (Mehliss, 1986).

As far as the mineability of coal reserves is concerned, there is still considerable scope for increasing the application of particularly underground high-extraction methods (Management Committee, Department of Agriculture, 1990). As illustrated in Fig. 8, only 6 per cent of the reserves needs to be mined by room and pillar, while 50 per cent of current production is still derived from this method. However, a recent modification in the existing design of underground pillars has allowed the mining of as much as 26 per cent more coal in given areas without sacrificing safety.

If, in the interest of optimal recovery, high-extraction methods are to be expanded in future, the accompanying increase in environmental challenges will obviously have to be reckoned with.

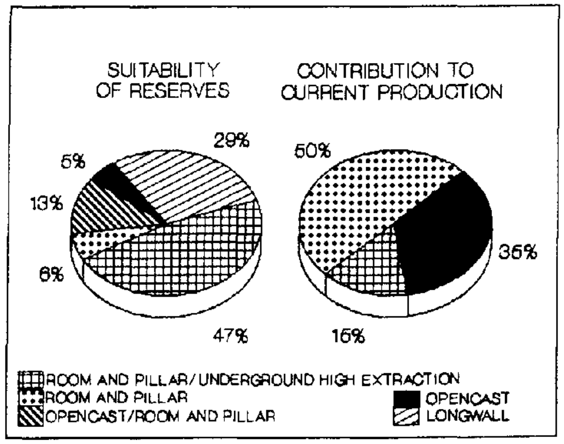

Figure 8: Coal reserves and production in terms of mining methods

Coal mining and the environment

The multi-faceted interaction between coal mining and the environment is particularly accentuated in an area such as the Eastern Transvaal Highveld where extensive mining activities have to co-exist with the development of high-potential agricultural land. Such a situation clearly demonstrates the need for not only close co-operation between all parties concerned, but also for the responsible joint management of the interface by especially the mining and agricultural industries. Strategies and organisational structures to achieve this have been recommended by a recently completed study on the long-term effects of high-recovery coal mining on agriculture in the ETH (Management Committee, Department of Agriculture, 1990).

This study, which was directed by the Government but carried out by a fully representative body of experts from all interest groups, also provided a balanced and objective perspective of the extent of the coal mining/environment interface. It has, for example, been found that opencast mining, which obviously has the most radical influence on the land surface, will in the long term be applied in only 1,6 per cent of the total surface area of the ETH. Seeing that rehabilitation of the disturbed areas takes place as mining progresses, the impact on the environment is temporary and eventually most of the rehabilitated land will revert to agriculture. Tests on rehabilitated land involving a wide variety of pasture cultivars have, for example, showed that yields of 6 to 8 tons of hay per hectare are common under dryland conditions employing high fertilisation.

Underground high-extraction methods such as longwalling and pillar extraction have a less destructive effect on the surface but these effects are more difficult to prevent or rectify. Surface depressions due to subsidence over mined-out panels may lead to waterlogging and salination, particularly in flatlying areas. Experience so far has shown, however, that only 4 per cent of areas undermined by high-extraction methods can no longer be used for the purpose it was suitable for before mining. In view of the fact that these mining methods are expected to be applied in only about 7 per cent of the total surface area of the ETH, the permanent long term effects on the surface are expected to be minimal.

Most coal mines also affect the local groundwater regime and surface water to some extent. In South Africa where water is a scarce and precious commodity, these matters are controlled by strict legislation and a great deal of research has also been conducted on this subject. Further research is, however, required on particularly the long-term effects of mining on the quality of groundwater resources.

In South Africa, the coal mining industry has always displayed a very responsible attitude towards environmental issues by their willingness to initiate and voluntarily implement solutions in this regard. This is in contrast to many coal mining industries in the rest of the world where much of the progress has been achieved by legislative measures.

Coal beneficiation and the environment

Most of the South African run-of-mine coal production needs to undergo some or other form of processing to meet market requirements - if not to decrease the ash content, then at least to obtain the required size range. In this process of upgrading, especially when washing plants are used, a product with highly consistent properities and reduced polluting potential is produced. Unfortunately, and mainly as a result of the generally high inorganic content of the raw coal, large volumes of discards are produced at the same time. The latest available figures indicate that during 1988 39 million tons of discard coal was produced, consisting of 34,5 million tons of coarse and small discards, 3,1 million tons of slurry discards and 1,4 of unsold duff coal (Smit, 1990). It is estimated that more than 500 million tons of discards of varying quality have already accumulated on surface. A forecast of expected future discard production is presented in Fig. 9 and the heat value of currently produced discards in Fig. 10.

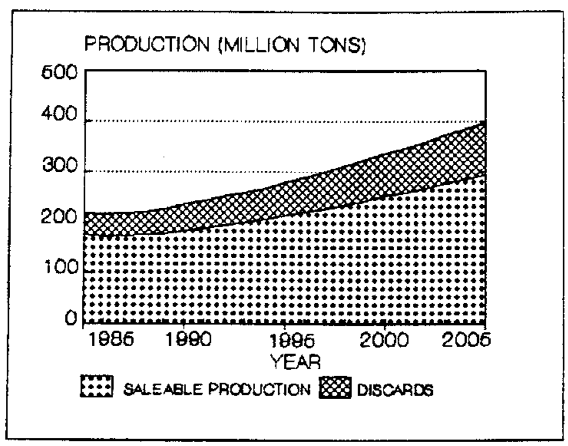

Figure 9: Forecast of run-of-mine and discard coal production

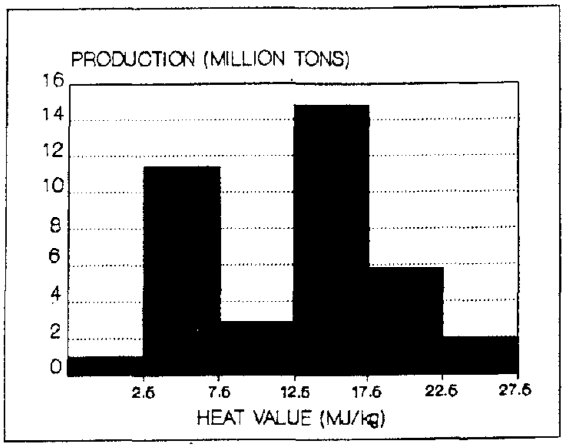

Figure 10: Heat value of currently produced discards

The accumulation of these discards impacts on the environment in basically two ways, namely the occupation of valuable land surface and the potential to pollute both the atmosphere and the groundwater system. Finding appropriate economically viable options to address this challenge is a matter of national priority and forms the subject of a continuous research and development programme. In the meantime the pollution aspect is adequately controlled by compacting and covering discard dumps.

Encouraging progress has been made in addressing the growing challenge of utilising discard coal. Fluidised-bed combustion has already proven to be a promising process for the utilisation of both fine and coarse discards, whilst recently, a low-smoke domestic fuel has successfully been produced utilising discard coal as raw material.

Coal utilisation and the environment

In the ETH, the main coal consumption area in South Africa, substantial amounts of air pollutants exceeding some 125 million tons annually are released. This comprises (in tons per annum) particulates 374 692, sulphur dioxide 1 038 556, nitrogen oxides 355 246, carbon monoxide 339 574, hydrocarbons 276 503, and carbon dioxide 123 605 162.

The air pollution situation in the ETH is exacerbated by the fact that climatic conditions in the area, especially in winter, are very unfavourable for the efficient dispersion of air pollutants (Louw *et al*, 1990; CSIR, 1991). A tall stack policy complemented by various other control measures has so far succeeded in avoiding unacceptably high ambient air pollution concentrations at ground level. This has, however, been achieved at the cost of pollution apparently accumulating in an elevated layer over the ETH, some of which is subsequently being wet and dry deposited with possible deleterious environmental consequences in the medium to long term in and beyond the area in question.

Indications have been found in the ETH of air pollution effects in terms of decreased visibility, corrosion of materials, increased levels of pollution in surface waters and putative foliar injury in adjacent forest plantations. In addition, naturally occurring acidic soils in the area which are not under cultivation might also be effected adversely in the long term.

In view of this situation, various organisations, industries and the government are closely collaborating to monitor the environment in the area so that timeous and appropriate measures can be implemented to mitigate or prevent detrimental environmental impacts. In the interim, more stringent requirements with regard to allowable air pollution emissions have been set by the control authorities for all new coal-based industries in the area as a safeguarding measure. Moreover, it is of late required that such industries which are erected in areas adjacent to the ETH should make provision for retrofitting of appropriate gaseous control equipment should it become necessary.

Because of the environmental constraints existing in the ETH, it is regarded essential that the coal assets are utilised in such a way that the accrued economic advantages can be best used also for coping with the impact on the environment in this and adjacent areas. This would mean that the energy demand is satisfied, whilst maintaining a healthy balance with the requirements of the environment.

The optimum utilisation of coal with minimum attendant effects on the environment is regarded a high priority in South Africa. In this regard a novel process of coal conversion has been developed which yields high-value products with broad application possibilities and which are particularly environmentally benign. Coal-derived product evaluation programmes by multi-disciplinary teams of specialists have already yielded such promising results under laboratory conditions that field trials have been initiated in the areas of agriculture, water purification and mine dump rehabilitation.

A recent investigation has indicated considerable local potential for the extraction of coal-bed methane which has already been established as a viable option in the quest for alternative clean energy sources in countries such as the USA and Australia.

Utilisation of coal in South Africa for electricity generation, synfuels production and other industrial applications yields some 29 million tons of ash per annum. It is estimated that about 350 million tons of ash has already been accumulated on the surface which, besides rendering large land areas useless for other purposes, is aesthetically unacceptable. However, concerted efforts are being made to utilise coal ash for various applications in mining, building, road construction, agriculture and other areas (Kruger, 1990).

FRAMEWORK FOR A POLICY ADDRESSING THE COAL/ENVIRONMENT INTERFACE

Policy priorities

In order to provide for future needs in South Africa and considering the privatised nature of the country's coal industry, the following priorities for a future energy policy have been identified:

- Provision of adequate and consistent energy for economic development.
- Effective and efficient generation, conversion and utilisation of energy.
- The making available of affordable and appropriate forms of energy to the developing sectors of the population.
- Development and application of clean coal and related technologies.
- Utilisation of renewable sources of energy.
- Using a wider spectrum of the available sources by making more use of nuclear power, natural gas and renewables.

The effective implementation of these priorities will not only lead to increased prosperity and quality of life, but will at the same time have a direct and particularly beneficial effect on the environment.

Policy requirements

In the formulation of an appropriate coal/environment policy for South Africa it was regarded as indispensable that the sustainable development of coal, the country's main energy resource, should be stimulated, whilst taking into account the attendant, economic, social and environmental implications (National Energy Council, 1990).

Against this background the following basic requirements were borne in mind:

- Integrating the planning of coal development with environmental conservation and recognising their interdependence and interaction.

- Providing for changing needs and circumstances, thereby retaining flexibility.

- Implementing a pro-active policy to be able to take preventative and timeous action.

- Establishing a scientifically based pool of information for continuous use as a basis for responsible and appropriate policy formulation and decision making.

- Educating the broad community to recognise the interdependence between development and conservation, as well as consulting with this community in an early stage of development to address their needs and interests as far as practicable.

Integration of coal and environmental strategies

Considering then the practical challenges already outlined and the above requirements that recognise the importance of both coal development and conservation of the environment, a number of strategies have been formulated that are regarded as appropriate to effect a synergism of coal and the environment. These strategies are briefly outlined below:

Development of appropriate and clean technologies for the mining, beneficiation and utilisation of coal

The development of improved technologies that make the optimal and cost-effective mining, beneficiation and utilisation of all qualities of coal possible, and that at the same time will have a positive impact on the environment. A few examples are the following:

- Safe and maximum extraction of coal reserves with minimum attendant affects on the environment.

- Improved coal beneficiation for obtaining products with a low environmental pollution impact.

- Clean coal combustion and post-combustion technologies.

- Clean coal conversion producing high value products with a wide scope of application.

- Appropriate technologies for promoting the multi-product concept of coal utilisation which endeavours to achieve total utilisation of mined coal.

The promotion of energy efficiency and conservation

The development of technologies for the effective provision and utilisation of energy, as well as the encouragement of energy conservation, which would at the same time result in less emission of pollutants into the environment. Examples are as follows:

- Power stations with more efficient generating technologies

- Co-generation based on the use of a single source of energy to supply both electricity and heat.

- Household appliances and industrial equipment that are more energy efficient than the present ones.

- Building design that is focused on energy conservation.

- Recycling of waste material such as paper, glass, aluminium and steel whereby considerable energy savings can be achieved, as well as the re-refining of used mineral oil, thus avoiding the pollution of groundwater in particular.

Here, it is worthwile noting that a research and development programme has produced sufficient information for the development of a draft national energy efficiency strategy which can be implemented at a controlled rate because of the present surplus in energy supply capacity in South Africa. Besides being economically sound, this strategy would result in reducing emissions of pollutants into the environment.

The development of new and renewable sources of energy that are economical, socially acceptable and friendly to the environment

Because of the fact that network electricity and coal is not readily accessible and affordable to all developing communities, particularly those located in the outer-rural areas of South Africa, an appropriate strategy has been developed for such communities. This entails the provision of appropriate and adequate energy from a balanced least-cost mix of available energy resources in order to satisfy basic community needs and to contribute to the improvement of quality of life.

The ongoing assessment of changes and developments that may influence the coal energy sector and the environment in future.

Scenarios are developed and mathematical models used to help identify future policy priorities regarding more effective, and therefore also cleaner coal related energy.

Promotion of the guidance and education of the broad community

Energy guidance programmes are implemented that are aimed at particular target groups and educational programmes on energy are being developed that are aimed at primary, secondary and tertiary levels.

The strategies oulined above are being implemented on a continuous basis. This is achieved by initiating and supporting appropriate research and development projects in close collaboration with the private sector on the basis of information obtained by monitoring national and international developments.

CONCLUSION

In the final analysis it is firmly believed that the ultimate solution to effectively manage the interface between coal and the environment does not lie only in well intended political motives, nor for that matter in legislation. These have a role to play of course, but ultimately the achievement of a real and lasting solution will depend on only two criteria, namely -

- the extent to which science and technology can be successfully applied as tools for generating wealth and increasing living standards; and following from that

- the degree of responsibility, co-operation and goodwill that can be fostered amongst all institutions and individuals involved in managing the interface between energy and the environment.

By using these two criteria as a yardstick, and building on the successes of which some examples have been given in this paper, coal and the environment will certainly be able to co-exist in harmony for many more years to come.

The vision of converting coal to quality of life is indeed an attainable goal.

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Environmental Aspects of Underground Mining Operations

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ABSTRACT

The dramatic improvements in productivity achieved in the UK in recent years would not have been possible without attention to the underground environment. The Health and Safety of the workforce has remained a top priority of British Coal's strategy.

This paper covers recent developments and evaluations carried out within British Coal, that have and will contribute to improved Health and Safety in the fields of explosions, fires, dust and noise. The key to success is the use of appropriate technology.

Methane is not only a hazard in the underground environment, methane emissions also have a detrimental impact on the global environment. Opportunities for utilisation bring both economic and environmental benefits. New and conventional methods of methane drainage in the UK are explained; and utilisation schemes involving sale of gas and electricity generation are described.

1. INTRODUCTION

In 1990 around 70% of electricity in the UK was generated from coal, accounting for some 82.5 million tonnes. These figures are little changed over the last five years. Over the same period, changes in British Coal's face production and productivity have been far more significant. Daily output per face has increased by 60%, from 1067 tonnes to 1697 tonnes, while productivity has gone up from 3.29 OMS to 4.7 OMS; an increase of over 40%. The number of production faces has decreased over the same period: from 305 to 155. Such dramatic changes in rates of production can only be achieved by dealing with the associated effects on underground environmental conditions.

Progress has been made at all levels:

(i) education and training;

(ii) better practise of proven techniques;

(iii) application of known engineering principles in novel circumstance;

(iv) adoption of techniques that have proved successful outside the UK;

(v) major research efforts.

Experience has shown that significant results have been achieved by the use of appropriate technology.

In addition, the effect on the surface environment of deep mining must be taken into account. As stated in the previous paper there is increasing public concern about methane emissions. This paper will examine some of British Coal's schemes to utilise the methane gas extracted from the mine and the steps taken to reduce the hazards due to methane below ground.

Not only must the environmental impact of deep mining be minimised, but it would not be acceptable to pay a higher human cost for higher productivity. British Coal's safety record has improved steadily since the industry was nationalised in 1947, and the Health and Safety of the workforce remains a top priority of the Corporation's strategy.

Effort is currently being concentrated on reducing the already small numbers of underground fires, and some of the work in this field is described. Achievements in dust control, and initiatives to meet new noise regulations are also included for completeness.

In essence, this paper illustrates British Coal's commitment to the Health and Safety of the workforce, together with continuing efforts to lessen the impact of production of coal on the world environment.

2. EXPLOSIONS

Explosion is one of the most feared hazards underground. In addition to the use of approved apparatus in hazardous areas, British Coal's approach to the risk of explosion is to:

(i) monitor methane concentrations throughout the mine,

(ii) maintain good continuous ventilation;

(iii) reduce methane emissions by use of effective drainage;

(iv) avoid potential co-incidence of factors which cause frictional ignitions; and

(v) take steps to reduce the effects of an event by the installation of barriers.

Taking these in reverse order:

2.1 Barriers

Stone dust explosion barriers, used in UK mines until the late 1980s, have been largely replaced with distributed water barriers. These barriers, developed in continental Europe, have advantages in maintenance, effectiveness and cost. Installation of passive barriers on a fast advancing face presents problems. A Belgian triggered water barrier is under evaluation for use in British mines in such situations (CEC 1990).

2.2 Frictional Ignition

The statutory limit in the UK for removing power from electrical apparatus (other than approved equipment which is permitted to remain energised) is when the concentration of methane exceeds 1.25% by volume in the general body of the air. Following the explosion at Cardowan Colliery in 1982, caused by a plug of methane ignited by frictional sparking, it was recommended that where there is a known potential of frictional sparking from the cutting machinery, power must be tripped automatically if methane is detected local to the equipment. *Cardowan protection* is now always installed where rocks with a high incendive temperature potential are being cut.

The danger of frictional ignition on the coal face has been reduced by the introduction of the extraction drum. The extraction drum is the first system successfully to reduce the risk of ignitions at the shearer and control dust levels.

A number of dust capture tubes are fitted within the central hub of a standard cutting drum. These comprise high pressure water sprays directed into the inlet of 100 mm diameter, open-ended tubes. They extract typically 1.6 m^3/s of dusty air at the face side, remove the dust from it, and expell the cleaned air from an annular gap at the other side of the drum. Here, a deflector plate turns the water spray and a proportion of the exhaust air back into the drum. At least 0.5 m^3/sec of fresh air is also drawn down into the cutting zone, thus diluting the methane out of the explosive range and preventing frictional ignitions.

British Coal has, this year, received the Queen's Award for Technological Achievement for this development.

2.3 Methane Monitoring and Ventilation

Continuous monitoring of methane (and other environmental parameters) is practised throughout British Coal using British Coal's standard MINOS monitoring and control system. MINOS is a surface computer system, providing the colliery control room with automatic control of plant, real time monitored displays and alarms on underground operations and environment. In addition, real time information is available to engineers and management using PCs connected to the colliery network. Easy access to monitoring and data analysis for ventilation enables mechanical, electrical and mining engineers to use their expertise to identify and prevent problems.

The underground data transmission equipment used for data collection for MINOS is intrinsically safe, and, in the case of environmental monitoring, normally powered from a battery-backed power supply. The data transmission system is approved to remain energised in concentrations of methane greater than 1.25% by volume, so that monitoring can continue throughout a hazardous occurrence. Methane concentration is measured using pellistor-based instruments. There are some 2500 fixed methanometers in use in British Coal at the present time. Maintenance of these instruments, which need frequent recalibration, requires considerable effort. Research into intrinsically safe methanometers using optical techniques is underway.

Methane concentration is dependent on the flow of air in a roadway or heading. Headings are particularly susceptable to high concentrations of methane, and the number of men permitted to work in such a situation where there is only one exit is limited by law. Should the auxiliary fan ventilating the heading stop, high concentrations of methane can quickly result.

In such a situation, regulations required that the fan be started by manual intervention. A recent initiative has introduced the automatic restarting of some auxiliary fans under carefully monitored conditions.

Automatic restarting is permitted after a short time interruption; or based on monitored environmental conditions; or both. Local controllers implement the restart, with full monitoring at the surface. An initial trial has proved successful and is now being applied at selected sites throughout British Coal. Automatic, or remote, restarting of auxiliary fans can maintain effective continuity of ventilation and, hence, significantly improve the possibility of avoiding a degassing operation. It can also reduce the likelihood of a plug of gas being propagated outside the heading. The technique has been extended to underground booster fans and surface fans and should avoid loss of production as well as improving safety. This change from the traditional manual restart was proposed as a result of an investigation of the causes of an explosion. It employs well established monitoring and control techniques.

2.4 Methane Drainage

In a gassy coal mine, emissions of methane have to be further controlled by the use of methane drainage techniques. Using boreholes drilled normal to the roadways, the gas is captured before it can enter the district. Methane emission increases with coal production, and can be the limiting factor on production rates. At Harworth Colliery, boreholes are drilled 55 m into the roof every 10 m and 46 m into the floor every 25 m. This drains 1000 litres/sec from the district and maintains the methane concentration in the roadway at less than 1.25%. Control over the drainage is by means of a fully automatic extraction plant using the required combination of eight available pumps. At the Trentham Complex, underground pumps are used in addition to those at the surface. By increasing suction, problems of high methane in underground roadways due to surface barometric pressure drops are avoided. Comprehensive environmental monitoring installed at Trentham, using the MINOS system, provides the ventilation engineer with a real time display of the entire drainage system and underground roadway conditions. Automatic alarm annunciation brings problems immediately to the attention of control room staff. Data is stored on the colliery information system for longer term analysis.

Conventional methods of methane drainage are widely applied in British Coal, although they are less effective on retreat working than on advance faces.

An ECSC-supported research project aims to carry out trials of three novel methods of methane drainage in the near future which could enable methane to be effectively drained for retreat panels and provide high purity gas suitable for utilisation:

(a) The first of these involves draining a virgin seam through a surface borehole prior to mining, using hydro-fracture to improve gas flow. This technique has proved very successful in America.

(b) The second is the use of gob wells to drain methane to the surface from destressed ground, prior to further extraction.

(c) The final method applies the guided long hole drilling technique, which has proved very successful in exploration, to drill horizontal holes in a seam above the panel to be mined by retreat working.

In each case it is anticipated that the gas drained will be of consistent high purity and, hence, be of potential use as a fuel. If successful, these methods will lead to a safer underground environment and dispose of methane by a means which is better for the global environment and which gives some economic return for the colliery.

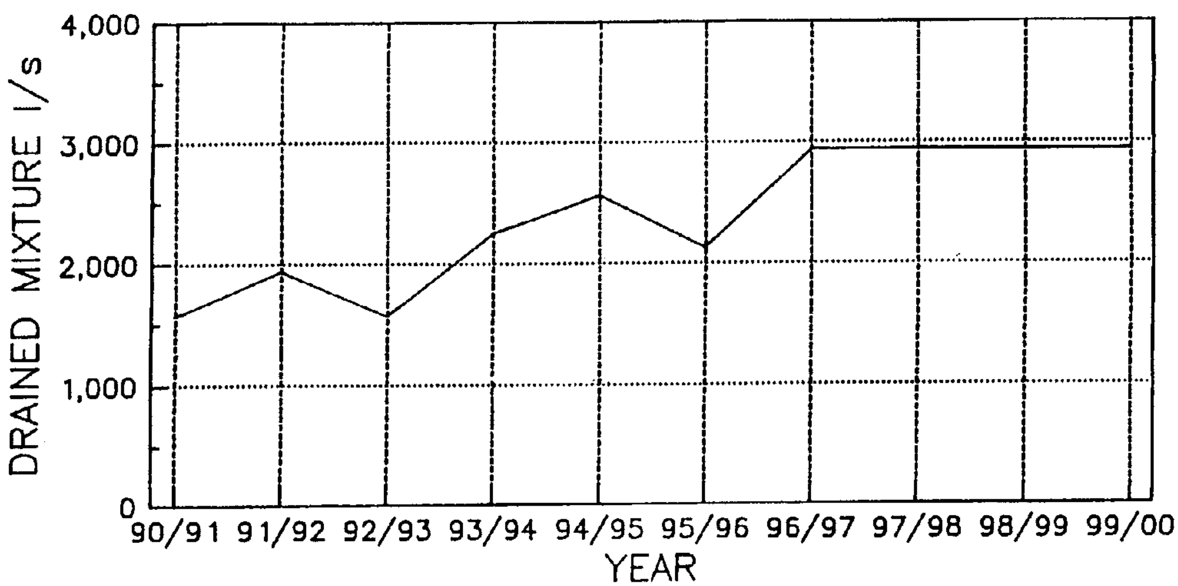
2.5 Methane: Utilisation

Although the prime purpose of methane drainage is to protect the underground environment, the high purity methane is itself a valuable source of energy. There is a long history of using such methane for fuel in colliery boilers, generators, etc. The concentration of production at fewer higher output mines; the recognition that methane released into the atmosphere is a harmful greenhouse gas; and the drive to increase revenue has led British Coal to re-examine the potential for methane utilisation. Two examples of methane utilisation are:

(a) Trentham Colliery, in conjunction with others in Staffordshire, sells the gas from the methane drainage system over a grid to large industrial users. As with all methane utilisation schemes, the difficulty is matching supply and demand. An enrichment plant is used at Trentham to ensure consistency of supply. Figure 1 illustrates the anticipated supply of gas from the Trentham Complex over the next 10 years. Fluctuations due to face changes and variation in production rates cannot be avoided. Short term fluctuations to protect the underground environment during a barometric pressure drop are also necessary, and on occasions result in gas of too low a purity for use on the surface. Despite these problems, the Staffordshire gas grid generates some £1.2 million revenue from gas sales, the majority of which goes to Trentham.

(b) Harworth Colliery has been chosen as the site for a 15 MW power generation scheme. A novel combined cycle plant has been ordered and should be in operation within two years. It is planned to satisfy Harworth's own electricity demand and to export up to 10 MW to the National Grid by taking advantage of the new, freer market for electricity supply in the UK brought about by the transfer of electricity generation from the public to private sector.

A generating plant of this size requires a constant supply of fuel of consistent purity. This places additional constraints on the control of the methane drainage at the mine, where the protection of the underground environment must remain paramount. Harworth has shown that by careful installation and monitoring of the



ASSSUMES DISTRICTS DRAINED AT 50%
25% RELAXATION FOR STOPPINGS & SALVAGE ETC

Figure 1
Trentham Colliery – Predicted Methane Mixture Drained to Hem Heath 1990 to 2000

methane drainage these conflicting requirements can be met, although every change of production face alters the methane quantities available for utilisation.

Research is currently taking place on techniques to improve the control algorithms for methane extraction plant to optimise the constant purity of the output while maintaining safety underground.

A number of other schemes for methane utilisation at UK mines are under active consideration; in each case a detailed study of past and future production is analysed, against the colliery's own energy needs. Capital costs are then established for the various types of equipment which could be used to burn the predicted gas quantities, and the potential market analysed. It is vital that the selected scheme takes all these factors into account, and provides added value to the colliery while disposing of methane in an energy efficient manner that reduces environmental damage.

Any plant generating electricity from fossil fuels for supply through the National Grid in the UK has to pay a 10.6% *Nuclear Levy* - this contrasts with the situation in the USA where tax incentives are given to encourage the use of captured methane.

3. FIRES

There is a very strict definition of underground fire in the UK. A reportable incident of fire in the UK is defined as:

The outbreak of any fire below ground.

OR

An incident where any person in consequence of any smoke or any other indication that a fire may have broken out below ground has been caused to leave any place pursuant to Regulation 11 (1) of the Coal and Other Mines (Fire and Rescue) Regulations 1956 or Section 79 of the Mines and Quarries Act 1954.

OR

The outbreak of any fire on the surface endangering the operation of any winding or haulage apparatus.

TABLE 1 UNDERGROUND FIRES 1987 -1991

	87/88	*88/89*	*89/90*	*90/91*
Fires	56	41	46	54
Suspected Fires	14	9	13	5
Total	**70**	**50**	**59**	**59**

The Health and Safety Mines Inspectorate deem that a fire has broken out if there is any sign of a flame or if any incandescent material at all is present. The number of underground fires and suspected fires over the last four years is shown in Table 1, with a breakdown of causes in Figure 2. Although the total number of fires is low, efforts continue to reduce the number further. It can be seen that, of the reasons attributed to fires, conveyor related fires form a significant proportion.

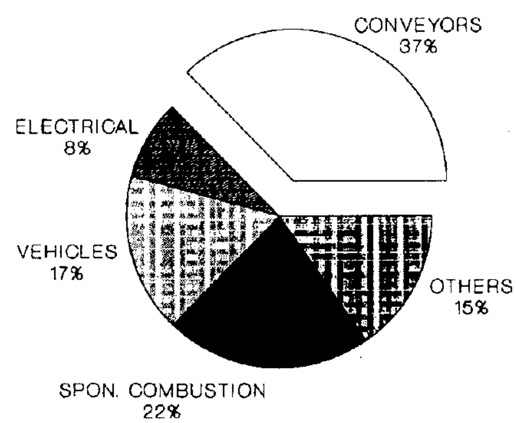


Figure 2
Causes of Fire – 1990/91

British Coal is participating in a tripartate working group with the Mines Inspectorate and Health and Safety Unions aimed at further reducing underground fires.

3.1 Monitoring

In addition to statutory inspections, comprehensive automatic monitoring for outbreak, or potential causes, of fires is undertaken. In addition to carbon monoxide detectors, the sensitive FIDESCO instrument is used to detect products of combustion, giving early warning of a possible fire. Remotely-controlled conveyors are monitored for faults which may be indicative of fire, such as slip, bearing overheat and smoke.

A new infrared detector has been developed to identify faulty conveyor rollers. This device is activated following a short stoppage on the belt when heat from a faulty roller is transferred into the belt, causing a *hot spot*. When the belt starts, the speed of the belt is measured, and the location of the *hot spot* passing over the detector heads can be identified to the exact roller. The information is displayed locally, and can be transmitted to the MINOS system in the surface control room. Twelve such devices are in use on the main spine conveyor at the Selby Mine Complex. The belt is over 12 km long and travels at a maximum speed of 8.4 m/sec. Identification of faulty rollers is very important for avoiding conveyor fires, and difficult to achieve by simple inspection. Gascoigne Wood, part of the Selby Complex, aims to predict roller failures from careful study of current results, although the behaviour of the rollers suggests that this may not be possible to achieve.

3.2 Control Room Alarms

As monitoring has increased, a typical colliery control room may have several thousand measurements available for examination. Within British Coal, the majority of this information is provided by a pair of MINOS systems, with production control normally separated from environmental safety monitoring. This volume of information has led to the need for a prioritised alarm handling facility within the MINOS system. Colour and sound are used to differentiate between alarm priorities and highlights any dangerous situation, such as a fire. It has proved to be of great assistance to the control room operator. The start of the alarm condition and the time of acknowledgement is recorded.

This system is already in use at over forty collieries in the UK and will shortly be installed at all long life mines.

Additional computer analysis of carbon monoxide readings is carried out at a number of collieries to give early warning of spontaneous combustion. This technique is known as Multi Discriminating Alarm (MDA), and provides warning of the underlying problems that may well be masked by variations due to everyday mining operations such as firing of shots, diesel-powered vehicles, or falls in barometric pressure (Hunneyball 1988). Further development is aimed at reducing spurious alarms and identifying the cause rather than the effect. Carefully applied computer technology can improve the effectiveness of the control room and hence be a powerful tool for mine safety.

4. DUST

No paper on safety and the underground environment would be complete without reference to the achievements in the field of dust control. British Coal's programme has been based primarily on eliminating the causes of airborne dust in mines. Average dust concentration on the coal face has been reduced from nearly 6 mg/m^3 in 1970 to just over 3 mg/m^3 today. Dust sanctions on faces have reduced by 75% in the last five years.

The most recent innovation in dust control is the extraction drum, already mentioned for its effect on reducing frictional ignitions. Exploitation has increased steadily in the late 1980s and it is now installed at 57% of UK collieries.

In the field of personal protection a compact integrated environmental helmet is being developed to combine dust, noise and eye protection in a streamlined, comfortable unit.

5. NOISE

Since the availability of intrinsically safe instrumentation for use underground, extensive and detailed studies of noise from mining machinery have been undertaken for subsequent reduction of workers' noise exposure. This has enabled British Coal to evolve a rigorous and practical noise policy based on the identification of sound pressure level zones (Broughton and Bennett, 1990).

Emphasis is placed on the control of noise at source, principally by modified machine design and the planning of equipment layout.

The key areas of hearing protection and education and training, have also been addressed. A range of helmet-mounted earmuffs are now mandatory for hazardous working environments. Education of the workforce is undertaken by a combined approach of courses, promotional material, including videos and press articles, safety competitions and issue of noise handbooks to individuals.

6. CONCLUSION

Coal is already the largest source of electricity generation in the UK, and has the merit of secure home supply. Continued attention must be given to environmental issues, in both the underground environment and the world atmospheric environment to meet public expectation of an economic, *green* fuel.

British Coal aims to continue with improvements in productivity together with reduced environmental impact through methane utilisation. These aims are entirely consistent with continued improvements in the Health and Safety of the workforce and can best be achieved by the application of appropriate technology

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Reduction and Disposal of Dirt from Underground Mining Operations

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SUMMARY

It is an inevitable consequence of mining that dirt is produced and requires disposal. Even in-seam mining produces dirt, and unless the run-of-mine (ROM) product can be sold directly, the resulting coal preparation will result in a waste product. Dirt reduction begins at the point of production. In-seam drivages supported by roofbolts minimise dirt production during face development. On longwall faces, the use of vertical steering not only results in higher productivity but also in a higher quality ROM. Nucleonic monitors can be used both underground and on the surface. Their use underground permits the early identification of dirt problems whilst on the surface they can be used for control of the coal preparation process. The cheapest option for disposal remains surface tipping, but recent research has opened up new possibilities for environmentally acceptable disposal. It is possible that these techniques can be extended to disposal underground in the goaf area. The paper describes British Coal's work in these topics.

1. INTRODUCTION

The global environmental impact of coal utilisation is well known and need not be repeated here. Suffice to say that there is a premium on the production of high quality coal. The surface environmental impact of deep mining includes:

¤ dirt disposal

¤ subsidence

¤ methane emission.

British Coal's largest customer is the UK's Electricity Supply Industry (ESI). The privatisation of the ESI has exerted great commercial pressure on the coal industry. There is a need to supply the ESI a product at the quality desired and at competitive prices. In particular consistency of product is vital; nett calorific value must be within narrow well-defined limits. Ash (or dirt), moisture, sulphur and chlorine content are all important.

An inevitable consequence of deep coal mine operations is that waste material, or dirt, is produced as a by-product of both mining and beneficiation. Each year British Coal has to dispose of about 40 million tonnes of dirt. The principal sources are the coal seam (which is never dirt free), bands, faults, inadvertent cutting of roof and floor, and roadway development. Mine waste disposal on surface tips within the colliery curtilage costs between £0.50 and £2.00 per tonne, whilst off-site disposal costs can be considerably higher. The environmental pressures against surface tipping continue to mount and, in a densely populated country like the UK, have become of the utmost importance in seeking planning consent for both continuing and new mines.

In this paper we will deal with the topics of quality and dirt disposal (and, by implication, subsidence). A companion paper will tackle the methane problem.

Clearly the best means of minimising environmental impact is to avoid the problem in the first place. A few years ago, virtually all of British Coal's roadways were of the arched support type. Such design naturally gave rise to considerable production of dirt. Now there has been a substantial switch to in-seam, roof-bolted drivage. Although the *raison d'etre* for this change was the requirement of faster development and lower costs, a spin-off benefit has been reduced dirt.

On the coalface itself, British Coal has persevered for many years with the development of shearer guidance systems. The intention is to steer the coal cutting machine to a predetermined path within the coal seam thus giving benefit in productivity and reduction in dirt. Steering systems are now available from three manufacturers and significant benefit has been derived. However, their use is not universal and not without problems. Perhaps these systems should be regarded as first generation. The next section of this paper describes this work, the benefits, and points the way to the future.

There is no question that steering has greatly improved the quality of the mined product. This run-of-mine (ROM) material flows into the conveyor transport system. Clearly at the outbye end of the mine belts there is a requirement to measure the quality of the product on the belt. This information is used for decision making and control purposes in identifying which material should be dumped, which washed, or even utilised without beneficiation. The required information is provided by the natural gamma coal quality monitor which is the subject of the second major section of the paper. Essentially this device provides a means of quality control.

In spite of these efforts a large quantity of dirt is produced which must be disposed. The last section of the paper reviews the progress that has been made to develop stable slurries from tailings and crushed mine waste, capable of being pumped long distances and stabilised on discharge. The current programme is directed towards disposal at an abandoned quarry, but underground discharge is also possible, as demonstrated by German work. Disposal in the goaf, or gob, of a longwall face helps to alleviate subsidence.

In summary, this paper demonstrates some of the steps that are being taken to mitigate the environmental impact of underground coal mining.

2. MACHINE STEERING

Machine steering is a means of automatically controlling the vertical position and height of the extracted section within a coal seam to values specified by management. A set of sensors provides measurements of variable parameters, which enable the system processor to position the shearer and drum relative to the coal seam and determine the required control actions. If the vertical position, or height, of the extracted section within the seam has to be changed, then the steering system will do this in a controlled manner, ensuring that the advancing face equipment will negotiate the changing horizon without disruption of the mining process.

The successful commercial exploitation of steering has demonstrated that the main benefit is that of reducing the amount of dirt mined. The following are examples of this benefit:

(a) In January 1987, seven coalfaces in the UK were using automatic guidance. For analysis purposes these can be split into categories determined by extracted height; advance or retreat; heavy duty, or non-heavy duty, equipment. The production rates for each of these faces was then compared with the national average for coalfaces in similar categories which used manually steered shearers. The results showed an average of 20% increased production rates on the coalface which employed machine guidance.

(b) In May 1989, a comparison was carried out at Riccall Colliery in the Selby Coalfield. On the face employing the steering system a 54% increase in production rates was shown along with an 8% reduction in the amount of dirt mined. On increased production alone the initial investment in the MIDAS equipment was repaid in four days.

(c) At Whitemoor Colliery in the Selby Coalfield the application of machine guidance to H01s coalface led to dirt being reduced from 41% of the total output to 12%.

(d) On Silverwood S21s the sulphur content of the product had to be reduced in order to retain a lucrative contract to supply the Atlas steelworks. The problem was high sulphur bands in the lower measures of the seam. Automatic steering was installed on the coalface and adjusted to avoid taking the high sulphur bands, thus supplying a product to the customer's specification and enabling the colliery to keep the contract.

Other less tangible benefits include reduced fluctuations in consumed power, less wear and tear on equipment leading to reduced maintenance costs of the principal equipment, and improved roof control. It must be emphasised, however, that the steering system must be properly maintained if these benefits are to be realised.

Management also benefits from the information provided by the surface terminal. In the UK it is used by managers to:

(i) assess the performance of the machine;

(ii) assess the performance of the guidance system;

(iii) improve the efficiency of the production operation since accurate, unbiased information is reliably provided.

Engineers also benefit since faults on the machine can be more quickly identified by examining the information at the surface than by examining the machine underground.

Unfortunately steering in its current form is not universally applicable. Although the roof and floor cut control systems can be applied to any conveyor-mounted ranging drum shearer, their use is restricted to an estimated 50% of current coalfaces for reasons associated with the measurement of roof coal thickness and roof step. At present current technology cannot be used on coalfaces where:

¤ The desired roof coal thickness exceeds 450 mm, or is less than 25 mm, or where there is sandstone roof strata, since this affects the accuracy of roof coal thickness measurement;

¤ The roof coal continually falls away,

exposing intermediate layers of the roof strata;

¤ The clearance between chock support and the coalface is less than 250 mm, since roof coal and roof step measurements are made in this area.

It should be noted that some sandstones may be sufficiently gamma active to permit steering with about 100 mm roof coal.

The design of suitable roof followers to measure roof step prevents the use of steering on certain machines. Guidelines are that steering cannot be used on machines with a drum diameter of less than 1.3 m, or on single pass DERDS for extractions greater than 2.5 m. Machine and face design play an important part in fixing these limits and, hence, they may vary slightly.

Current development work is aimed at making steering technology suitable for wider exploitation by increasing its application range and making the control system more adaptable. For example, methods of control suitable for use on faces where there is no need to leave roof coal are being investigated. Other control techniques currently under development will:

(a) Avoid the need for the current roof follower system.

(b) Allow automatic control to be used on short lengths of face where the roof coal has fallen, or the roof is broken.

(c) Enable a gradual progression from a widely varying extraction to the desired extraction by preventing large steps being made in the floor.

(d) Allow the desired values of extraction and roof coal thickness to be varied along the face in a predetermined manner. This will enable the system to follow variations in seam thickness or, for example, leave thicker coal at the face ends.

(e) Enable the control system to cope with variations of seam gradient along the face.

(f) Remove the 2.5 m upper extraction limit at present imposed on a single pass DERDS.

It has become clear that in order to meet British Coal's future automation and monitoring needs, machine mounted, intrinsically safe computers are going to be needed for a variety of applications. To meet these requirements MACE (Multi-purpose Automatic Control Equipment), a powerful general-purpose computer suitable for use on mobile machines, is being developed. The flexible MACE design allows it to be adapted to suit a wide range of applications, so removing the need for specifically designed intelligent units. This approach will prevent duplication of effort and lead to reduced development times and costs. The initial applications of MACE will be for shearer automatic steering.

In conclusion, automatic steering

(i) minimises the dirt cut, improves productivity and product quality;

(ii) provides extraction control while optimising coal production; and

(iii) provides better strata control with an associated reduction in machine downtime and maintenance costs.

3. PRODUCT QUALITY

The advent of automated steering of the coal cutting machine has enabled British Coal to improve the quality of ROM coal, but significant quantities of dirt are still extracted. The ROM coal is rarely suitable for selling directly to the customer and coal preparation plants process the ROM into a saleable product. For electricity generation, this product is usually obtained by blending washed coal with a proportion of untreated coal to achieve the target specifications.

The electricity supply industry, British Coal's most significant customer, is requiring increasingly tight specifications for the quality and consistency of the product. Moreover, the pricing for the saleable output is now based on the nett calorific value of the fuel with additional penalties for inconsistencies in ash and moisture.

Faced with this challenge, British Coal have developed, and are in the process of extending, a range of on-line ash and moisture monitors. A *Quality Management System* has also been developed. This will help collieries plan and maintain their strategies to meet the required customer specifications.

3.1 The Natural Gamma Coal Quality Monitor

British Coal has been able to exploit the useful fact that the mudstones and shales surrounding the coal seam contain significantly higher concentrations of radioactive elements than the coal seam itself. For a given weight of mined material the level of gamma activity increases linearly with ash content. The Natural Gamma Coal Quality Monitor (NGCQM) calculates the ash content from the simultaneous measurement of the natural gamma radiation emitted by the conveyed material and the mass of that material. In circumstances where the mass loading is constant, such as on a feeder, it is possible to dispense with the mass signal. As the natural gamma detector has been certified Intrinsically Safe the system can be used on underground feeders. The data from these systems are relayed to the surface for display and storage purposes through the colliery data transmission system. The surface systems all have a control/display unit which combines the gamma and mass signals to provide the ash estimate. It also has comprehensive display and data storage facilities.

Eleven systems have been located on the underground bunker outfeeds from the satellite mines in the Selby complex. The information from each of these monitors is used to calculate the contribution to the saleable output of the complex from each individual mine. In so doing the source of poor material can be identified and measures can be taken to improve the quality.

The increased significance of quality and consistency of the final product has led to a significant demand for a final product monitor. Recent trials at Kellingley Colliery have shown that the NGCQM can be used to good effect in this situation. The NGCQM has been installed on the final product belt and a continuous display of instantaneous ash and cumulative shift ash is available to the coal preparation plant operators. Armed with this information the operators are now able to control the blending process to a much finer degree. The standard deviations of the average shift ash taken over three-monthly periods before and after the installation of the NGCQM show a reduction of about 30%. Perhaps more importantly, the range of minimum to maximum ash values shows a reduction of over 50%.

As of April 1991, a total of 25 NGCQMs are in operation throughout British Coal.

3.2 Ram-feed Ash and Moisture Monitor

An ash monitor, designed some years ago, using low energy backscatter techniques has been in operation on substreams of final product coal at a number of British Coal collieries. This device, known as the AERE Phase 3a, is automatically fed with a crushed sample of coal which is profiled on a rotating table. The sample on the table is irradiated by a Plutonium 238 source and the level of back-scattered energy gives a measure of ash content. These systems did not achieve universal approval because moist fine coal often caused handleability problems.

In order to assist with the handling of this difficult material and to ensure a positive flow through a compaction system, a horizontal reciprocating ram has been developed. This ram is used to displace the material from the bottom of a collecting hopper through a compaction zone and along an open topped trough. The material maintains a constant profile while being transported along the length of the trough thus providing the necessary geometry for the backscatter measuring head. This geometry is also appropriate for a microwave moisture measuring system. Such a system is in the final stages of development using *C* band attenuation.

The ram-feed presentation system enables the simultaneous measurement of ash and moisture to be made thus allowing an estimate of calorific value to be made.

3.3 Quality Management System

Quality management is more than just a measurement of quality, or the control of ash, or moisture. It is the ability to make strategic choices to achieve the quality requirements of the customer over a consignment or an accounting period. To present these choices to plant management, British Coal have developed the Quality Management System, QMS. The system maintains data from all sources:

(a) Central laboratory data – this is the most accurate sample data set, but supplied to the colliery up to a week after the sample has been taken.

(b) Plant laboratory data – this is less accurate but usually presented one shift after samples have been taken. In certain critical cases data can be supplied hourly.

(c) Transducer data – NGCQM and Ram-feed readings of blend ash and/or moisture are usually available in minutes. Weighbridge data and information from beltweighers are also important in weighting quality measurements over a period.

The QMS keeps a database of all values in order to make estimates of current performance and to model the strategic choices open to the plant manager. Underlying trends are calculated using a fitting algorithm, and this has proved invaluable in making accurate estimates a priori. A set of spreadsheet models can be used to calculate the best ratio of blending washed coal and untreated coal to achieve optimum ash, moisture, total inerts, price, nett CV, etc. These models can be augmented for different collieries with, or without, blending; or indeed for other industries. A plant-specific set of models is created for each plant to reflect the individual circumstances. The present set of validated models is growing into a library of techniques that can form the basis of special requirements. Quality control charts give the manager sight of the underlying trends and provide guidance on plant operating parameter changes that may be necessary.

British Coal has actively sought to meet the tight specifications required by its customers by developing and then using a range of monitoring systems. The NGCQM has already improved the product quality at a number of collieries. The increasing use of this device should result in further improvements for British Coal. The provision of the ram-feed ash and moisture monitor should extend the scope for increased product quality. It is envisaged that the QMS system will maximise the benefit from all these monitors and provide colliery management with fingertip control over their product quality.

4. DIRT DISPOSAL

Following much research into the subject, the science of tip construction is now well understood. Spoil heaps are constructed in such a way that they are stable and can be landscaped upon completion, or made suitable for building development. In many cases however, capacity for mine waste disposal within the colliery boundary is limited and mine operators are being forced to find alternative means of disposal. Ultimately, if the colliery is to continue in operation, this means transporting the dirt off site to an alternative disposal point. Objections are frequently raised to the use of heavy road transport on local roads.

A solution to these problems is the hydraulic transportation of dirt in the form of a semi-stable slurry. The system has applications in the overland transport of dirt to off-site disposal points and for disposal by underground stowing behind active coal faces and in disused roadways. This latter application carries additional benefits of increased underground stability and reduced surface subsidence.

Semi-stable slurry transportation techniques have been used by British Coal in the down-shaft pump packing system and are also being exploited in Germany in their underground waste disposal research.

For the dirt disposal application, the slurry must possess a number of characteristics similar to the pump packing slurry, namely:

(a) It must be stable, with the solids remaining in suspension over a long period.

(b) It must be free flowing to aid pump cylinder charging and facilitate placing at the disposal point.

(c) Friction losses must be low in order to minimise the pressure gradient in the pipeline and to maximise the pumping range.

The slurry must have two additional characteristics necessary for this application:

(d) The slurry must have the highest solids content possible consistent with good pumping properties in order to maximise the system throughput and minimise any water problems at the disposal point.

(e) It must be inexpensive to produce, precluding, where possible, the use of additives to aid pumping.

To meet the first of these two criteria, reference was made back to the grading curves established during the pump packing development.

For the second criteria, however, it was obvious that the use of a bentonite-based carrier fluid, or any other bought-in component, would be too costly given the quantities involved. The mine waste comprises coarse dirt and flotation tailings. The most logical step, therefore, was to see if the froth flotation tailings could fulfil the role of carrier fluid. Tailings are available in different forms within a coal preparation plant, the most suitable for this purpose being that of underflow from a thickener. From laboratory tests, a slurry with a 77% solids content and a 20 mm maximum particle size was selected for full scale pumping trials. These tests established the relationship between pressure gradient, flow rate and pipe diameter.

Depending upon the method of disposal, stabilisation may, or may not, be required. Injection through trailing pipes into the caved strata behind the coal face, for example, should not require any stabilisation as water absorption by the surrounding strata is sufficient. If the same technique is used for pumping slurry to a surface disposal site, such as a disused quarry, stabilisation should not be necessary if adequate fencing is provided during disposal and that a raft of coarse material is used to cap the completed infill.

Other methods of disposal would require stabilisation such as surface disposal where immediate tip stability may be a problem or, underground disposal to disused workings. Following extensive testing, it was established that on a cost/performance basis, Ordinary Portland Cement gives the best results for stabilisation. The task of introducing and mixing the cement must be accomplished as close as possible to the disposal point, as it is an undesirable risk to have a cement-stabilised slurry remain in a pipeline for any longer than necessary.

A full scale pumping plant has been constructed at Trentham Colliery. With a capacity to handle up to 150 tonnes/hour of slurry, the plant is currently being used to pump through a 250 mm bore pipe to a surface disposal point some 1.5 km distant, whilst its performance and reliability are monitored.

The plant comprises an inclined feed conveyor taking coarse dirt direct from the washery to a screen and crusher positioned over a 25 tonne storage hopper. From the hopper the dirt is metered out through a weighfeeder into a twin trough paddle mixer along with tailings from a storage tank. This mixer then discharges the slurry into a hopper over the slurry pump, which is a twin cylinder piston pump rated at 500 kW and capable of delivering 100 m^3/h against 100 bar pressure.

Normal pumping pressures are in line with the predicted pressure for a 250 mm bore pipe at 30 bar/km. The plant has a practical range of about two kilometres, allowing for an initial increase in pressure when the system has stood for several days. Distances in excess of this would require a stage pump to boost the pressure. For surface transport up to two kilometres, the cost would be in the region of £1.00/tonne of slurry.

For the next phase of this project, it is proposed to install an underground pipeline from the surface plant to an underground disposal point. Disposal into disused workings will be used to prove the reliability of pumping to this depth before an underground stage pump and full, or partial, face trailing pipe system are installed.

Cost estimates for the underground disposal of mine waste using the techniques described and based on 0.5 million tonne/year of slurry are £1.80/tonne of slurry, or £2.35/tonne of dry dirt. These figures include capital depreciation, running and material costs. They do not include assumptions for spin-off benefits, such as reduced subsidence and roadway maintenance costs.

5. CONCLUSIONS

This paper has demonstrated British Coal's commitment to minimising the environmental impact of underground mining.

ACKNOWLEDGEMENTS

The opinions expressed in this paper are those of the authors above and do not necessarily represent those of the British Coal Corporation. The authors are grateful to many colleagues at the Technical Services and Research Executive, and to colliery personnel too numerous to name.

COMPUTER-ASSISTED MINING SYSTEMS....KEY TO IMPROVED SAFETY AND EFFICIENCY IN MINING

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ABSTRACT The vast abundance of high-quality coal in the United States figures strongly in our country's future energy picture. For coal to be a competitive and affordable future energy source, it must be mined safely and in a more efficient manner than is currently practiced today. Advances in high technologies such as micro-computers, smart sensors, sophisticated signal-processing software, etc., can make it possible to operate mining equipment from a remote location, away from the dangerous face area. This increase in worker safety would be accompanied by an increase in efficiency by allowing the mining equipment to operate for a higher percentage of the production shift. The U.S. Bureau of Mines is pursuing a research program to develop the technology necessary to achieve this goal. The direction of the overall program will be discussed, along with selected recent research results and future plans.

INTRODUCTION

Safety and productivity are often considered to be mutually exclusive; however, several Bureau projects (Gaertner 1987; Randolph and Peters 1990; Zabetakis 1981) have shown that they are positively related. Following a decline in productivity during the 1970's which was reversed in the 1980's, the Bureau studied the Mine Safety and Health Administration's (MSHA) accident statistics to determine the relationship between safety and productivity. It was found that the incidence rates for both fatal and lost-time accidents tended to be lower in years with the highest productivity: 1988, with the highest productivity, also had the lowest fatality rate; 1980, with the worst productivity, had the worst lost-time accident record.

Another Bureau study (Page 1987) that evaluated 25 high-production continuous miner sections showed that all of these outstanding producers promoted good engineering practices and positive labor-management relations. Production from these continuous mining sections at these mines averaged 2 to 5 times the national average of 370 tons per production shift. Based on MSHA statistics, their lost-time injury rates (per 200,000 employee-hours) were significantly lower than those of the rest of the industry (5.4 to 7.2 vs. 10.2 to 11.0). These lower accident rates translate into substantial cost savings, as well as improved productivity. Related studies (Gaertner 1987) of safety performance support these findings, showing that mines with lower injury rates tended to have higher productivity, better labor-management relations, clearly enforced safety policies, and more worker participation in job management.

INTERNATIONAL COMPETITIVENESS

In 1987, the U.S. was the world's second largest coal exporter, next to Australia. The U.S. exported 79.6 million tons of coal, or approximately 21% of the coal traded in world markets. In addition to Australia, the U.S. coal exports competed with major suppliers from seven other countries, including South Africa, Poland, the USSR, and Canada. Until 1984, however, the U.S. was the largest coal exporter. U.S. coal exports were over 100 million tons as recently as 1982. Since then, new sources of low-cost coal, primarily from Columbia and China, have displaced U.S. coal exports to Europe and Asia, respectively. As a result, the future of U.S. coal exports is not promising at the present time. Although the total world coal trade is expected to expand from the 1986 level of roughly 370 million tons to about 500 million tons by the year 2000, U.S. coal exports are not expected to exceed 91 million tons (DOE/EIA 1988).

Assuming a constant demand for energy, increased sales of U.S. coal can be achieved in two primary ways: (1) as a substitute for another fuel (i.e., interfuel competition) and (2) via increased coal exports. In a study by the Energy Information Agency (EIA) for the Bureau of Mines, EIA concluded that, given certain assumptions, U.S. exports would increase substantially if our mining costs were lowered by at least $8 per ton in the year 2000. The study suggests that as U.S. mining costs are reduced, total U.S. exports will expand only slightly until the costs are $8 per ton below the base case levels. At that cost level, U.S. coal exports will surge by 53 million tons (46%) above the base case level of 114 million tons to 167 million tons, and U.S. steam coal will displace significant quantities of South African coal in Europe. U.S. exports will continue to expand to about 250 million tons in the final $20-per-ton cost-reduction case covered in the study. At this level U.S. coal will be cost-competitive with South African and Australian supplies in both the European and Asian markets. China, Venezuela, and Columbia are the lowest-cost suppliers and will maintain their markets (per the study), limiting further expansion by the U.S. While a $20-per-ton reduction is conceptually realizable, an $8-per-ton reduction is realistic and the results of implementing it can be quite significant.

As we have seen, poor safety has adverse cost, social, and humanitarian implications. Further, some dramatic improvements in the export position of coal could be realized based on a rather modest reduction in the cost per ton. However, coal is coming under increasing pressure in terms of acid rain. Clean coal technology will be a technical success, but at an economic price. Hence, as we look at the domestic energy market, we must recognize that the cost of energy from coal will undoubtedly increase, unless other changes are made to compensate for the cost of additional coal cleaning and/or smokestack cleaning.

The challenge is clear: there is a need to improve health and safety, and lower the cost of producing coal if the U.S. industry is to remain competitive in the domestic market and in order to regain the competitive edge once held by the U.S. coal industry in the international market. These challenges can be met through the utilization of new technology and the more effective use of the invaluable human resources.

Recent Bureau research shows that decline in the risk of fatalities in bituminous coal mines is correlated with periods of technical innovation. The Government began collecting reliable information on the number of employee-hours worked beginning in 1930. Since that time, the number of fatalities per million employee-hours has declined from 1.60 in 1930 to 0.23 in 1989. Much of this improvement has been the gradual result of accumulating improvements in machinery and work practices, and safety regulations and enforcement. It is also possible for the gradual rate of improvement to be accelerated by major technical improvements. A statistical analysis of available accident data was conducted to determine whether major technical innovations in the bituminous coal mining industry had discernible effects on the overall fatality trends. Three technical eras were identified:

1. Pre-mechanization (until 1940) - Hand loading and conventional mining predominated, with large concentrations of the workforce at the most hazardous work location--the mine face.

2. Mechanization (1940-1970) - New machinery, including loaders, continuous miners, and longwalls, became prevalent during this period and fundamentally changed the work process at the face.

3. Post-mechanization (1970-present) - Increasing regulation focused attention on hazards most commonly responsible for fatalities (including groundfalls, explosions, and electrocutions). The resulting strategies have involved changes in

machinery, training, and work procedures.

From the trends shown in figure 1 it can be inferred that a major improvement in safety will require the introduction of a new technologic era--Computer-Assisted Mining Systems.

COMPUTER-ASSISTED MINING SYSTEMS

The focus of the Bureau's research program in computer-assisted mining is to perform an evolutionary development of the critical technology necessary to advance a multi-entry room-and-pillar coal mining section with workers located away from the active face area. Continuous mining machines, roof bolting machines, and continuous haulage and mine ventilation systems will be transformed into computer-assisted, remote-supervised machines. In the near-term, research is directed specifically to the computer-assisted control of present-day underground equipment and the relocation of equipment operators to a nearby area of safety. The major efforts focus on developing the fundamental machine control, guidance, and computer technologies for continuous mining machines, which can thereafter be applied to other mobile face equipment. Highly mobile coal mining machines such as the continuous miner will have a significant role in the future of coal mines as the major method for longwall development, room-and-pillar mining, shortwall mining, and highwall mining.

A Bureau-owned Joy 16CM continuous mining machine was used as the test bed for the initial testing and evaluation

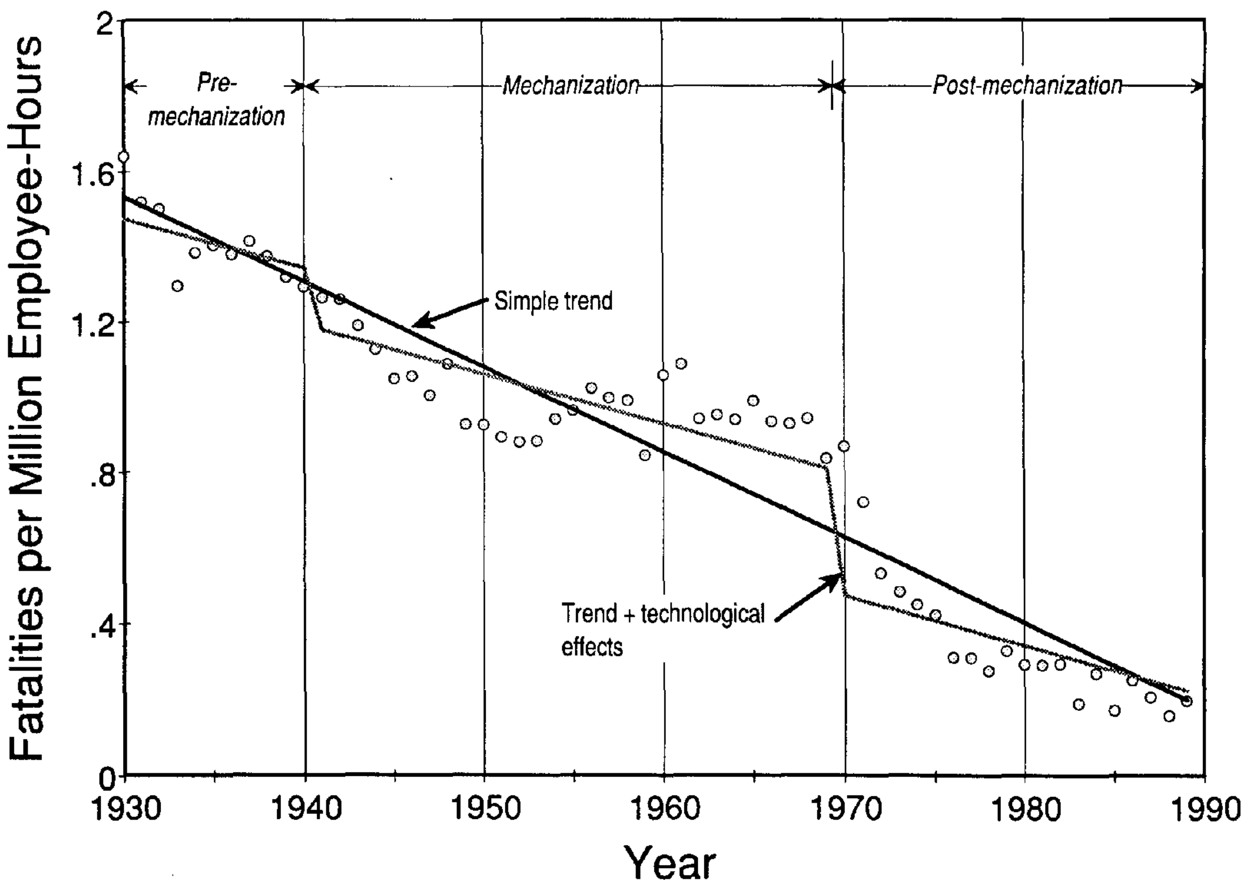

Figure 1.--Trend lines for time and technology eras fitted to bituminous coal industry fatality rates, 1930-1989. Fatality rates were adjusted to exclude disaster fatalities.

of sensing and control systems at the Bureau's surface test facility. Sensors for the position of the movable parts of the mining machine, the electrical system, and the hydraulic system were selected, installed, and interfaced to a network of micro-computers. A micro-computer was interfaced to the electrically actuated hydraulic-control valves for movement of parts and to the control relays for the crawler tracks.

A Joy 14CM was similarly prepared (figure 2) for in-mine evaluation studies. Solicitations were made to coal companies to provide a long-term underground site with production scenarios in which to test the evolving technology. A Memorandum of Agreement was initiated with a mine in West Virginia for the commencement of an extensive in-mine evaluation program. An advanced experimental system consisting of a Joy 14CM continuous mining machine with laser scanner navigation system and line-pull transducers for mechanical navigation system added, and an associated mobile control center (figure 3) has been shipped to the mine to conduct research experiments on machine control, navigation, and coal interface detection (CID).

The machine control system deals with closed-loop control of the machine's movable parts and the response aspect of the machine locomotion system. Using open-loop test data, algorithms for closed-loop control were formulated to manipulate the position of the machine's movable parts employing machine position sensor feedback to obtain a desired position. The system was tested in free space and while cutting a simulated coal seam; the accuracy and stability of the closed-loop shear control was quite good. For example, the shear position error is less than $\pm 0.36^\circ$ as tested in free space and while cutting simulated coal. A data acquisition system, built for this purpose, records machine control commands and sensor data against time in a set of experiments that determine the control delay times and correlate sensor reading with appendage position.

Navigation and guidance: Fluxgate compasses proved inappropriate devices for changes in machine yaw for our application due to the local magnetic distortion in the earth's magnetic field caused by movement of the massive iron mining machine and its movable parts. However, two systems, based upon triangulation, have been developed. A laser-scanner navigation system (figure 4) and a mechanical navigation system (figure 5), which were fully tested at the surface test facilities of the Bureau in Pittsburgh, are being individually tested underground. The initial locomotion control system will use the gyroscope and either the laser or mechanical navigation system to measure xy position and yaw for locomotion control.

Coal interface detection is needed for the operation of a computer-assisted miner operation and will enhance even manual operation of mining machinery. Because of the complexity of determining the coal strata boundary, no single coal interface detection scheme will suffice. It will take the intelligent interpretation of data from a suite of sensors, each operating on different principles for each of the different strata characteristics, to keep the cutting head in coal. The only technique commercially available is natural gamma radiation. This system will work in 90% of the mines in the U.S. where the immediate roof consists of shale or draw slate. In the long run, extensive computer processing and multiple sensors will be needed. Several approaches to vibrational CID, including machine vibration, in-seam seismic, and acoustic, using state-of-the-art adaptive signal discrimination (ASD) techniques to perform feature extraction and classification of complex vibrational signals, have been pursued, with results to date showing successful signal classification rates of 65%-75%. Preprocessing of the data by removing "air cutting" could improve the classification accuracy to as much as 98%.

A complete duplicate of the machine control system is maintained at the Bureau in Pittsburgh so that systems and software can be completely tested aboveground before being tried on the Joy 14CM miner underground. A working computer simulation of the Joy 14CM

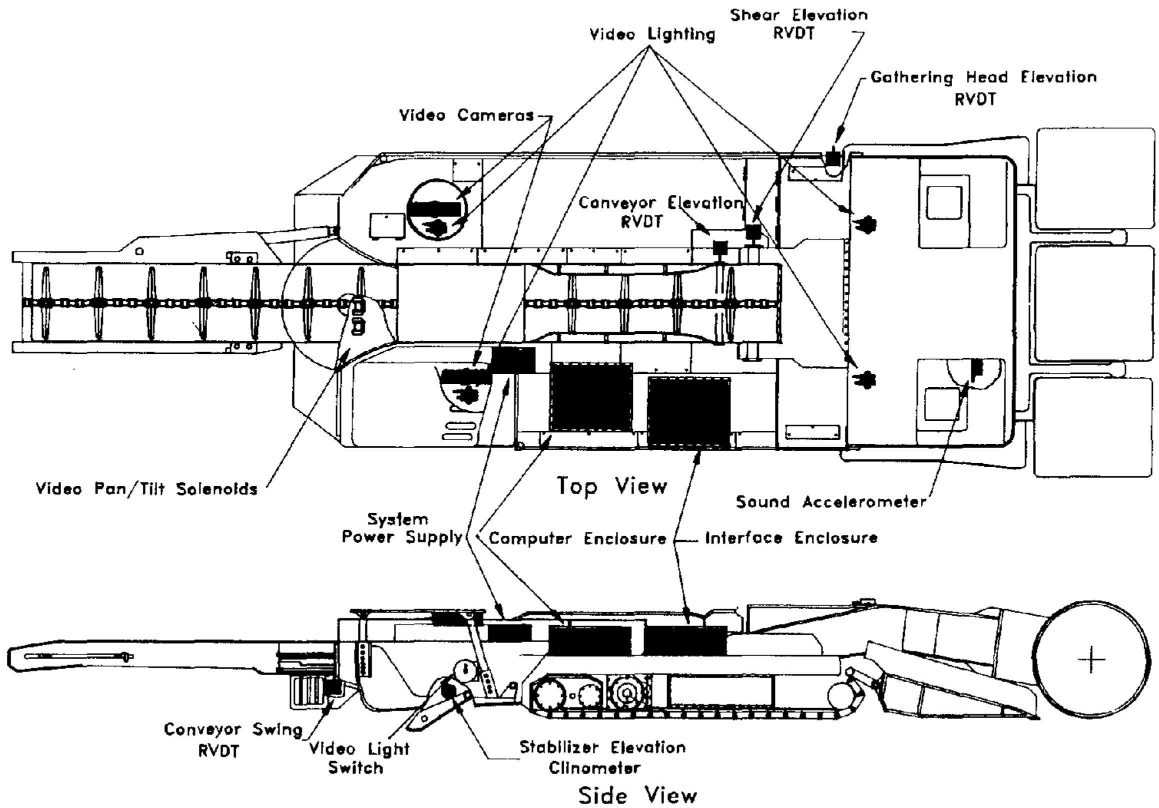

Figure 2.--Schematic of an altered Joy 14CM mining machine with angular position measurement sensors to all moving parts, television cameras, and several large explosion-proof housings for machine control electronics and computer systems.

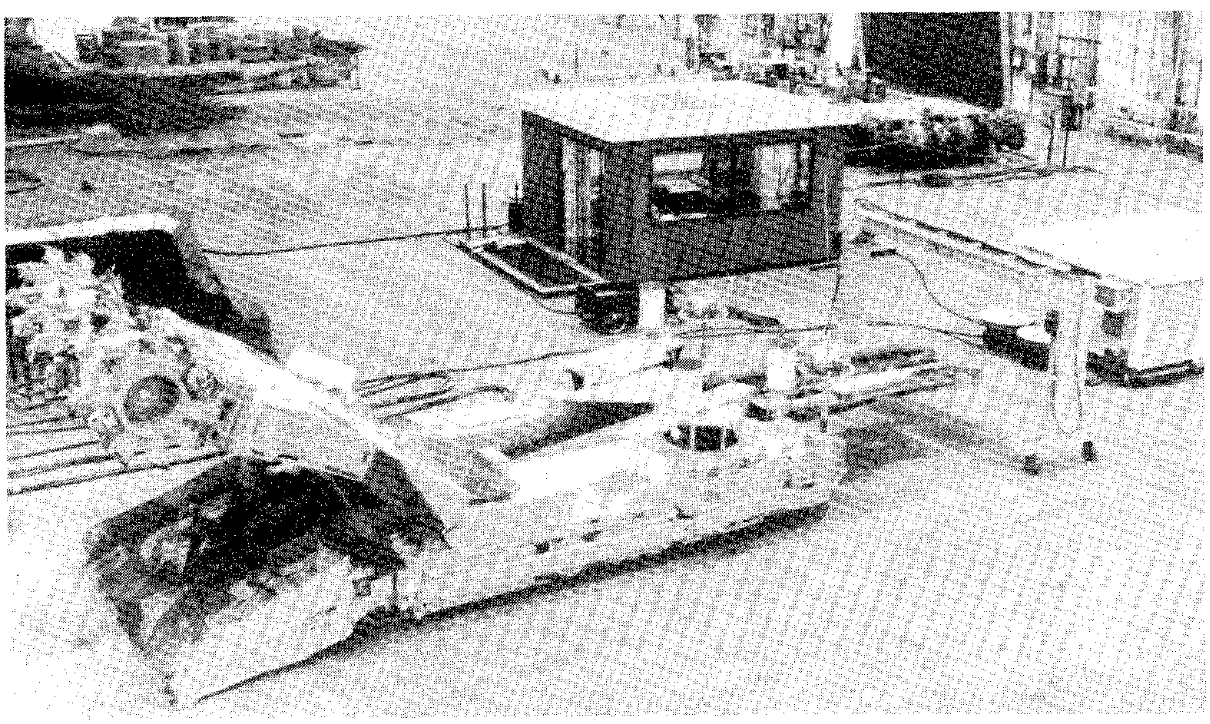

Figure 3.--Advanced experimental system consisting of a Joy 14CM mining machine, mobile control center, and control room.

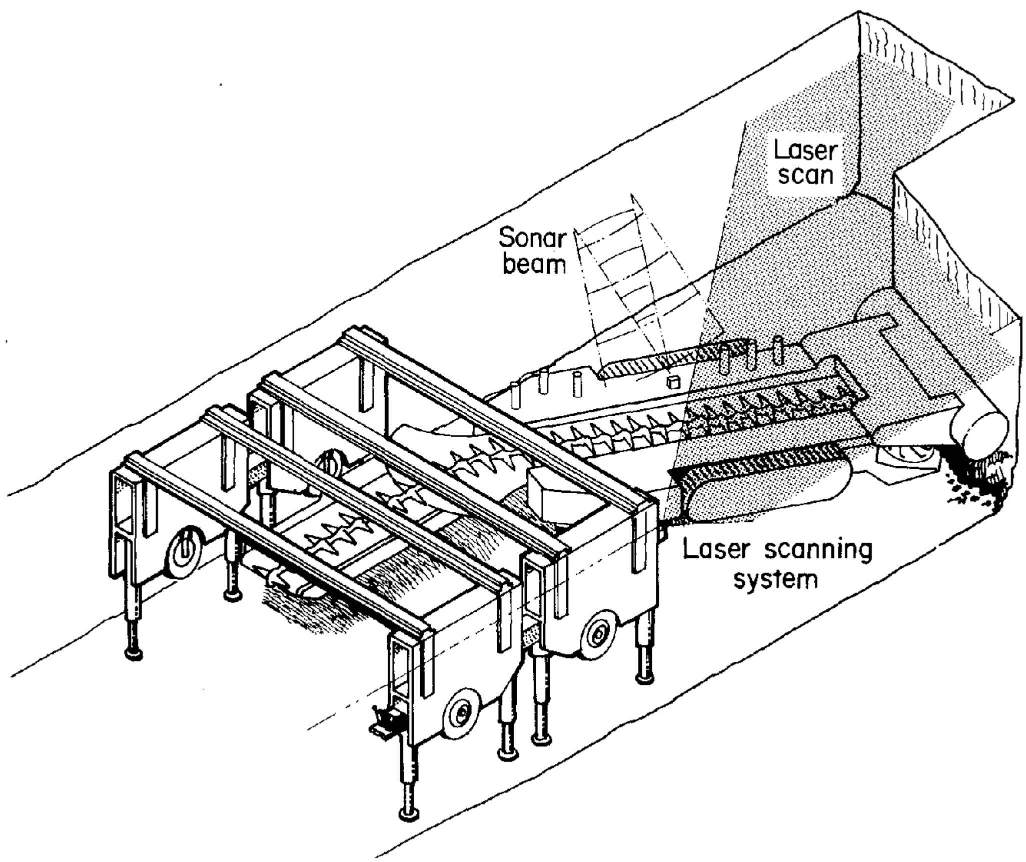

Figure 4.--The Lasernet measurement system for machine guidance at the face.

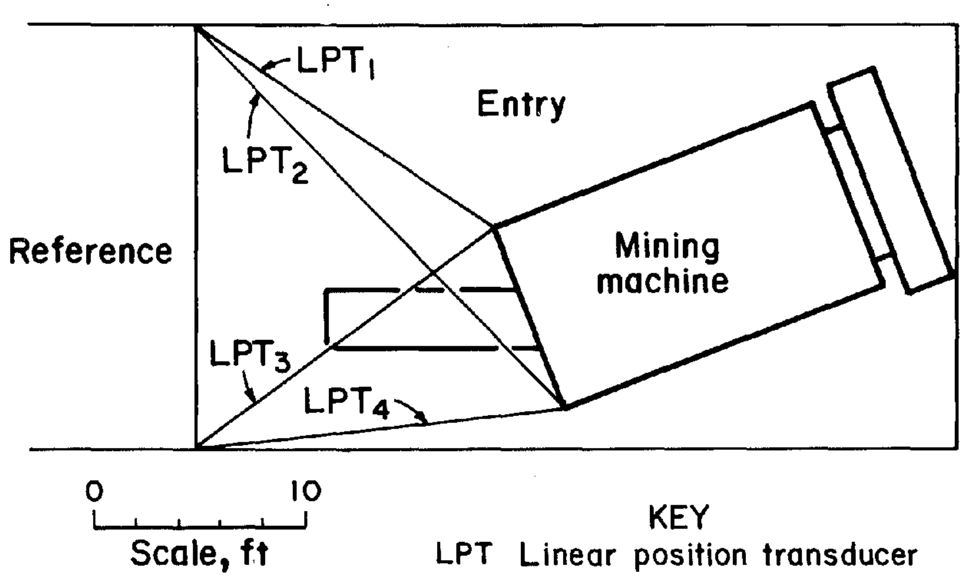

Figure 5.--Mechanical navigation system for locomotion control system.

mining machine along with the guidance systems has been developed and can be used to test advanced computer-assisted control software.

The results of the Bureau's underground experiments with guidance, computer control, and coal interface detection technology over the next two years are most critical. These experiments allow us to gain practical experience and to field demonstrate technologies to the mining industry. Valuable knowledge will be obtained by subjecting the equipment to the rugged mining environment and from feedback from mine personnel. Operators working the equipment can be relocated to a safe and sheltered command center away from the health and safety hazards of the face, resulting in the reduction of deaths and injuries attributable to the face activities.

This research and other efforts currently being pursued show promise for creating the breakthroughs in mining technology that will improve worker health, safety, and efficiency and also increase productivity of the U.S. mining industry.

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THE ENVIRONMENTALLY-AWARE MINE

A Prevention and Disposal Strategy for Underground Waste

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Environment-compatible mining and preparation of coal is an absolut requirement for the acceptance of mining by the population. Not only the mine waters need to be kept clean and the portion of mine stone in the run-of-mine is to be reduced, but also the production of wastes needs to be reduced underground already, and the inevitable wastes needs to be disposed of correctly. Ruhrkohle AG (RAG) in Essen who, besides coke oven plants and power stations, runs 18 coal mines, developed within the framework of their concept "The Environmentally-Aware Mine" an effective strategy of avoiding and disposal of wastes. A main point of this strategy is the complete change-over from HFD (PCB/PCDM-) containing hydraulic fluids to fluid-free technologies and/or to environmentally non-hazardous fluids. The investments and conversion measures required to these ends are described. Solid wastes - if further use is out of question - are deposited in abandoned mine workings of the own mine. Furthermore, Ruhrkohle cycles their waste sludges from preparation plants and residual matter from power stations back into mine workings, and thus contributes to minimization of wastes on the surface. Details are described here-below.

In public discussions, the hardcoal mining's environmental impact is centered mainly on the product, viz. the coal (fig. 1). There is comprehensive discussion and research work concerning atmospheric impacts by coal combustion. Over the past years, the SO_2 and NO_x emissions of coal-fired power stations in the Federal Republic of Germany have been reduced substantially by an expensive retrofitting programme. In addition, the thermal efficiency of the power stations was increased, and this resulted in a reduction of the specific CO_2 emissions.

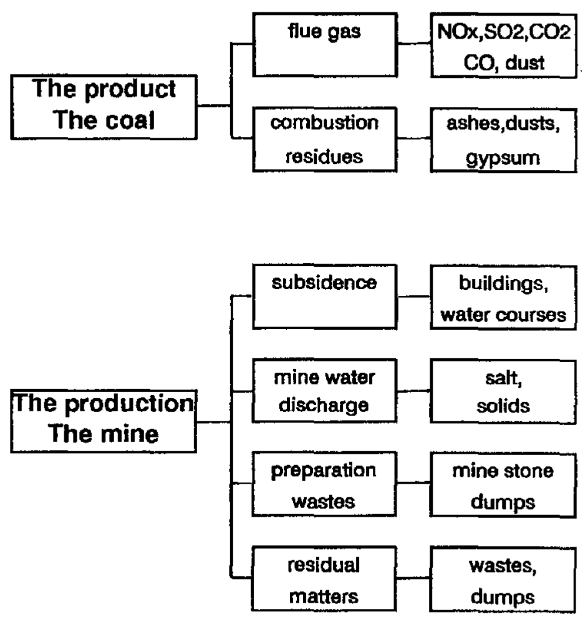

Fig. 1: Hardcoal's environmental impact

The operation of a colliery, however, affects environment, too. Subsidence which affects natural water courses and which results in damages to plants and buildings may be mentioned here as example. These phenomena, of course, entail reactions of the neighbours of coal mines, who, quite naturally, require these effects to be limited to the strict minimum.

Of course, it is in the first place the responsibility of the mine operators to keep environmental impacts at a minimum. This applies, in particular to regions where mining is done below densely populated areas. The operators of the mines are helt to take a maximum of counter-measures against these harmful effects on the environment. In addition, ways and means is to be looked for in order to solve environmental problems in other areas. Some approaches have been made. Accordingly, critical wastes are disposed today in Germany in closed-down mines.

However, not only the sense for own responsibility, but also requests emanating from public opinion which in the end have influence on legislation and regulations, are a reason for us to reduce environmental impact by mining. To an increasing extent, we state participation of the general public in approval procedures. In this field, the mine operator, whenever justifiable, is held to take measures on his own before.

He does so by particular examination of projects implying larger environmental factors. This necessity arises in deep mining for hardcoal, e.g. if larger areas are required for surface installations or if the projected subsidence exceeds pre-set limits so that major influence on ground water, soils, or water courses is to be expected.

The examination is to cover the definition, the description, and the assessment of a project effect's on human beings, animals, plants, soil, water, air, climate, and landscape including the interactions involved, as well as on monuments or other objects of value. In view of an effective environment related prevention scheme these examinations are to serve for early comprehensive assessment of environmental impacts in order to take these risks duely into account.

The viewpoints of effective prevention are colliding with economic aspects. However, everybody is to adopt the idea that raw materials are mineral resources which have to be recovered in an environmentally compatible way, and of which parsimonious use is to be made. Economic savings to the detriment of environment today will mean disproportionate costs for remedial action in the future.

Mine Stone Disposal

The run-of-mine product of German coal mines contains by 40 to 50 pct. mine stone. In coal preparation, coal and stones are separated. In densely populated areas the dump of the mine stone is a problem.

We aim therefore, at reducing the mine stone portion of the run-of-mine production. These ends, exploration is intensified for obtaining early enough better information on the facial development of the seam for better mine planning.

Research is centered i.a. on developing multisensors to operational readyness which are capable of recognizing coal from adjacent strata, and thus allow coalwinning equipment, such as shearer-loaders and coal ploughs, to be controlled in a way that only a minimum of rock is cut along with the coal.

Furthermore, we look for ways to make use of the mine stone, e.g. in dyke and road construction and as a feedstock for the manufacture of construction materials.

This allows to use less raw materials, such as sand and gravel whose recovery, after all, affects environment quite substantially too. In addition, quarries are backfilled with mine stone: a standard procedure which shows that the coalmining industry can solve cost-effectively environment problems of other industries.

All these measures, however, do not change mine stone being produced. Accordingly, also in the future mine stone dumps will be unavoidable. Ruhrkohle AG makes great efforts to create landscape-integrated structures by dumping mine stone. These are planted as early as possible to harmonize with the surroundings by becoming part of these (fig. 2). Wherever finished dumps was given access to the public, the latter accepted them as close-to-nature recreational area.

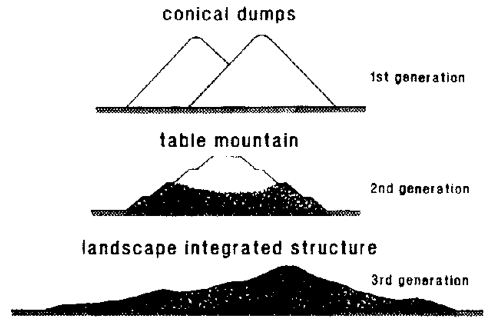

Fig. 2 | Development of dump design (schematic)

Cavity Filling Underground

Wherever economically justifiable (a matter of seam thickness) the excavated gob is filled by injecting mine stone (pneumatic stowage). However, cost-effectiveness sets narrow limits to this method. 1.9 m are stated as minimum seam thickness required. In our company's concessions, however, the pre-requisites for such measures are given only in very few places and, accordingly, the quantity of mine stone used for stowage accounts for only 5 pct. of the total mine stone make.

In this context, another method in the development phase at present should be mentioned, viz. the filling of the caved-in gob. Progress and success of grouting with paste-like slurries allowed the development of this method. At present, froth flotation sludges and fine-particle mine stone are pumped into the caved-in gob of working coalfaces.

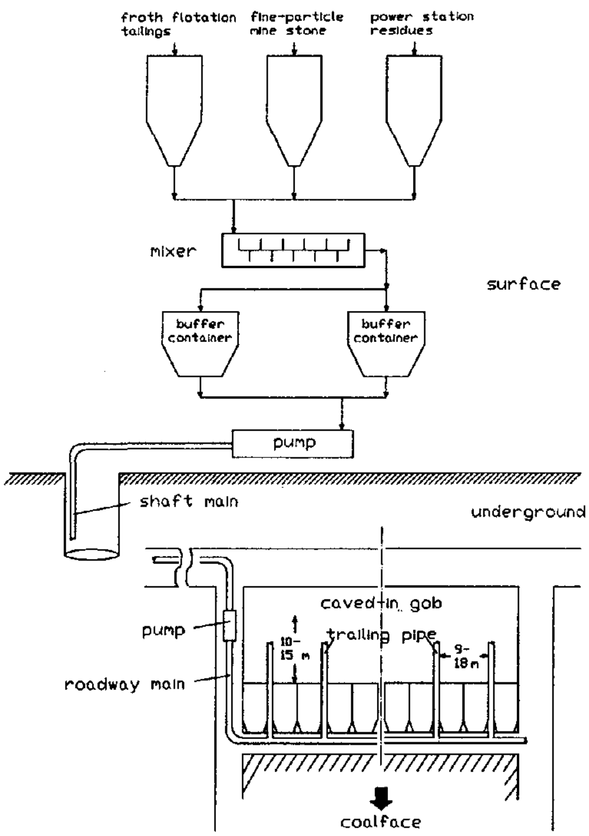

Fig. 3: Flow sheet: Filling of the caved-in gob

It is also envisaged to dispose of residues from coal-fired power stations and other firings, such as ashes from electrostatic filters, residues from flue desulphurization systems, and ashes from fluidized-bed firings in this way, thus also contributing to maintain hardcoal sales.

Eventually, we suppose that also other residual matters can be disposed of in this way without harm to environment. Since one year, we run a 1,200 m^3/d pilot system on Walsum colliery with quite some success. Fig. 3 shows a layout scheme of this system.

With this system the excess water contained in the paste is absorbed by the surfaces of the caved-in debris so that no water is discharged from the gob. Meanwhile, initial knowledge is on hand that the injected matters cannot be eluted. In addition, the matters are injected in zones where, geogenically conditioned, the mine waters contain the same matters as the residual water from the paste so that there is no concern about the mine water quality being affected.

Keeping the Mine Waters Clean

The water ingress into the mine workings, but also industrial water used for mining operations, needs to be recycled to the water courses as cleanly as possible. For collecting and treating mine waters, the collieries installed central pumping and cleaning stations with high buffer capacity.

The system run on Haniel colliery may serve as a good example. The cleaning of the drainage road is done mechanically by an adjustable scraper collecting the sludges deposited on the floor (fig. 4). A pump ahead of the scraper cycles the sludges to a centrifuge where the solids are removed automatically. The water runs back into the sump.

In addition, also partial water streams within the system of mine workings need to be treated. This is absolutely necessary above all in zones where operations-inherently, oil may flow into the water. In maintenance workshops underground the wash waters are treated as carefully as in workshops on the surface.

Successful adaptations of various water treatment systems, matched to quantity and pollution of the wash water, are used and have turned

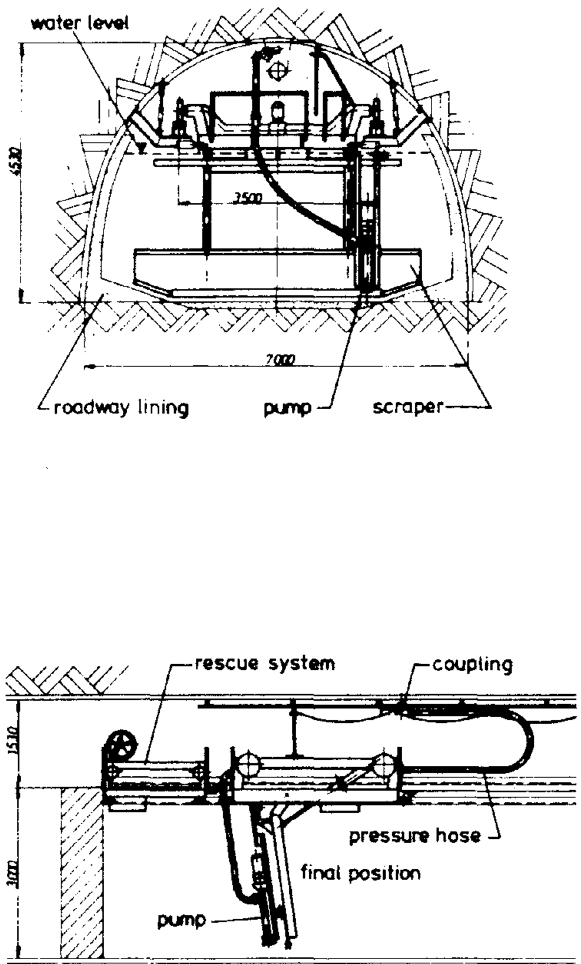

Fig. 4: Cleaning system of the drainage road of the main pumping station

out to be fit for underground operations. Generally, a mechanical oil/solids separation takes place in a preliminary step, i.e. the oil floating on the water is removed by a skimmer. In the treatment step, a separation-promoting agent is proportioned automatically according to the composition and pollution of the wash water, and thus the oil/water emulsion is cracked, and the oil is precipetated. On some operation sites the wash water is treated via activated-carbon filters. The wash water thus purified may then be recycled to the heating unit or the high-pressure cleaning system.

Organization of Environmental Protection

Ruhrkohle's strategy for avoiding and for disposal of wastes is integrated into the overall concept "The Environmentally-Aware Mine". This concept also implies that, when purchasing consumables and other materials, consideration is not only given to criteria such as technical properties, value-for-money, etc., but also to hazards to environment.This goes as far as even packing being specified.

For efficient environmental protection and early prevention, fields of responsibility need to be clearly defined (fig. 5).

For consulting and monitoring of the collieries in all matters concerning environmental protection, a full-time manager was appointed for each operating company (Ruhrkohle Niederrhein AG and Ruhrkohle Westfalen AG together run 18 collieries). Furthermore, agents were appointed for wastes management and water course protection.

On the collieries, the underground and surface operations managers have been appointed by the colliery managers to be responsible for wastes disposal and water course protection. They are held to assure by clear and concrete instructions that the environment-related tasks are fulfilled. The responsible managers are assisted by engineers appointed for environmental protection and assigned to each colliery's operations planning service.

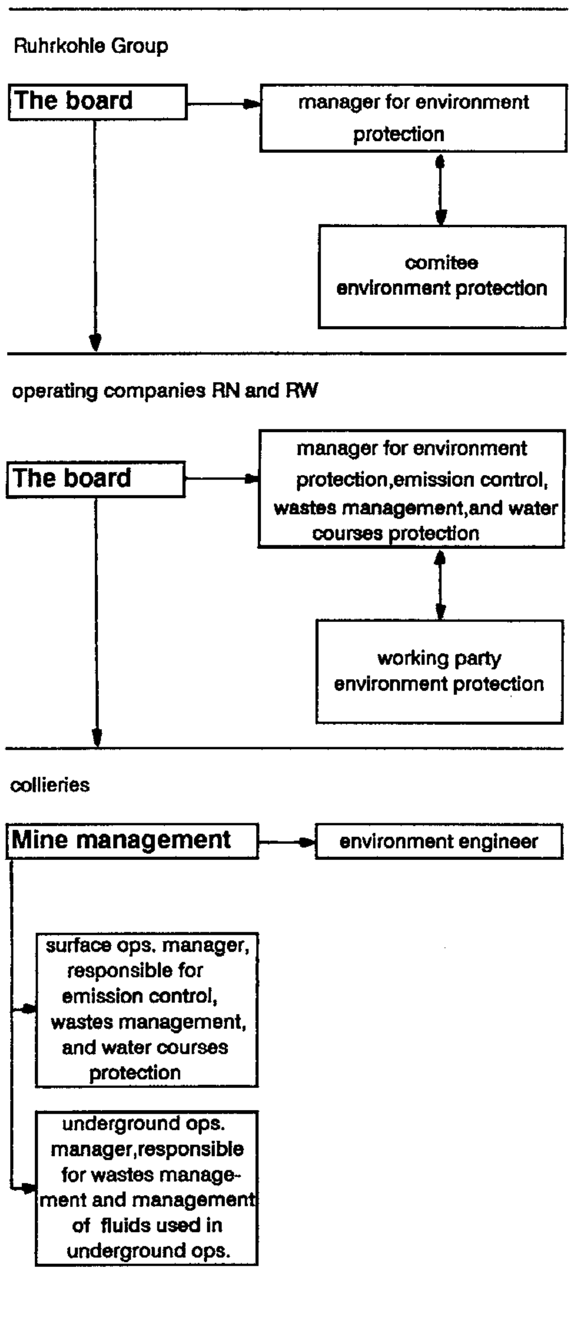

Fig. 5: Organization scheme for environment protection

These engineers deal with environment only, i.e. they are not assigned to any other functions.

The environment engineers are entrusted, i.a. with the following tasks:

- Development and fielding of environmentally acceptable methods for reducing production of wastes; assurance of a correct and harmless use of residual matters produced in operations or

- if this is not possible or out of question for other reasons, to assure correct disposal of these residual matters as special wastes.

In addition, the environment engineers are to instruct the staff on harmfull effects on environment possibly caused by wastes and residual matters as well as on equipment and measures to prevent harmfull effects.

Eventually, they are entrusted with the task to monitor conformity with regulations and to carry out inspections, and to present proposals on measures for doing away with deficiencies in operations.

Strategy of Avoiding Wastes

After the severe catastrophe on Marcinelle colliery in Belgium in 1956 - mineral oils had leaked from a damaged shaft main, and caught fire - considerations were made how to reduce potential fuels for mine fires. In the early sixties, the inspectorates in Germany banned use of mineral oils in certain operations underground, and they made the use of uninflammable hydraulic fluids (HFD fluids) compulsory. At that time, PCB-containing fluids seemed to be technically suited and they were used accordingly in drum-shearer loaders, hydraulic gear boxes of free-steered vehicles, hydromechanical clutches, and in rope-driven systems. Environmental criteria at that time were not contained in the approval procedures for hydraulic fluids. When, end of the seventies, the environment and combustion problems of PCB were found, the use of PCB-containing hydraulic fluids in mining was stopped.

By overcoming substantial technical difficulties and with high costs for conversion, a halogenized replacement fluid (PCDM) was introduced. This fluid's properties were similar, and the environmental compatibility was regarded to be good, based on scientific examinations. More recent investigations, however, certified for this replacement fluid an environmental risk, even though a somewhat smaller one. Accordingly, for the disposal of PCDM and PCDM-contaminated used oils and wastes, criteria were implemented which were as strict as those for disposal of PCB. The reduction of fire risks by banning mineral oil brought about serious other risks. The introduction of a replacement fluid for mining hydraulics thus was no solution to the problem.

Ruhrkohle AG reacted logically and, since a number of years, makes all efforts to reduce HFD fluid use. Compared to a consumption of 1,000 t in 1980, only 43 t of HFD were still used in 1990 on Ruhrkohle's 18 collieries. In 1992 the conversion will be completed.

The essential elements of this successful strategy for avoiding dangerous wastes read:

- use of non-risk fluids:
  Up to present nearly all turbo couplings have been converted from HFD to water. Machines for rope-driven systems are converted to non-halogenous fluids of the category 0 for risks to water (HFC). In hydraulic coalface support, biologically degradable emulsions (HFA) are used.

- non-fluid drive technologies:
  Since 1985 approximately 100 drum-shearer loaders were converted - at costs amounting to approx. 250 Mio Deutschmarks - from hydraulic to electromechanical travel systems. Rope-driven systems are fitted with converter-controlled electrical drives. The brakes of belt conveyors are run on compressed air and electric control. Electric equipment is supplied with dry-type transformers and condensors.

- technical measures for reducing fluids leaks:
  A variety of measures is taken for retrofitting existing machinery and equipment. An essential point is the protection of hoses against mechanical stresses. In addition, rapid couplings for hose connections with automatically locking valves as anti-leak protection have been introduced.
  An important point is the fitting with suited level indicators and overfill protection devices, good accessibility of filling and bleeding openings as well as user-friendly and clearly identifiable supply and evacuation connections. Newly purchased machinery needs to come up to the above requirements.

- Supply with operational fluids tailored to measure to needs:
  The solution of this logistic task is difficult due to the particular features of underground mining conditions. It is important to have available on all operation sites concerned, the fluids in best-configured containers, and at the right

time, in order to keep consumption and losses at a minimum. For avoiding wastes, re-useable container systems are prefered whenever possible. The transport of the fluids is done in special bins and by suited transport and transshipment systems.

- Organizational measures: Leakages whenever they occur need to be cleaned-up immediately. In case of risks of uncontrolled discharge of oils and hydraulic fluids, the machinery concerned is to be stopped if said risk cannot be countered in any other way. Staff who has to handle hydraulic fluids is given special instructions according to their job. The staff is supplied with operation instructions containing rules of behaviour and rules for correct disposal. Generally, containers and transport systems are marked clearly and visibly to inform on contents and place of destination.

By strict application of the above measures in the field, leakage of oil and environmentally hazardous hydraulic fluids into the mine waters, which then would have to be treated, is avoided. It is also possible not to contaminate the normal wastes which create no risk to water, such as packing material, wood, and conveyor belt material so that these can be cycled to further use or, at least, that they need not to be treated as hazardous wastes for disposal. Machinery and equipment out of repair can thus be scrapped without problems. However, if such machinery or equipment has been run on environmentally noxious isolating fluids or hydraulic fluids, only expensive disposal underground in a salt formation is admitted.

<u>Disposal Strategy</u>

In spite of the above-described strategy of avoiding, underground operations produce residual matters which need to be disposed of correctly. The disposal strategy for residual matters produced underground is based on the following way of proceeding:
First, any possibility of use or re-use is to be checked. If re-use is not possible the company-owned disposal capacities are to be examined. Only if the latter are insufficient, external disposal is to be provided. In that case, regulations are reliably to be met.

For reaching the aims defined, a selective collection system catering for various kinds of residual matter is an essential pre-requisite within underground operations. In this field the disposal logistics are to assure transport back to the surface of the residual matters and wastes produced underground as well as used or spent utilities and materials, so that, with a minimum of selection and treatment efforts, these matters can be cycled to other use, repair, scrapping, or disposal. In this context it is extremely important that during transport and selection a contamination by used oils and spent hydraulic fluids of the materials coming back from underground is avoided.

For the whole transport and disposal cycle a separation of liquid and solid wastes is assured.

As to the liquid wastes, spent motor oils, gear box fluids, and other machine oils are kept separate from spent hydraulic fluids. The individual fractions as well as no longer useable residual quantities are transported to the surface and undergo there treatment in a central treatment plant which receives the spent fluids from all Ruhrkohle operations. For safety and prevention, it is generally supposed that the spent operation fluids (spent oils) do contain traces of PCB and/or PCDM. Water and solids are removed. Once PCB and PCDM concentrations are down beyond specified thresholds, the spent oils are used for energy recovery. In the majority of cases, however, the spent oils constitute special hazardous wastes, and are cycled to a high-temperature combustion plant.

Recently, Ruhrkohle developed a process for treating PCB-containing spent oils to operational readyness, and run a plant. Under hydrogenation conditions, i.e. in presence of hydrogen and at higher temperatures, the organically bound chlorine is cracked and converted to hydrochloric acid. Due to the reducing process atmosphere, i.e. the absence of oxygen, formation of TCCD and furanes is excluded. The products obtained are free (below detection limit) of PCB, PCDM, and organo-chlorines, and can be cycled without any problems to further use, e.g. in raffineries. Due to the plant's high capacity going far beyond the quantities of PCB-containing oils produced in Germany, Ruhrkohle also accepts such oils from other industries, and thus substantially contributes to environmental protection by this non-polluting process.

The solids separated in the central treatment plant contain still liquid matter. They are consolidated by anhydrite addition, filled into metal barrels, and deposited underground in salt formations. The separated water is cleaned from residual oils in an emulsion cracking unit with downstream ultra filtration. The oil- contaminated solid wastes coming from underground workshops and maintenance facilities will continue to be collected in separate containers (as long as PCDM-containing fluids are still in use) and, after expensive preparation, be cycled to the above-mentioned underground deposits. Decommissioned transformers and condensors are transported to specialized companies who, subsequent to bleeding-off of the fluids and re-fill with oil-binding agents, store them underground. Fluorescent tubes and batteries are recycled.

The other solid wastes are cycled to disposal on the colliery premisses if further use or recycling is out of question. The competent authority approved the underground disposal of packing material, used air ducts, rubber, cables, and hose material as well as wood and wastes from construction work which are declared to constitute no risk to water courses. Since on a colliery with an annual production of 3 to 4 Mio t/a round about 7,000 to 10,000 t of such wastes are produced, approximately 2 to 3 Mio Deutschmarks/a of costs for external disposal can be saved.

Wastes for which there is no room in the place of origin are normally transported to the surface and, as other materials brought back, are checked in a special hall on a sorting belt for further useability (fig. 6). The transport back to underground for definite disposal is generally done by the usual means of transport. On several collieries it is tried to find out at present

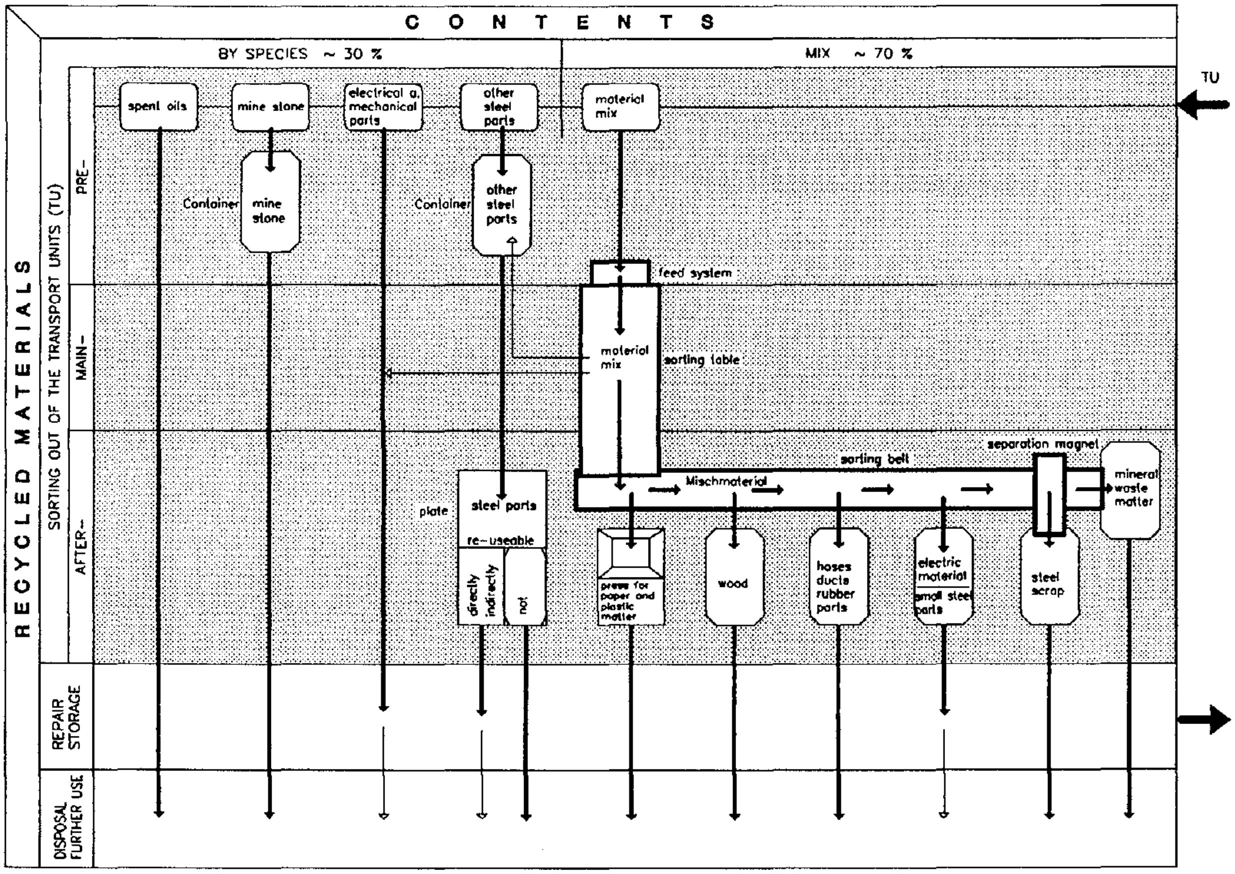

Fig. 6 : Sorting of recycled materials

whether more efficient use of the transport units can be arrived at by shredding or compaction of the wastes. Abandoned mine workings are used for disposal. The wastes are there either stacked or compacted by suited equipment. The air in the workings used for disposal must be monitored for CH_4 release and CO formation. Once disposal in a mine working is completed, said mine working is sealed by an explosion-proof stopping.

Conclusion

Above all in the course of the past decade, management and staff of the coalmining industry became comprehensively environment-minded. A variety of technical and organisational measures was developed and implemented in order to come up to justified requirements and, in addition, to bring solutions to environmental problems also of other industrial sectors.

The design of clear structures of responsibility within the management and the motivation of the whole staff to work in that sense was, and still is, the most important prerequisite for environmental protection.

By the above-mentioned manifold measures the underground workings and the waters collected underground are kept clean to a far-going extent. Products and mine stone are kept free of polluting matters. By selective collection of wastes, secondary contamination of the recycled matters is avoided. Wastes constituting no hazards to waters can now be dumped underground. In this way, space for dumping on the surface - scarce anyhow - is made parsimonious use of.

HEALTH AND SAFETY IN U.S. COAL MINES -- OVER TWO DECADES OF PROGRESS

by

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ABSTRACT

Over the last two decades, considerable progress has been made in improving the health and safety of the U.S. miner. In 1970, for example, 260 coal miners lost their lives in the United States; 59 coal miners died in 1990. Even one fatality is too many. However, this reduction in fatalities is an indication of the progress the U.S. coal mining industry has made in the past 20 years.

During this period, Bureau of Mines research has played an important role. It has provided much of the technology to reduce accidents, fatalities, and health-related problems in the coal mining industry. This report provides examples of some of the more significant research achievements that have led to this reduction. Results in such areas as dust and noise control, fire and explosion prevention, methane control, ground control, survival and rescue, and human factors will be covered.

INTRODUCTION

Historically, mining has been considered one of the most dangerous, if not the most dangerous, occupation for a person to pursue. Coal mining in particular regularly accounts for the bulk of fatalities and injuries in the mining industry. Over the last two decades, considerable progress has been made in improving the health and safety of the U.S. miner. In 1970, for example, 260 coal miners lost their lives in the United States; 59 coal miners died in 1990 (see Figure 1 for fatalities from 1970-90). While even one fatality is too many, this reduction in fatalities shows the progress the U.S. mining industry has made in the past 20 years. It is progress for which all involved can be proud.

The Bureau of Mines was established in 1910 as a result of Congressional reaction to a series of coal mine explosions in 1907. Since its creation, the Bureau of Mines has played an important role in dealing with the problems of coal mine health and safety. Early research concentrated on developing safer blasting materials for underground coal mines, the prevention of underground mine gas and dust explosions, and postdisaster survival and rescue. It established permissibility standards for explosives and equipment. It provided conclusive evidence, based on large-scale explosion tests in the experimental mine at Bruceton, PA, that coal dust alone can propagate an explosion.

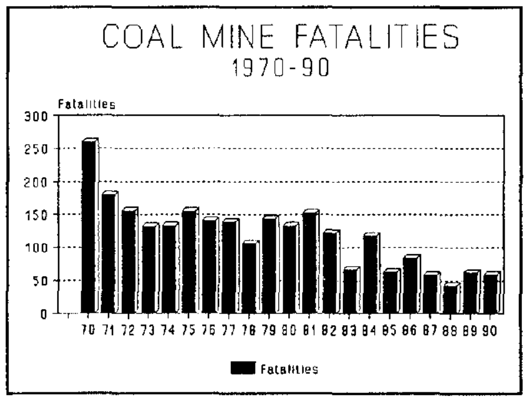

Figure 1

Beginning in the 1940s, the Bureau began intensive research into the problem of controlling mine rooffalls. Throughout the years, this has been the principal cause of mine fatalities. This led to the practice, and later legislative requirements, of widespread roof control in coal mines.

In 1952, Congress passed the Federal Coal Mine Safety Act, authorizing the Bureau of Mines to enforce specific recommendations aimed at preventing disasters (the

Mine Safety and Health Administration (MSHA) now has this responsibility). This act resulted in many more changes in the mining industry directed toward improving the miner's safety. For example, systematic roof control plans, including wood supports and roofbolts, were adopted in more than 2,000 mines and the use of black powder for shooting underground was discontinued. It also resulted in the installation of main ventilating fans in hundreds of mines and the widespread use of water to suppress dust at the mine face. Preshift gas examinations and the requirement for rock dusting began as well. In 1966, the Small Mines Act extended the same protection against disasters to mines employing fewer than 15 people.

In 1968, a series of explosions at the Farmington No. 9 Mine in West Virginia killed 78 miners. This disaster prompted a renewed demand for improved safety measures in coal mining that led to the passage of the Federal Coal Mine Health and Safety Act of 1969 (Public Law 91-173). This legislation again directed the Bureau to conduct research and development needed to eliminate coal mining hazards and reduce the risks of health impairment, injury, or death. It extended the Bureau's role into problems associated with the increasing use of mechanized mining and the exploitation of deeper, less accessible resources.

Some of the most significant Bureau of Mines research accomplishments since the passage of the 1969 Act that have had an impact on improving the health and safety of miners are described below. The accomplishments would not have been possible without the active participation, cooperation, and support of many individuals, professional organizations, labor, and industry groups. The U.S. Congress made this research possible through its legislative actions and appropriations. Congressional concern for the U.S. coal miner has been clear since Congress established the Bureau of Mines in 1910. However, the passage of the 1969 Act provided the resources necessary for research resulting in major improvements in miners' health and safety.

All those involved in the coal mining industry contribute to the Bureau's research program in many ways. Mine operators and equipment manufacturers have been major partners in the conduct of this research and have aided in the commercialization of research products. MSHA has often provided the impetus for research directed toward major safety and health hazards. The United Mine Workers of America (UMWA) has supported the Bureau in its efforts, helping to focus the Bureau's research from the miners' point of view. Industry groups, such as the National Coal Association (NCA), continue to provide formalized input to the research program. Representing large sectors of the mining industry, this is vital input to the research program. These types of interaction are essential to the Bureau's research program and will continue to play a major role in determining the program direction.

DUST

Following passage of the Federal Coal Mine Health and Safety Act of 1969, the Bureau of Mines began a research program aimed at controlling respirable dust exposure of coal mineworkers, long recognized as a severe health hazard to mine workers. The act established a 2.0-mg/m^3 standard for all coal mining operations. At the time of enactment, the industry was averaging 4.0 mg/m^3. Bureau research helped bring the industry average into compliance. Research results included technologies such as improved water spray systems and ventilation, and dust scrubber systems on mining equipment.

In 1976, more than 70% of the longwall shearer faces in the United States were out of compliance with the dust standard. The Bureau's aggressive dust program identified alternative technologies for the industry. The alternatives included shearer clearer water sprays, improved localized ventilation control, modified cutting sequences, and deep cutting. These approaches lowered airborne dust levels substantially. Overall, average respirable dust levels on longwall faces were reduced from 6.8 mg/m^3 in 1976, to less than 2.0 mg/m^3. However, recent increases in longwall panel size and production have made it difficult for operators to continue to meet the 2.0-mg/m^3 standard.

In addition, methods to reduce quartz dust, generated when cutting floor or roof rock and during drilling for roof bolting were developed. Through Bureau development and industry implementation, quartz dust generation during roof bolting is today greatly reduced.

NOISE

Many regard noise merely as a nuisance. The extent and severity of the noise problem in mining was revealed in a 1976 study by NIOSH. This study showed that underground coal miners experience greater hearing impairment than most other industrial workers because of their greater exposure to noise.

The Bureau's approach to noise control has been to emphasize engineering controls for the major noise sources in the mining workplace. Engineering noise controls in mining can be as simple as adding sound-absorbing material to the inside of a bulldozer operator's cab. Controls can also be as complex and demanding as redesigning the inner workings of percussion drills to produce less noise while maintaining the same drilling power. The Bureau used two basic engineering noise control strategies in its noise control research. They were (1) to install noise control treatments on existing mining equipment (the retrofit approach) and (2) to design inherently quieter mining equipment. Drill manufacturers are now designing noise reduction technology into their equipment, and a "quiet" drill is now commercially available. Recently, the Bureau constructed a mining noise laboratory to provide Bureau researchers with a well-controlled acoustical environment to study mining related noise.

GROUND CONTROL

The past 20 years has seen Bureau ground control research span a wide range of subjects. In the early 1970s, research concentrated on the reduction of roof falls by improving support techniques, such as roof bolting. It also addressed the analysis of geologic factors contributing to ground failures. These factors included kettlebottoms, clay veins, and ancient stream channels. Roof monitoring methods were developed as well.

The Bureau developed instrumentation that accurately measures roof movement, including borehole extensometers, continuous roof displacement recorders, and mechanical and ultrasonic convergence meters. Monitoring techniques using microseismics and resistivity were shown to have a high probability for successful application in a commercially practical roof fall warning system. The Bureau researched several new roof control concepts. These included a pumpable rockbolt, a yielding rockbolt, a roof truss, a flexible helical rockbolt, and various cement-based bolt grouts. These studies have provided the mining industry with alternatives to standard roof bolting practices.

Research identified, developed, and evaluated lightweight support substitutes, some of which were adopted by the mining industry. Bureau research was also instrumental in the adoption of both coal mine sealants and roof reinforcement by chemical injection. Several types of spray-on sealants were evaluated and shown to stop effectively coal and roof spalling.

The foremost developments in ground control involved the improvements in longwall mining, especially in the use of support shields. The Bureau introduced and demonstrated shields to the U.S. mining industry in 1975 in mines in Illinois and New Mexico. The Bureau designed and constructed a mine roof simulator for testing of longwall supports and supplemental support materials. The testing conducted in the mine roof simulator provided the information needed to enhanced the design and performance of longwall supports and supplemental support materials. Field verification of laboratory support testing added to the wealth of roof support information available to the mining industry.

HUMAN FACTORS

Before 1969, the mining industry did not fully recognize the potential contribution of human factors research. Often, mining systems and equipment were developed based solely on tradition and production specifications. The role of management and supervisors was not well defined as to their safety and health responsibilities. Inadequacies were also found in the training system, characterized by the notion that "experience is the best teacher." These factors all combined to contribute to fatal and nonfatal injury rates.

Research studies from 1970-76 highlighted human error as a principal contributor to fatal and nonfatal injuries. Problems in human performance impact all mining activities, and the importance of human factors research was implicated. Several research studies and expert opinion suggested that from 50% to 85% of all mining injuries are due, in large part, to human error. Research evidence also suggested that many performance errors usually lie outside the individual. Often they are induced by poorly designed equipment, the work environment, and less-than-effective training programs.

Early research emphasized attention to the human element. This was in response to the congressional mandate outlined under the 1977 Amendments Act. Among other items, the act required mining companies to increase their investment in human resources. This particularly related to periodic health and safety training and retraining of underground and surface miners.

In 1977, the Bureau extended its human factors research to include both basic and applied research. The research ranged from the ergonomics design of the mining workplace and projects that focused on personal and organizational variables, to projects to develop training programs. Three basic studies to identify human factors problems addressed surface mining, underground coal, and underground metal and nonmetal mining. The product of each effort has served as source documentation for application of state-of-the-art solutions to identified problems or for recommending future research.

INDUSTRIAL SAFETY

A major thrust of the Bureau's industrial safety research program involved monitoring the mine environment. The goal of the environmental monitoring program has been to increase mine safety by providing mine management with continuously updated information on underground conditions. This would allow early corrective action before hazardous situations developed. The focus of this program, however, changed three times from 1974-84 as industry needs changed and technology advanced.

The Bureau investigated the feasibility of continuous environmental mine monitoring from 1974-79. Techniques were evaluated for bringing information to the surface from underground locations, including hardwired, tube-bundle, and telemetry. The Bureau demonstrated the feasibility of monitoring in U.S. mines, generating an interest in industry to develop commercial monitoring systems for mine use. Mine monitoring began to be seen as a way to provide increased safety for mineworkers.

By 1983, the basic technology for mine monitoring systems was available, and the mining industry had begun to accept them. Twelve manufacturers were selling monitoring systems, with about 38 systems installed in U.S. underground mines. Research then refocused on system-user interfaces and management information systems. The research aim was to help the mining company utilize the information from mine monitoring systems and equipment monitoring and control for improved management.

Bureau research has had a direct impact on the progress of mine monitoring to where it is today. About 100 underground coal mines have monitoring systems installed, and 10 manufacturers are marketing systems to the industry. The Bureau's mine monitoring research program developed sensors and intrinsically safe mine monitoring power systems. The program also evaluated telemetry systems and developed recommendations to increase the reliability of systems.

The Bureau's industrial safety research program also addressed mine communications. The 1969 Act called for the availability of a system to communicate both on the surface and underground. In the early 1970s, the Bureau assessed the overall problem and established eight requirements for underground communication systems. The requirements were (1) intrinsic safety, (2) compatibility with the environment, (3) rugged structure, (4) size flexibility, (5) a total system, (6) compatibility with present aboveground communications, (7) reasonable cost, and (8) a full service support system. Several manufacturers incorporated the technology that evolved from the Bureau's in-house and contract research efforts into their own product lines.

The Bureau's electrical research addressed incidents of electrical injuries and fatalities in the mining industry, targeting three basic areas. They were shock prevention, permissibility, and electrical system analysis. Accomplishments in the area of shock, for example, are noteworthy. These included the refinement of the ground check monitor, allowing compliance with the 1969 Act, and development of AC and DC ground fault interrupting relays. The latter should eliminate many electrocutions in mining. In addition, improved splice kits provided for greater electrical safety of repaired electrical trailing cables.

Further complicating the miner's work is the dark mining environment. Humans get most of their information about the world around them through their eyes. Historically, limited lighting and visibility underground contributed to an already hazardous worksite. The electric cap lamp was an improvement over the carbide and other flame-type lamps of the past. However, it provided only a limited spot of light, still effectively limiting peripheral vision. The Bureau's research in this area has resulted in face equipment used in today's coal mines that are equipped with permissible illumination systems. Miners now enjoy improved visibility in those areas of the mine that are the most hazardous.

The operators of underground coal mining face equipment are at greater risk than other miners from the ravages of roof and rib falls. These machine operators normally operate within 7 to 8 meters (about 25 feet) of the working face. This is an area widely documented as the most hazardous zone in mining. The Bureau conducted research to define specifications and designs for canopy protection on face mining equipment. As a result of this effort, all face equipment used in thicker seams is now equipped with these life-saving devices. Cabs and canopies have established an impressive record of protecting operators, with hundreds of saved lives and avoided injuries having been documented.

METHANE CONTROL

Though the fatality and injury rate due to explosions has declined dramatically, coal mine explosions are still an ever-present danger. As recently as 1981, 36 miners were killed in explosions. The mining of increasingly deeper and gassier coalbeds reflects a particularly ominous trend. While mine methane emissions have increased significantly in the 20 years since implementation of the 1969 Act, fatalities and injuries resulting from explosions have remained relatively low. Fatalities, for example, have averaged fewer than seven per year between 1978 and 1987. This is due, in part, to the fundamental coalbed methane research conducted by the Bureau.

The primary means of controlling mine methane emissions is ventilation. The Bureau's coal mine ventilation research has concentrated on fundamental investigations, primarily directed toward the evaluation of the effectiveness of mine ventilation. In addition, the Bureau developed cost-effective ways of maximizing the efficiency of all mining activities and practices that influence a mine's ventilation system. The Bureau also pioneered the use of tracer gases for in-mine ventilation assessments. This was a significant factor in determining where and how methane enters and disperses in the mine atmosphere and led to the development of improved ventilation technology.

When ventilation alone cannot effectively control underground methane emissions, methane drainage may be necessary to maintain safe working conditions at optimum coal production rates. The Bureau developed several methane drainage techniques the industry now uses during or in advance of mining. These techniques provide the operator with the appropriate solution to emission problems related to site-specific geologic and engineering conditions. Horizontal holes drilled into the unmined coal have been shown to provide significant relief in existing mines where a short-term immediate solution is required. This technique is the most widely used gas drainage method in the United States for methane drainage on longwall panels. Methane drainage has permitted the safe and efficient mining of coal in situations where mining would not otherwise be possible.

FIRE AND EXPLOSION PREVENTION

The prevention of mine fires continues to be one of the Bureau's most important goals. The underground fire at the Sunshine Mine in Kellogg, Idaho, in 1972 had a major impact on the safety of coal mining. This disaster, which resulted in 91 fatalities, occurred in a non-coal mine, but it emphasized the need for research to better control combustible materials introduced into underground mines. It also pointed out a need to improve fire warning systems and to develop more effective methods for fighting underground fires.

The Bureau conducted large-scale studies on the fire hazards of rigid plastic ventilation tubing, conveyor belts, and the storing of combustible fluids. The results led to new Federal test procedures for determining the fire resistance of these materials, as well as regulations on their use underground. Spontaneous combustion studies were also conducted that identified the factors that contribute to self-heating. Mine operators and MSHA used these results to reduce the risk of spontaneous combustion mine fires.

Many mine fire detection and monitoring systems were designed, fabricated, and subjected to long-term in-mine evaluations. Many of these evaluations were conducted in actual full-scale fire tests. This research resulted in an increase in commercially available mine fire detection systems. Recently, the Bureau started open industry briefings on mine fire preparedness to demonstrate the most up-to-date approaches to detect, prevent, and suppress mine fires.

An understanding of mine explosions was one of the Bureau's first research goals. The Bureau's research and development later made it an international authority in this area. The rapid growth of mechanized mining in U.S. coal mines in the early 1970s created new explosion problems. The change in production methods also eliminated any margin of safety associated with the practice of generalized rock dusting, a practice developed when conventional mining was the rule rather than the exception.

In 1982, the Lake Lynn Laboratory, a 400-acre underground laboratory located in Fairchance, PA, became operational. Designed to simulate the newest coal mines, Lake Lynn allowed for full-scale explosions like those that might occur in current U.S. coal mines.

The development of an optical meter for measuring the rock dust content in mine entries is another recent accomplishment. The meter is now undergoing commercialization and has great potential for improving explosion protection in coal mines.

SURVIVAL AND RESCUE

When a mine disaster occurs, the basic survival strategy for a miner is to escape from the mine. The atmosphere inside a mine may become oxygen-deficient or filled with smoke and toxic gases after a mine fire or explosion. Under these circumstances, escape is nearly impossible unless a miner has a self-rescue device that supplies oxygen that is isolated from the mine air. A mine disaster also may result in the entrapment of miners, their normal egress from the mine cut off. This often requires a rescue operation by specially trained and equipped mine rescue teams sent into the mine from the surface.

The Bureau of Mines life support research has emphasized development of breathing apparatus technology. The results of this research increased the chances of miners to survive a mine disaster. It also improved the effectiveness of underground firefighting and mine rescue and recovery.

A self-contained self-rescuer (SCSR) and training in its use are provided to every person who goes into an underground coal mine in the United States. Federal regulations require this. From 1970-79, the Bureau pursued the development of prototype SCSR technology, and commercialization of this technology began in 1980. NIOSH/MSHA-approved, 60-minute-rated SCSRs were deployed in U.S. underground coal mines beginning in 1981.

Because of their large size and weight, however, mine operators almost universally choose to store SCSRs near the work area. The units were too heavy and bulky for miners to wear the units continuously. One way of improving survival odds was to reduce the size and weight of SCSRs so they could always be bodily worn. The Bureau pushed conventional SCSR technology to the limits in the late 1980s with the development of a new, second-generation SCSR. This unit is called the SR-100. It is a NIOSH/MSHA-approved, 60-minute-rated SCSR one-half the size of the originally deployed SCSRs and weighs about 5 pounds. Previously deployed units weighed from 7-1/2 to 11 pounds. The SR-100 is now commercially available, and underground deployment has started.

EXPLOSIVES

The basic thrust of Bureau explosives research has remained essentially the same since passage of the 1969 Act. As has been the case since the Bureau's founding in 1910, a major part of the explosives effort is directed toward assuring the safety of permissible explosives used in underground coal mines. New explosives intended for use in underground coal mines are evaluated according to the test schedule specified in Title 30 of the Code of Federal Regulations. They are then approved as permissible if they pass all tests. Research continues into the development of improved tests for evaluating the tendency for explosives to ignite flammable gas/dust atmospheres.

The regulations governing blasting in underground coal mines have long prohibited the firing of unconfined explosive charges. Such charges can ignite flammable mixtures of gas and coal dust that may be present in the mine air. The only legal and safe way to shoot explosives was in stemmed shotholes. The Bureau conducted research to develop an explosive charge that could be fired safely unconfined. This charge could be used to break up large stones without the need to drill shotholes and stem to confine the shot. This research resulted in the development of a sheathed explosive charge that can be safely fired unconfined. Test schedules for the approval of the sheathed explosive charge as permissible were also developed, and a sheathed explosive charge is now commercially available. The 1989 revision to the permissible explosive approval schedule included the test schedule. Additionally, the regulations governing blasting in underground coal mines now allow the use of sheathed explosive charges.

CONCLUSION

The Bureau of Mines has conducted a major health and safety research program over the last two decades. Such a program would not have been possible had it not been for the passage of the 1969 Act and continued Congressional concern for the U.S. miner. The Bureau's research has, in part, played a major role in improving coal miners' health and safety in the United States. These improvements would not have been possible without the active participation, cooperation, and support of many individuals, organizations, and industry groups. Mine operators and their associations, equipment manufacturers, MSHA, and the UMWA have all been partners with the Bureau in this effort. This type of cooperation has been essential to the Bureau's research program and will continue to play a major role to further improve life for the coal miner.

DEVELOPMENT OF A DESIGN PROGRAMME FOR COAL PILLARS WITH LARGE WIDTH TO HEIGHT RATIOS

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Research Organization, Chamber of Mines of South Africa

ABSTRACT

The design of stable pillars is of paramount importance for the safe and economic extraction of coal reserves. Most design formulae suggested by researchers are based on small pillar width to mining height ratios. In practice many coal pillars have large width to height ratios and thus fall outside the range of the pillar design formulae commonly in use. This paper examines a formula for squat coal pillars and reports on full scale experiments of pillars designed according to the squat pillar formula after Salamon (1982). The results obtained are summarized together with associated strata control problems encountered. Benefits of the squat pillar formula are detailed. It is shown that the squat pillar formula substantially increases productivity and the percentage extraction of reserves without reducing the safety of men, equipment or the workings.

INTRODUCTION

Bord and pillar mining is the single most important mining method in the South African coal mining industry. It accounts for 76 per cent of all coal mined from underground and for nearly 50 per cent of South Africa's current coal production which is about 195 million sales tons, Figure 1.

The design of bord and pillar workings is based on a procedure which was proposed by Salamon in 1967. The key element in the design procedure is the pillar strength formula which was developed by Salamon and Munro in 1967. The pillar strength formula was derived from an analysis of 98 stable and 27 collapsed bord and pillar workings using the maximum likelihood method of analysis. An evaluation of the pillar design procedure by Wagner and Madden (1984) has shown that it performs remarkably well. At that time three areas for further improvement of the pillar design procedure were identified, namely:

i) the effects of regional difference in coal seam strength on pillar design;

ii) the effects of mining method on pillar design and

iii) the effects of large pillar width to mining height ratios on coal pillar strength.

This paper describes the development of a design procedure for squat coal pillars. In addition, the paper describes the economic benefits that result from the new procedure. Finally, some practical examples of the application of the squat pillar design formula are given.

THE EFFECT OF THE WIDTH TO HEIGHT RATIO ON THE STRENGTH OF COAL PILLARS

It is a well known fact that the strength of pillars increases as their width increases. This phenomenon can be attributed to the confinement provided to the core of a pillar by the surrounding strata and the pillar material which surrounds the core of the pillar. Using an arrangement of up to 25 individually controlled hydraulic jacks Wagner (1974) could demonstrate the important contribution that even failed coal at the circumference of a pillar can make to the load bearing ability of the centre core of the pillar, Figure 2.

A number of formulae have been developed to describe the effect of width to height ratio on the strength of pillars, Figure 3. The majority of these formulae are based on laboratory test of rock and coal pillars and suffer from the disadvantage that the loading conditions in the laboratory are an idealization of those prevailing underground. Furthermore, laboratory tests do not take into account the important effects of size and loading rate on the strength of pillars (Madden 1991).

Experimental difficulties and economic considerations have placed severe constraints on *in situ* tests of pillars. As far as coal pillars are concerned probably the most exhaustive series of tests were conducted in South Africa in the late 1960's and early 1970's (Hoek 1966, Bienawski 1968, Cook 1971, Bieniawski and van Heerden 1975). In these tests pillars measuring up to 2,0 m by 2,0 m in cross-section and with width to height ratios, ranging from 1,0 to 3,4 were tested. A comprehensive summary of these tests is given by van Heerden (1975). Van Heerden proposes that, within the range of width to height ratios covered by the tests the strength of in situ coal specimen can be described by the following relationship.

$$\frac{\sigma_p}{\sigma_{seam}} = 0,64 + 0,36.\left(\frac{w}{h}\right) \qquad (1)$$

where σ_{seam} is the strength of a cube of coal with a linear dimension of 1,0 m, and w and h are the width and height of the pillar, respectively.

Because of the difficulties in experimentally determining the strength of large coal pillars, Salamon (1967) adopted the approach of back analysis of real mining geometers in South African coal mines. Adopting rigourous criteria to ensure that the mining geometries satisfied the requirements of the tributary area concept Salamon selected 98 stable and 27 collapsed mining geometries to determine on a statistical basis the three parameters in his generalised pillar strength formula.

$$P = C h^{\alpha} w^{\beta} \qquad (2)$$

where C is the strength of a cubic of coal of linear dimension of 1,0 m and α and β are parameters which describe the effects of pillar width and pillar height on the strength of the pillar. Using the maximum likelihood method Salamon found the following values

C = 7 176 (KPa)
α = -0,66
β = 0,46

It is important to note that the 27 cases of pillar collapse fell in a narrow range of width to height ratios of 0,9 to 3,6, while the maximum depth of the collapsed workings was 190 m below surface.

Given the fact that Salamon's well known pillar strength formula is based on the back analysis of stable and unstable bord and pillar workings it is only valid for the range of parameters covered by his study.

While many people applied Salamon's pillar formula well outside the range of parameters for which it was derived it was Salamon himself who recognized the shortcomings of the design formula for pillars with large width to height ratios and in 1982 he proposed an extension to the formula to account for the increase in pillar strength beyond a critical width to height ratio as suggested by many tests on small laboratory specimens, (Bieniawski 1968b, Hudson et.al. 1971, Madden 1991).

Salamon proposed the following extensions to the original pillar strength formula of 1967.

The original pillar strength formula

$$P = 7176\frac{w^{0.46}}{h^{0.66}} \qquad (3a)$$

can be expressed in the following form

$$P = 7176\frac{R^{0.5933}}{V^{0.0667}} \qquad (3b)$$

where R is the width to height ratio and V is the pillar volume, that is,

$$R = \frac{w}{h} \quad , \quad V = w^{2}\cdot h$$

Formula (3b) is valid as long as the ratio R is smaller or equal to a critical ratio R_o. On the basis of practical experience, model tests and theoretical considerations Salamon suggested that when the width to height ratio of a pillar is greater than R_o the strength can be expressed more accurately by the following formula:

$$P_{squat} = 7176\frac{R_o^{0.5933}}{V^{0.0667}}\left\{\frac{0,5933}{\epsilon}\left[\left(\frac{R}{R_o}\right)^{\epsilon}-1\right]+1\right\} \qquad (4)$$

this formula has the properties that at $R = R_o$.

$$P = P_{squat} \quad ; \quad \frac{\partial P}{\partial R} = \frac{\partial P_{squat}}{\partial R}.$$

According to formula (4) the critical ratio R_o and the factor ϵ have to be known to determine the strength of pillar with width to height ratio $R > R_o$.

Laboratory tests and practical experience suggested that a value of 5,0 was a conservative estimate for R_o. More difficult was the estimation of a realistic value for the factor ϵ which governs the rate of strength increase at high width to height ratios. Model test on sandstone specimen width to height ratios ranging from R = 1,0 to R = 8,0 suggested that a value of 2,5 was a conservative estimate for the factor ϵ (Madden 1991). Figure 4 compares the pillar strength as calculated by the squat pillar and the Salamon formula.

EXPERIMENTAL EVALUATION OF SQUAT PILLAR DESIGN FORMULA

Given the importance of a reliable and safe design procedure for squat coal pillars an agreement was reached with the Government Mining Engineer, whose statutory responsibility is to ensure the safety of mines and works, to carry out a series of well supervised and controlled mining experiments to evaluate the new pillar design procedure. A number of field trials were conducted in the deepest South African coal mines. The purpose of these trials was:

i) to establish the fracture patterns in pillar designs according to the new formula for squat pillars;
ii) to confirm the suitability of the values chosen for the parameters R_o and ϵ ;
iii) to identify any strata control problems resulting from the new design procedure; and
iv) to quantify the benefits derived from the new design procedure in terms of improved coal extraction and productivities.

Table I gives an overview of the field experiments.

The field trials yielded the following results:

i) Fracture patterns

Stress-induced fracturing is expected to occur in coal pillars when mining exceeds a certain depth. To examine this aspect a series of pillar configurations were simulated on a two-dimensional elastic stress analysis program. The model assumes an infinite number of pillars separated by 6,0 m wide roadways. The only variable is the pillar width which ranges from 15 m to 50 m. The depth of mining is 320 m and the extracted seam height is 2,5 m. Figure 5 shows the stress and stress concentration factor (resultant stress divided by virgin stress) for pillars 15 to 50 m wide. In the analysis the pillars were divided into one metre elements. The stresses acting at the mid points of each element have been plotted. For ease of comparison the results of all five model studies are shown in Figure 5.

It should be noted that the simple model study does not take into account the effect of fracturing consequently the stresses at the edge the

Table 1 **SUMMARY OF FIELD EXPERIMENTS TO VERIFY SQUAT PILLAR DESIGN PROCEDURE**

Colliery	Depth Below Surface (m)	Pillar Height (m)	Pillar Width (m)	R	Per Cent Extraction
Piet Retief	550	2,0	28,0	14,0	32,1
Hlobane	180	0,8	14,0	17,5	51,0
Longridge	252	2,5	32,0	12,8	29,1

pillars are exaggerated. The results of the computer analysis can be summarised as follows.

(a) as the pillar width increases the average vertical pillar stress decreases, this is due to the decrease in the percentage extraction;

(b) beyond a pillar width of 30 m there is only a marginal reduction in the vertical stresses at the pillar's edge and in the centre of the pillar;

(c) even in a 50 m wide pillar the stress at the edge of the pillar is approximately twice the uniaxial compressive strength of the coal and, therefore, fracturing is unavoidable.

The most important finding of the pillar experiments at Piet Retief and Longridge collieries was that the fracturing in the pillars was confined to a narrow zone of less than two metres width and that the core of the pillars was unfractured, Figure 6. As anticipated from the model studies, severe sidewall fracturing occurred once the depth of mining exceeded about 250 m. The results of the pillar trials of Piet Retief Colliery were of great significance as they showed that even at depths of between 450 m to 550 m below surface there was a large unfractured core of coal in the pillars. Stress measurements showed that the coal in the fracture zone was capable of supporting significant stresses and that the stresses in the central position of the pillar were close to the virgin condition.

These observations are of considerable importance as they clearly indicate that regional pillar collapse involving a regular system of squat pillars can virtually be excluded and that most problems are those related to the control of the fractured coal at the pillar circumference.

ii) Parameters R_o and ϵ

According to available field evidence, no pillar collapse has occurred with a width to height ratio greater than 3,75. The field experiments provided insufficient information to refine the value of the critical width to height ratio (R_o). For the time being it has been decided to retain the conservative value of $R_o = 5,0$.

At Hlobane Colliery two bord and pillar panels were designed with the help of the new squat pillar formula using values of 5,0 and 2,5 for the parameters R_o and ϵ, respectively. The pillars of Hlobane Colliery were found to be stable. However, severe floor heave in one of the panels resulted in difficult mining conditions and the loss of some working places. This experience highlighted the need to include the surrounding strata composition in pillar design considerations at depth.

From an overall point of view the field trials showed that stable pillar layouts resulted from the application of the squat pillar formula. Furthermore, the theoretical benefits in terms of improved percentage extraction materialised without endangering the safety and stability of the workings.

Unfortunately the limited scale of the field trials did not allow for a variation in the values of R_o and ϵ. Consequently, it was not possible to optimise these two important parameter. The stress and fracture observations and the general observations in the panels confirmed that the choice of $R_o = 5,0$ and $\epsilon = 2,5$ is a very conservative choice and that there is further scope for improvements to the squat pillar formula.

iii) Strata control problems associated with squat pillar formula

Traditionally roadways in South African collieries are driven at widths between 5,5 m and 6,5 m. The latter applies to roadways driven under competent sandstone roof. At depths in excess of 200 m below surface the stresses acting at pillar sides and corners approach the compressive strength of coal and fracturing of coal at the pillar circumference becomes inevitable. If this process is not controlled or even worse if the fractured coal is removed the width of the roadways increases and roof collapse is a distinct possibility.

The field trials reported in this paper confirmed the need for systematic and timely sidewall support of coal pillars at depth. Where this support was applied it resulted in good roadwidth control and stable roof conditions. Where installation of sidewall support was delayed the effective roadwidth soon reached eight metres and roof control became a matter of concern. The field trials clearly showed that bolting alone is insufficient and that some form of areal support is required to ensure that the coal between the bolts is confined.

Another important lesson learnt from the field trials was the need for a systems approach to ensure safe and economic bord and pillar workings at depth. In particular floor heave, which is almost unknown in shallow pillar workings in South African collieries, can develop into a serious problem at depth. Careful evaluation of the properties of the surrounding strata is essential for the successful application of pillar mining at depth. Similarly, the choice of roadway width, equipment used and method of mining are more critical at depth than is the case in shallow pillar workings.

iv) Benefits of Applying the Squat Pillar Formula.

Permanent support pillars are required to be left under surface restrictions such as buildings, dwellings, railway lines, canals and roads. Main developments and shaft bottom design requires pillars to remain stable for the life of the mine, which may exceed 50 years. In these cases a design safety factor in excess of 2,0 is used.

The benefit of the squat pillar design formula, in terms of increased extraction of coal, can be seen by the absolute increase in areal percentage extraction of the squat pillar design over that of the current design, Figure 7.

The oversupply of coal on the world market and the rising costs of labour and stores has made it essential that working costs of coal mined be kept to a minimum. One way of reducing the cost of coal per ton mined is to increase productivity.

To determine the increase in productivity from the use of the squat pillar design formula, a computer simulation of production from sections designed to both formulae were investigated using the program COMSIM developed by COMRO Coal Mining. Pillar geometries were calculated using the current and squat pillar formula for mining heights 1,0 m, 2,0 m and 3,0 m at depths of between 200 m and 500 m, assuming a safety factor of 2,0 and a bord width of 6,0 m. Figure 8 shows the percentage increase in productivity as well as the percentage decrease in tramming distance of a shuttle car and indicates the tremendous benefits resulting from the application of the squat pillar formula.

Buddery and Vorster (1989) found that the introduction of the squat pillar formula resulted in a reduction of the pillar size from 35,0 m to 29,0 m and gave a measured increase in productivity of seven per cent. This conforms to the estimated increase given in Figure 8. Whilst other collieries using the squat pillar formula measured their productivity increase between 15 and 25 per cent which were in excess of the results shown in Figure 8.

The squat pillar formula gives substantial improvements in percentage extraction over the current design method, approximately 19 per cent for a 2,0 m high seam at 600 m, the current maximum depth of mining in South African collieries. The reduced pillar sizes result in increased productivity and reduced tramming costs which combine to give lower working costs. For example the squat pillar panels at Hlobane Colliery recorded an average increase in productivity of 15 per cent.

In addition, benefits from the reduced pillar centre distances calculated by the squat pillar formula result in improved ventilation as well as a slower rate of geographical expansion which gives more tons mined from one area which means better utilization of infrastructure per ton mined.

Sixty three sections in twelve collieries have applied the squat pillar formula in South Africa. This has resulted in substantial benefits in percentage extraction, productivity and reduced working cost without affecting the safety of men and equipment.

CONCLUSION

i) The development of an improved design procedure for squat coal pillars is an example of systematic research and development directed at improving the safety, productivity and competitiveness of the South African coal mining industry.

ii) The results of a number of large scale field trials have verified the validity of the new design concept and have demonstrated the practical benefits derived from this design approach.

iii) There is considerable scope for further improvements for pillar design in deep coal mines.

iv) Coal pillar design should not be seen in isolation but as part of a system comprising roof and floor strata, coal seam, and factors such as depth, panel dimensions and mining methods and equipment.

ACKNOWLEDGEMENTS

Many of the aspects of coal pillar design in South African Collieries have been established by Prof. M D G Salamon who headed the research effort of the South African coal mining industry from 1963 to 1986 and as Director General of the Research Organization of the Chamber of Mines was responsible for overall research directions for coal and gold mining research from 1974 to 1986. The Coal Mining Research Controlling Committee under the Government Mining Engineer sponsored much of the research reported in this paper. The rapid progress in the establishment of new design procedures for squat coal pillars would not have been possible without the support of the Government Mining Engineer and the Inspectors under this control. Finally, the many contributions of the management and staff of the collieries participating in this project are gratefully acknowledged.

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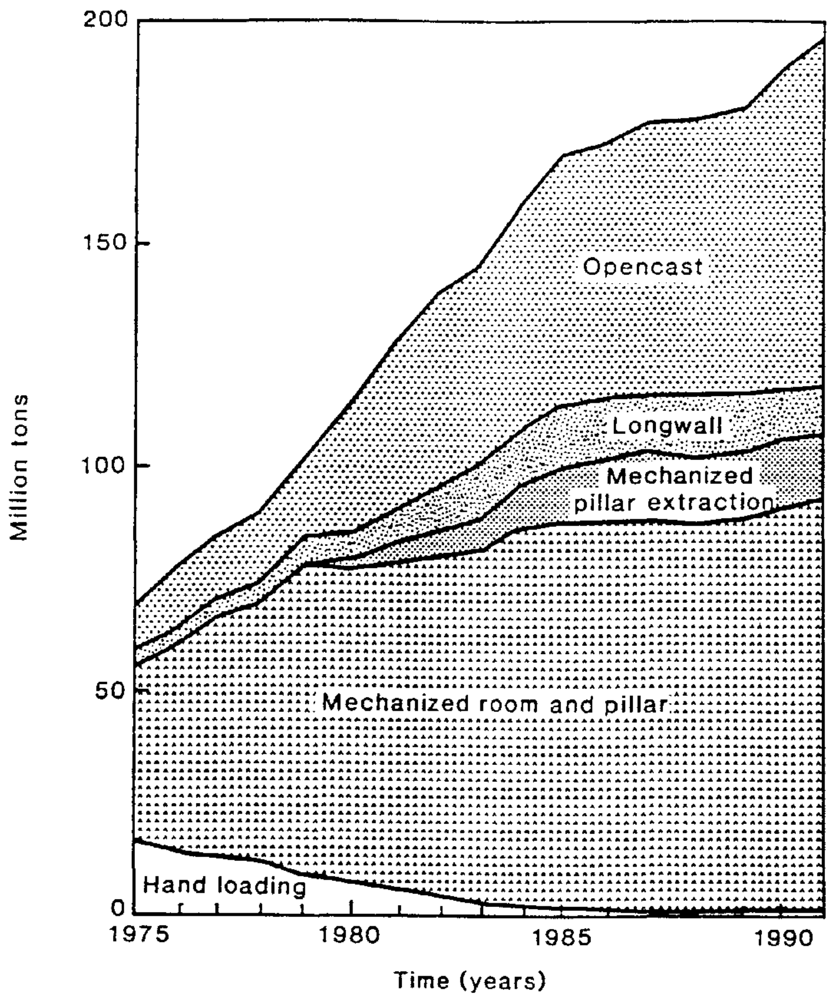

Figure 1. Coal Production by Mining Method.

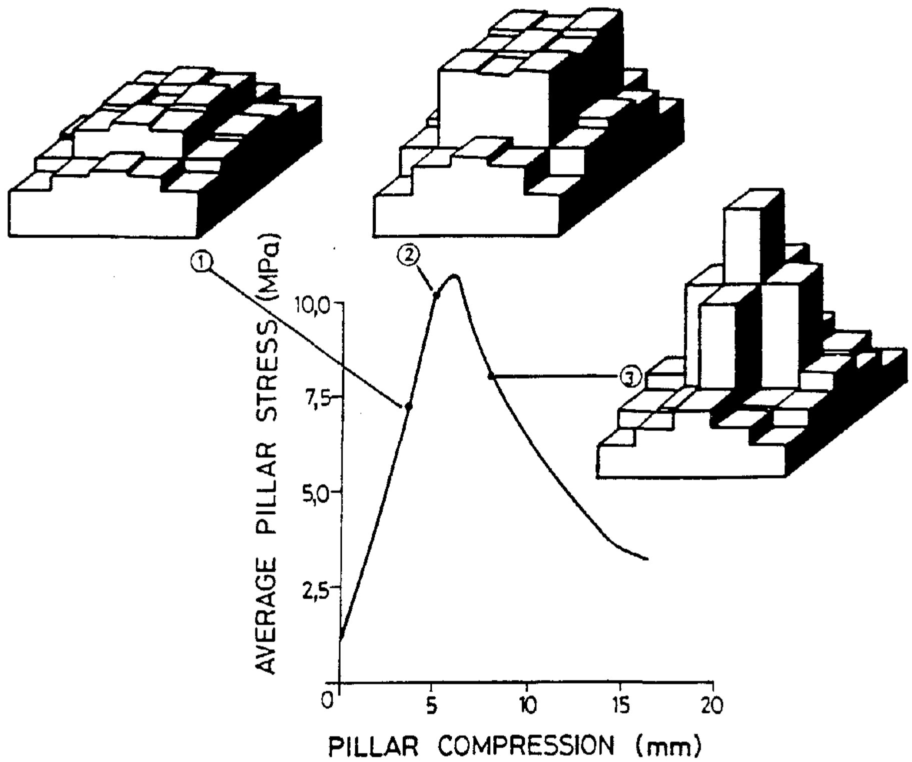

Figure 2. Stress Distribution in an *In Situ* Model pillar at Various Stages of Pillar Compression. (After Wagner, 1974).

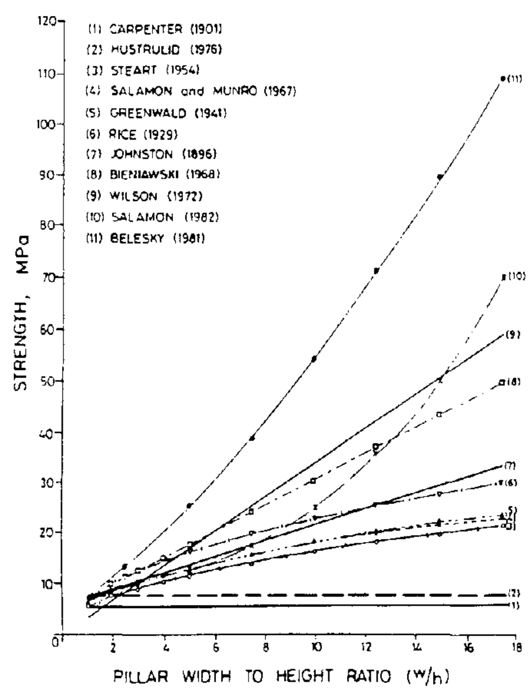

Figure 3. Effect of Width to Height Ratio on the Strength of Pillars.

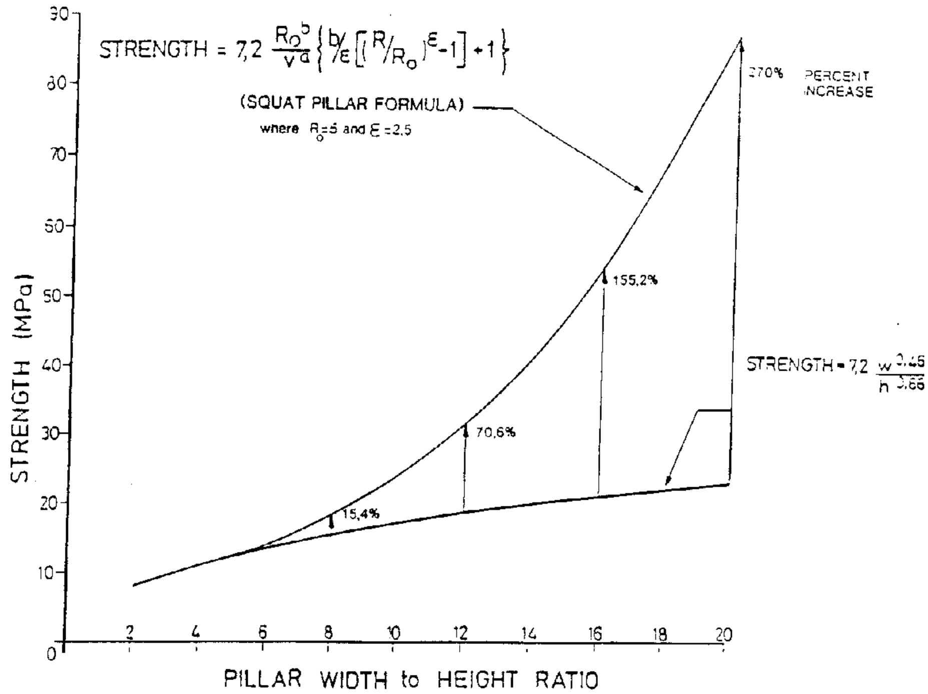

Figure 4. Comparison of Pillar Strength Formulae.

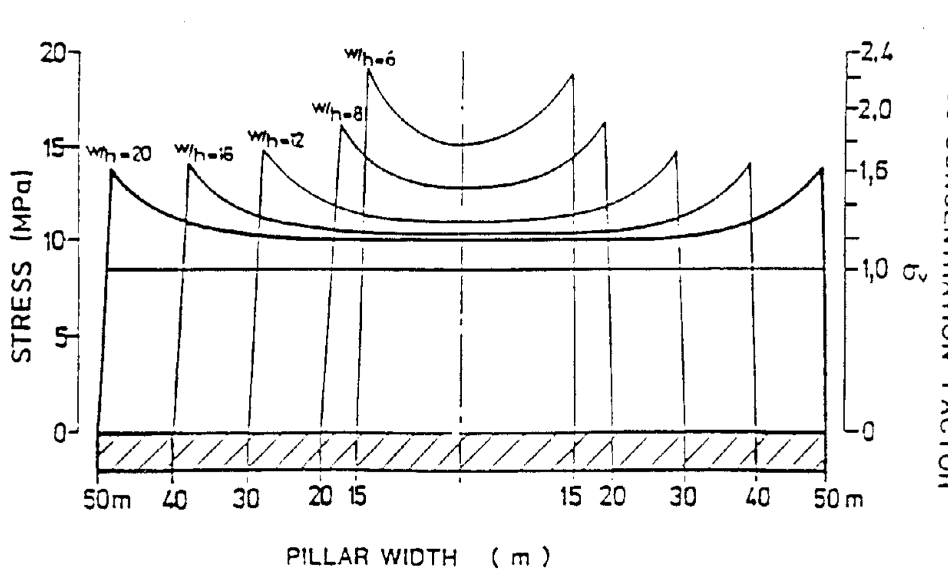

Figure 5. Absolute and Normalized Pillar Stresses For Strip Pillars of Widths Ranging From 15 m to 50 m. The Pillars are Separated by 6,0 m Wide Roadways. The Pillar Height is 2,5 m and the Depth of the Coal Seam 320 m Below Surface.

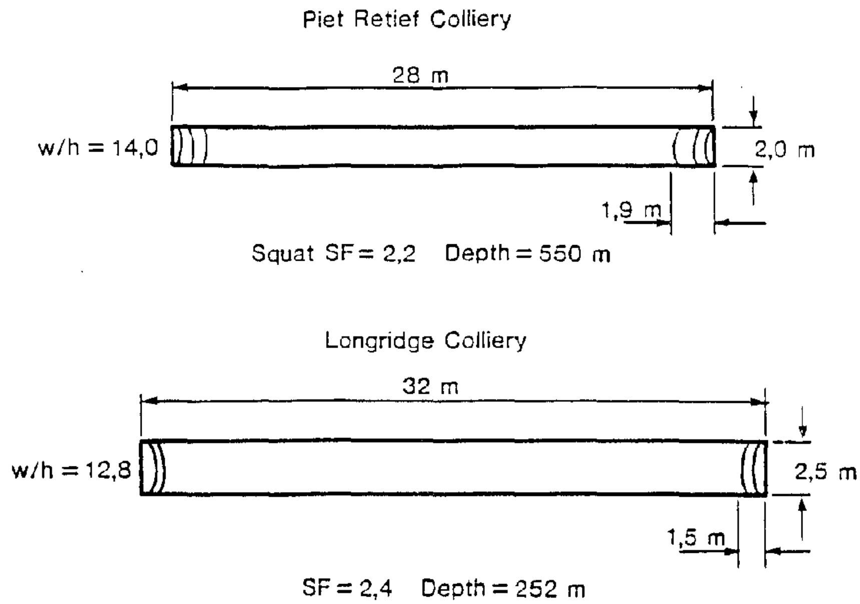

Figure 6. Sidewall Fracturing of Squat Coal Pillars.

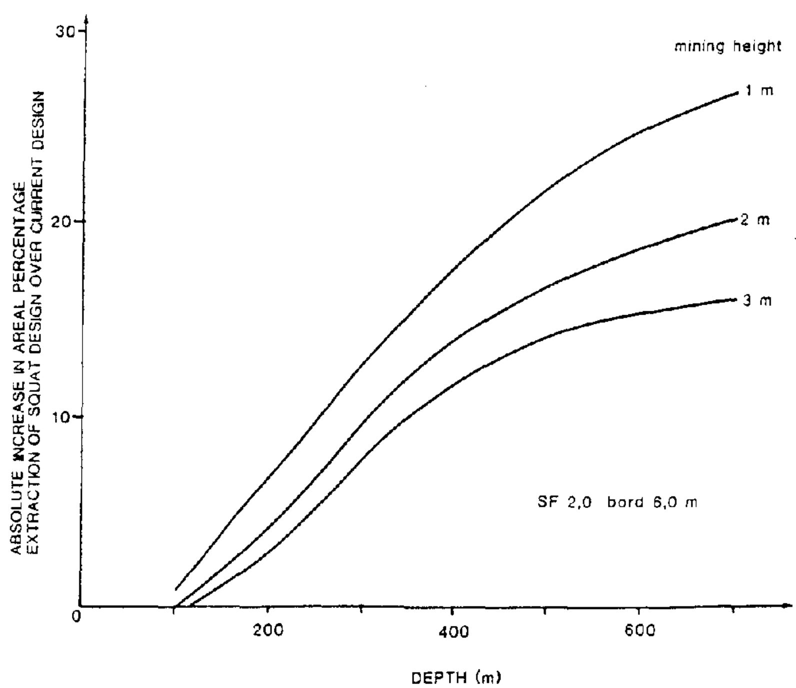

Figure 7. Improved Extraction Efficiency Resulting from the Squat Pillar Design Procedure.

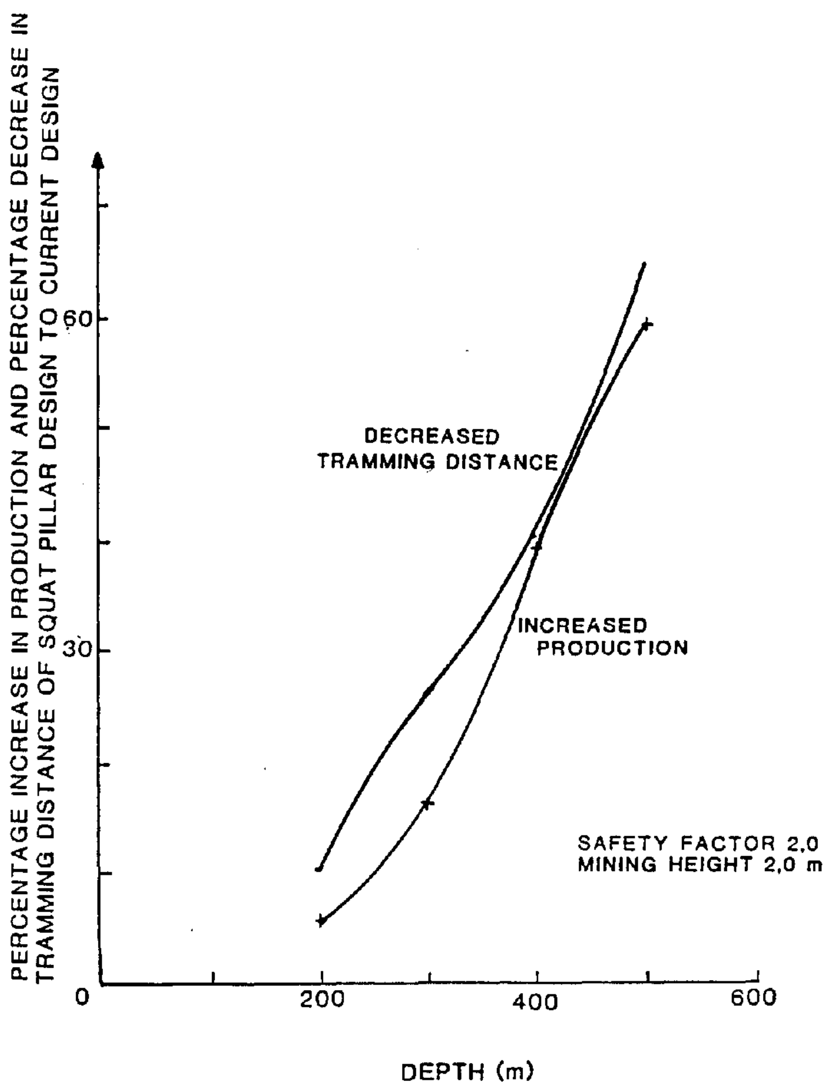

Figure 8. Effect of Squat Pillar Design on Production Efficiencies.

AUTOMATIC MALFUNCTION DIAGNOSIS BY ON-LINE EXPERT SYSTEM FOR UNDERGROUND MOBILE MACHINES

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ABSTRACT

In many underground workings, either for mineral production or for creating lines of communication, mobile machines have to operate under conditions that are very difficult for personnel and equipment. Problems such as excessive dust, rock falls, high temperature and humidity, or the presence of an explosive atmosphere are not uncommon. Today, it is possible to monitor such machinery from a surface station, in real time, using a highly reliable digital transmission system (developed by INERIS), at distances of up to 10 km from the working. Similarly, difficulties arising from in-situ maintenance have led to the development of an on-line malfunction diagnosis system that can detect such malfunction and halt operation by a conditionnal programmed stop. The software has been developed using Expert System techniques with GENESIA 1 (EdF-STERIA) and the hardware is compatible with IBM PC-AT. On-line communication is under JBUS protocol. Full analysis (data acquisition - processing - output) takes 20 seconds. The system can be interrupted at any moment to obtain correct status of operation.

INTRODUCTION

The mining environment in general, the working face in particular, is a hostile medium in which traditional industrial equipement has no place. Because the atmosphere may be explosive, all electrical equipment must either be protected against the risk of explosion or else must be intrinsically safe. Every installation requires adaptations to withstand rock falls, water, dust etc. On coal winning machines such as shearers, one must allow for vibrations and impacts, difficult access to components, lack of space in housings and high temperatures (up to 100 C).

Also, the risk of firedamp prohibits the use of live equipment, with open casings, for testing or repair work. In these conditions, it is all too easy to appreciate the importance of accurate, on-line diagnosis.

The developments described here are concerned with shearers, very powerful machines of 40 to 80 tonnes, 12 m long, fitted with two electric motors, each of 300 to 500 kW and the speed of which can be as high as 10m/min. In 1988 these machines provided 40% of the total coal production in France. It is easy to imagine the losses involved when such a machine breaks down.

In normal operation, the machine is radio-controlled (Figure 1). In automatic operation, with computerised on-line monitoring control from the surface, the personnel in the working may intervene to override and correct certain automatic instructions by means of radio-operated remote control.

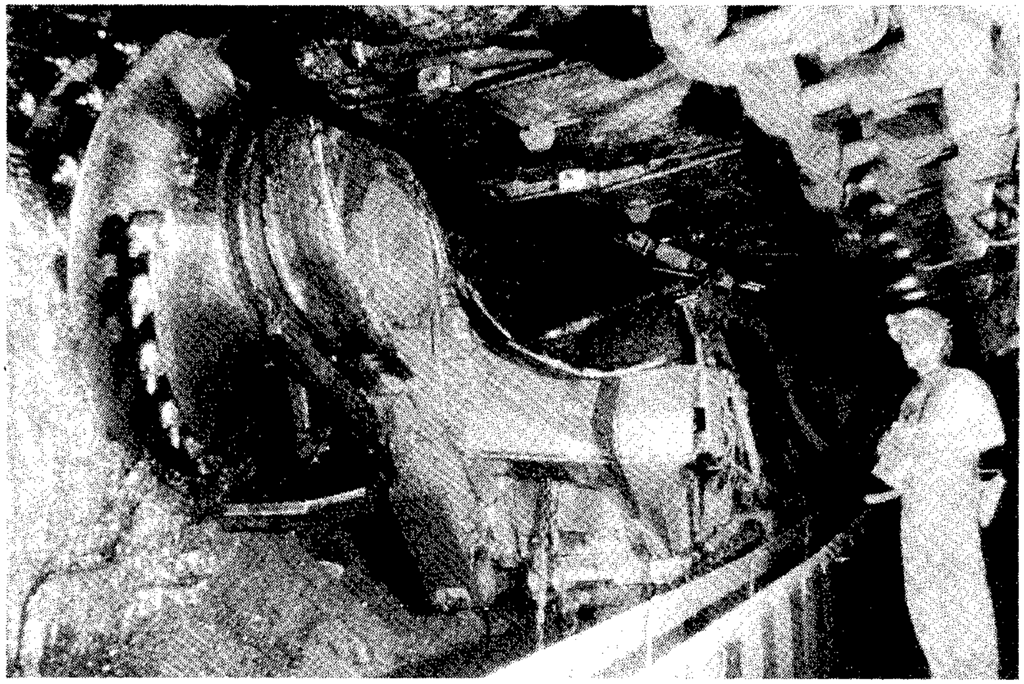

Figure 1 Radio controlled coal-winning machine

TELETRANSMISSION SYSTEM

Teletransmission is by the TELSAFE DV-CA system. This allows exchange of information between a mobile machine powered by an electric cable and a fixed point in the roadway or on the surface. It contains two independent groups working either simultaneously or separately on :

- a "tele-measurement" and "tele-signalling" channel for the acquisition of data on the state, position, functioning of the machine and the transmission to the micro-computer.

- a "remote-control" channel, allowing the transmission of messages formulated by the micro-computer for a monitor to be installed on the machine.

The shearer is also equipped with a series of transducers for obtaining the principal parameters characterising its functions. These data are collected in the machine, codified in digital form, then put into the power supply cables of the coalcutter via a coupler.

The power cable is necessarily in good state when the machine is running. So, we are sure that data can be transmitted. In the vicinity of the district transformer, the data are extracted from the power circuit, amplified and transmitted to the surface via a telephone pair.

The teletransmission capacity is 2550 useful bits per second (47 ms cycle) divided into 12 analogous measurements and 48 "all-nothing" data.

ON LINE DIAGNOSIS

A preliminary data-processing system for the on-line diagnosis of faults has been developed on a VME system under the MOTOROLA VERSADOS real-time operating system. The software, written in PASCAL, occupies 100k octets and is a sort of decision table which identifies what each particular group of data signifies as regards the state of the machine. A diagnosis as to the probable cause of malfunction is written and displayed in real time (Figure 2).

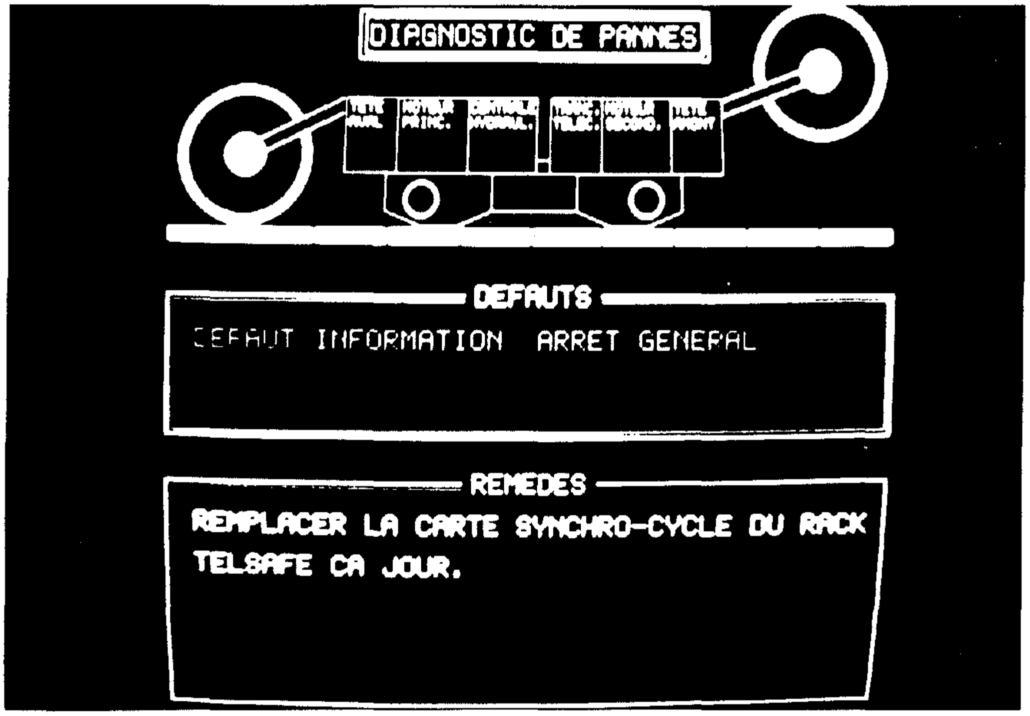

Figure 2 display of diagnoses with the PASCALprogram

The limitations of such software are the difficulties involved in parametering (considerable readjustment of the software in order to adapt it to the type of machine or to modifications in its instrumentation) and its unsuitability for treating cases of breakdown, where the diagnosis depends on the moment, the time or the sequence in which the events occur.
This software maintenance demands data processing services and limits the chances of success when applying the system to industrial operations.
In order to mitigate these disadvantages, the use of software of the "Expert System" type was decided on.

EXPERT SYSTEM ARCHITECTURE

Progress of data

The data transmitted by TELSAFE are sent via an on-line interface to the surface (frontal TELSAFE) ; this ensures the filtering and pre-treatment of certain data, which are then loaded into a JBUS letter box.
A serial link can be added to a real time VME computer for the monitoring and control of the movements and functions of the mobile machine underground. By a second serial link, the calculator, bearing a diagnosis of the operation (PC-AT compatible) consults the letter box of each inference (Figure 3), possible via modems.

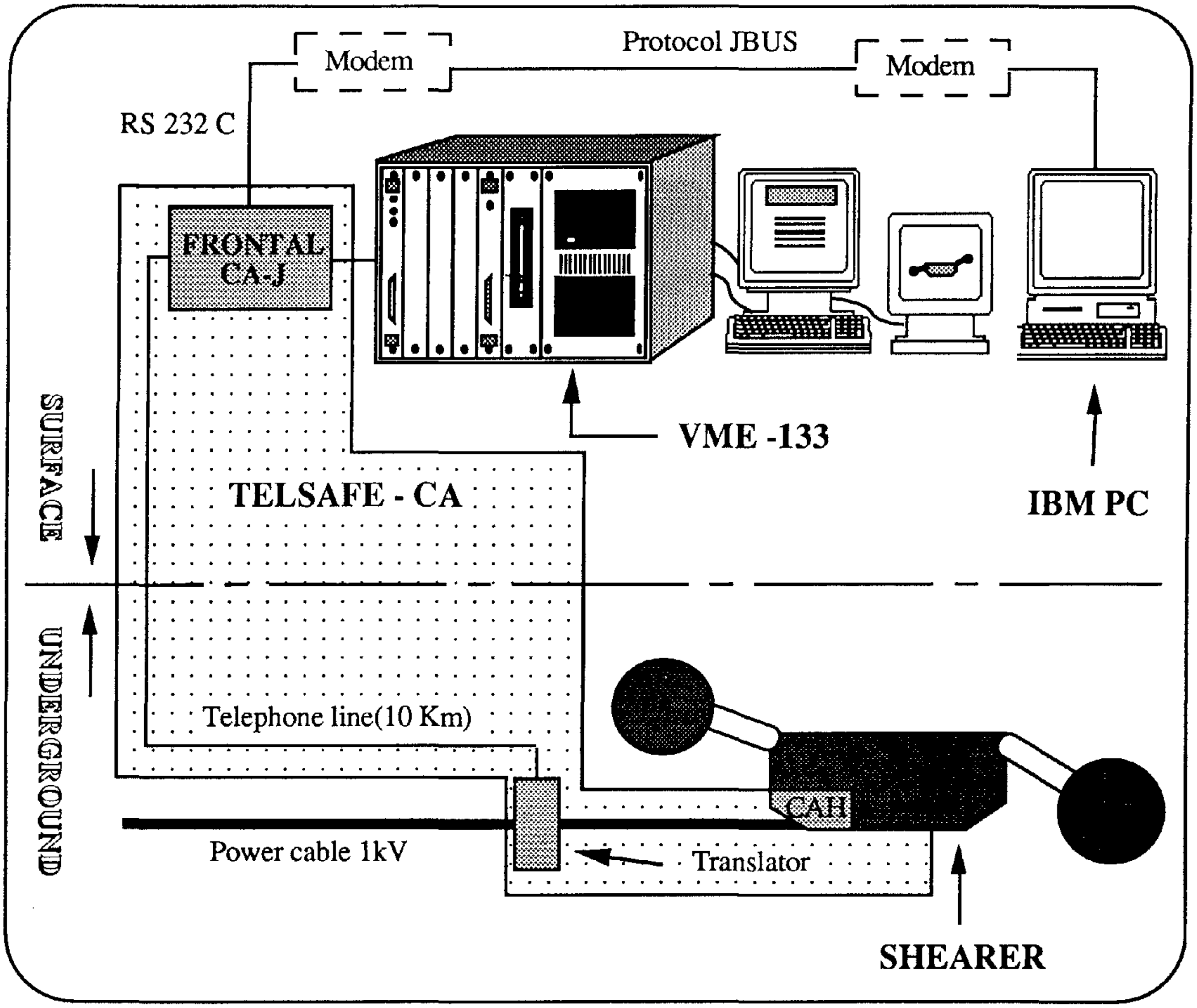

Figure 3 Progress of data

Hardware and software configuration

At present the machines used are COMPAQ 286 or 386 with 20 or 25 MHz of clock. The size of the group of files for the application is almost 1 Mo.

The generator

The generator of the GENESIA 1 expert system was adopted, for the following reasons :

- possible use, on-line, with the TELSAFE frontal which decodes the data from the shearer and manages the series link under the JBUS protocol ;
- the price is reasonable for a model for a feasibility study before extending the system to take in several mines ;
- consequent functioning on PC ;
- inference processing time is no more than a few seconds ;
- system of order 0+ ;
- possible explanation of diagnoses in order to facilitate development and give users confidence in this device ;
- it gives mechanical experts (who are familiar with the language used by automation specialists) a tool for development not requiring advanced training in data processing.

This Expert System generator functions with forward chaining. Programming is carried out by production rules of the kind IF...THEN,... The units processed may be of the chain,whole, real, unknown type.

It is possible to start an inference with the demonstrator. One may thus get to know :

- the rules involved ;
- the associated comments ;
- the reason why the premises were valid ;
- the original facts.

Special functions added to the generator

A certain number of special functions were incorporated, at INERIS's request :

- starting, without loading, a new inference with the same basis of rules, but operating on a new basis of facts ;
- acquisition of the variable CONVERGENCE, which changes to 1 when the inference is at an end ;
- writing in a file available at the end of the inference, without leaving GENESIA 1.

APPLICATION

Generality

The application consists of procedures written in Pascal and in C, files of data processing systems, by lots, starting DOS functions, with GENESIA run-time and basis of rules compiled.
The system is designed to work autonomously, without human intervention. The diagnoses are put on the screen of the PC, keeping pace with the inferences, every 15 to 45 seconds according to the processor used.
Each new diagnosis (occurrence of fault or return to normal) is recorded, with date and time, on a hard disc, in files peculiar to the machine inspected. These data can, likewise, be printed continuously.

Starting

It starts with a menu (Figure 4), which makes it possible :

- to select which machines one wishes to connect ;
- for central technical services, to compose, automatically, the telephone number to reach the corresponding modem ;
- to start the diagnosis (or other applications) ;

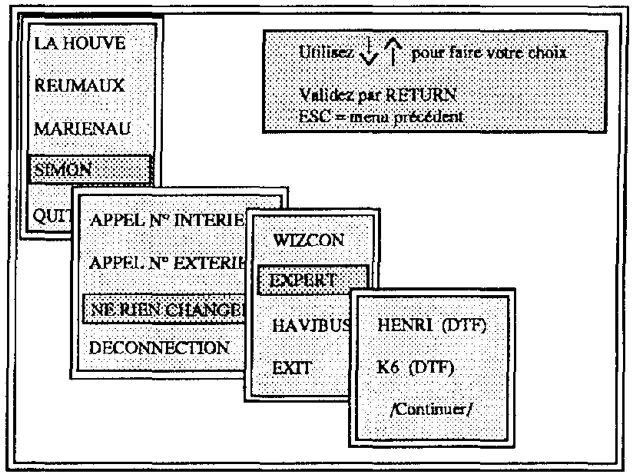

Figure 4 Main Menu

Another menu (Figure 5) gives an access, for each selected machine, to its related list of informations. This list can be edited and any information described in it can be inhibited. So, it is possible to tell the system not to consider an information if a sensor is disconnected or failing.

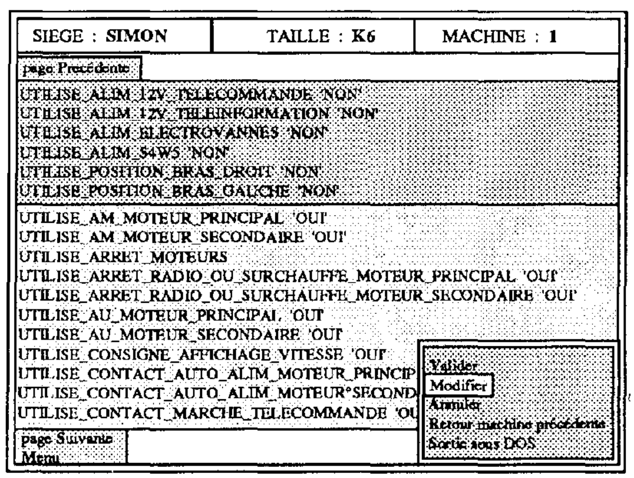

Figure 5 Sensor select Menu

Cyclic diagnosis

When this preliminary work is done, cyclic diagnosis can be launched :

- machine #i information reading,
- fact base construction,
- inference start on the basis of 200 rules, diagnosis elaboration,
- results printing (Figure 6),
- diagnoses edition (on disk or printer),
- if there is a new default, fact base saving for a future explanation,
- iteration for machine #i+1.

```
INFORMATIONS NON TRAITEES :                                   "Echap" pour
  .position_deux_bras                                          .Explication
  .alim_electrovannes                                          .Sortie DOS
  .alim_S4W5
  .alim_12V_télécommande

                    >> "Pause" pour FIGER   "Return"" pour REPARTIR <<
= SIMON K6 DTF1=== DTF_2_V5.07_du_14/06/90=====18/06/91  10:41:30=

  ALIMENTATION TRANCHE TELECOMMANDE
      Défaut d'au moins une phase

= ESC arrêt moteur=====================================Cycle n° 5=
```

Figure 6 Diagnosis screen

Explanation of the diagnosis

It is possible, at any moment, to stop the system in order to ask to follow the reasoning on which the diagnosis was based. This procedure enables one to visualise each of the rules validated, with its commentary, and to return, step by step, to the premises of the fact base (Figure 7).

```
Voici la règle qui a déduit le fait à démontrer ...
 CIRCUIT_GAVAGE = DEFAUT POMPE ou FILTRE, règle CENTRALE10

 REGLE CENTRALE10

 SI
      SEUIL_PRESSOSTAT_GAVAGE  =  0
 ALORS
      CIRCUIT_GAVAGE  <-  'DEFAUT POMPE ou FILTRE POSSIBLE'
   ET  CIRCUIT_HUILE_PRINCIPAL  <-  'FUITE POSSIBLE D'HUILE'

 Commentaire associé à cette règle  :
 Le défaut peut résulter d'un manque de gavage
   ou d'une fuite d'huile du circuit principal

 Tapez sur une touche pour continuer ...
```

Figure 7 Diagnoses Explanation

Utilisation

The system has been is use at the Unite d'Exploitation REUMAUX of the Houilleres du Bassin de Lorraine since April 1990. The principle qualities recognised are :

- accuracy of diagnosis permitting emergency repairs without proceeding by trial and error ;
- possibility of keeping the system in service even if a transducer is faulty ;
- explanation given as to the manner in which the diagnosis has been established.

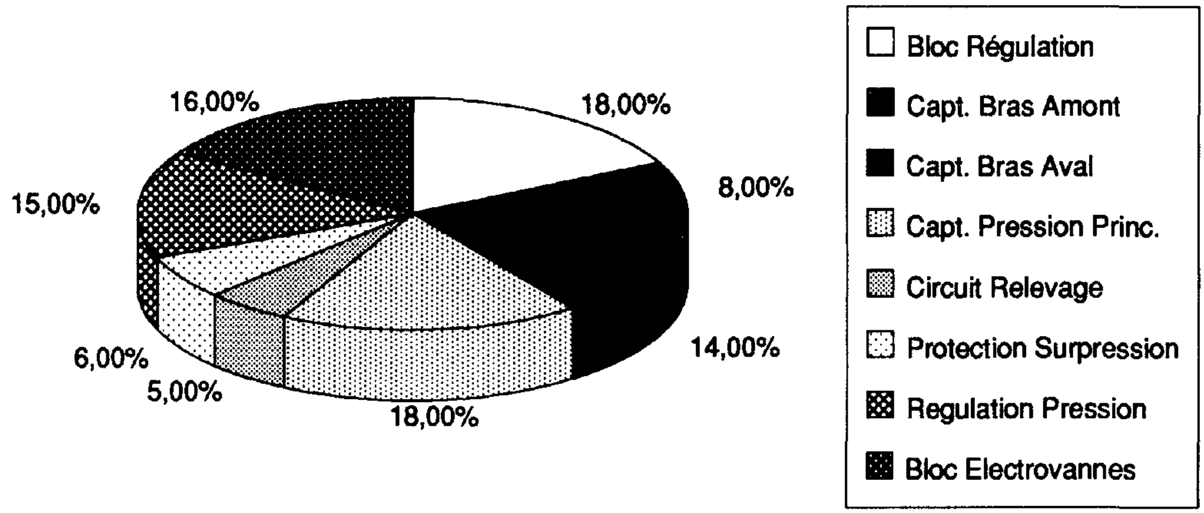

Figure 8 Frequencies of occurrence of faults classified by types of affected devices

CURRENTS DEVELOPMENTS

An application has been developed to consult the file of diagnoses by the shift, the week, month or operational cycle (5 months to 1 year or more), in order to get to know the most frequent and long-term faults etc. Statistical information on frequencies of occurrence of faults, classified by types of affected devices, can be displayed automatically (Figure 8).
The use of files over a long term will make conditional and preventive maintenance possible.

Extension to all types of machines

The rules written for the DTF shearer may be partly adopted for other types of machine. Even now the system is ready to select rule bases corresponding to the different machines working in a mine.

Spending-up the scanning cycle

Modification of the structure of application and better use of the resources of the PC should halve the time necessary for establishing a diagnosis.

Transfer to machines

INERIS's current improvements to the TELSAFE CA transmission system will extend the present possibilities of surface-to-underground. It will soon be possible to use a display unit on the machine, in order to bring the diagnoses as close as possible to the site.

Consideration is also being given to the installation, on the machine, of a sufficiently powerful and robust computer, in order to process the data at source. Such an installation which would no longer be limited by the rate of transmission over a distance, could deal with rapidly developing values (vibrations, starting power etc.) containing very important information as regards maintenance.

EXTENSION TO OTHER APPLICATIONS

The architecture of the system developed can, even now, be easily applied, to monitor any industrial process having development times of the order of a few seconds.

NUMBAT

A Mine Emergency Survey Vehicle

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ABSTRACT

NUMBAT is a single hulled, eight wheeled remotely controlled survey vehicle for use in underground coal mine emergencies. It sends information on underground conditions such as atmospheric composition, wind speed and temperature to the surface via a single optical fibre, with backup via low frequency radio. Navigation uses imaging via video or an acoustic imaging system, which also provide details of the physical condition of the mine..

1. INTRODUCTION

An emergency mine safety survey vehicle, code named NUMBAT has been developed for use in coal mines. The name is not an acronym; it refers to the nocturnal Australian marsupial.

The primary function of the vehicle is to provide detailed information on underground conditions to the surface following an emergency. It will be operated in support of rescue crews, and will provide operators with reliable information for planning rescue and mine rehabilitation while lessening the exposure of rescue personnel to hazardous conditions.

The underground environment, particularly in the post emergency situation (eg after fire or explosion) presents a number of difficulties for vehicle operation. These include access over challenging terrain following roof falls and water inflow, communication and control in the underground working complex, navigation in smoke and/or dust, and operation in explosive atmospheres.

This paper describes the complete NUMBAT system which has been developed to fulfil the above functions.

2.THE NUMBAT SYSTEM

This section summarises the overall specifications of the main elements of the system.

2.1 Operational Requirements

The NUMBAT concept is based on telepresence, allowing remote operation of the vehicle. Two operators in a surface station control the vehicle and receive data from it via a bi-directional communications link. The driver is responsible for piloting the vehicle through the underground workings, while the mission commander is responsible for the overall mission, including navigation, environmental sensing and vehicle condition management.

2.2 Environmental Sensing

The primary sensing requirement is to determine the composition of the mine atmosphere. An instrument package on the vehicle provides analyses of gases of interest. Dust concentration and wind speed are also measured.

Visual sensing of the environment for navigation is provided by a two camera stereo vision system, and for inspection by a third video camera with variable focus and zoom. Lighting is provided by five sealed beam incandescent lamps.

Navigation in opaque atmospheres is possible using a novel sonar array imaging system which produces a coarse resolution image of the area up to 25m in front of the vehicle.

2.3 Vehicle Configuration

The vehicle provides a platform for the sensing and communications systems, and is strongly constructed to negotiate obstructions which could be present following an explosion. It carries sufficient stored energy to enable missions of reasonable range and duration to be undertaken. An initial design range of 2km was chosen. (Leach et al. 1988)

2.4 Communications

The communications system used is determined by the bandwidth of the information which must be transmitted to and from the vehicle, and by the environment in which the communication must take place. The link from the vehicle to the surface (in this case the uplink) requires the larger bandwidth, carrying two video channels, acoustic imaging data, telemetry, and an audio channel. The downlink carries only command information and an audio channel, and consequently requires a lower bandwidth, but has a higher requirement for data integrity. Voice channels are provided in both directions to allow communication between the surface and underground rescue personnel. A single optical fibre deployed from the vehicle is used for bi-directional wideband communications, and a low frequency radio backup system is available for limited operation in case of failure of the high capacity system.

3. THE NUMBAT VEHICLE

Since the primary purpose of the vehicle is to replace human rescue crews in the initial re-entry to a mine after a disaster, and to travel no further than a human could reasonably go. It is not necessary to provide capability to traverse extreme terrain. It was decided that the vehicle should be able to cross obstacles such as soft going, loose rock piles and fallen timber, and to self propel across water bodies. These are conditions that are likely to be encountered. For this purpose a single hulled design was chosen, rather than more complex articulated forms.

3.1 Vehicle Construction

The vehicle is of steel construction, 2.4m long, 1.7m wide and 1.15m high. It has 8 rubber tyred wheels, each 600mm in diameter. Two drive motors, each developing 1.5 kw power all wheels on each side. Four quadrant servo control of each motor permits tight radius skid steered operation. Energy storage is provided by a 48V 78Ah battery giving a 2km operating range.

The vehicle hull is sealed for two reasons. First, operation in explosive atmospheres requires that the external atmosphere does not enter the vehicle hull. In order to achieve this, an over-pressure of nitrogen is maintained in the hull. A system of interlocks based on relative internal and external pressure measurements disconnects the vehicle electrical supply if the safety margin is not exceeded. Second, flotation of the vehicle is possible to traverse deep water. Two 200mm propellors, driven by the traction motors via mechanical clutches were originally fitted to provide propulsion through water. These have now been removed as it has been demonstrated that sufficient thrust is obtained in water from wheels alone.

3.2 Optical Fibre Cable Management System

A single glass fibre is used for communications. The reasons for the choice of fibre optics as the communications medium will be given later. The outside diameter of the complete cable is 3mm, and is carried on a drum with 2km capacity in the vehicle. This quantity of cable is compatible with the range allowed by the battery. The cable is deployed as the vehicle moves forward, and is rewound onto the drum as the vehicle reverses. A low tension is maintained in the cable to provide the input to the reel servo control system.

The cable management system operates as an independent vehicle sub system not requiring specific control from the surface station. The reeler automatically responds to changes in the tension in the paid out cable caused by vehicle motion. If the vehicle moves forward this tension will initially increase, so more cable is paid out until the tension reduces to its former value. If vehicle motion is continuous, the deployment of cable will occur at the same rate.

Cable drums are field replaceable, so the range of the vehicle from the surface station can be extended past 2km.

3.3 Acoustic Imaging System

The primary requirement of this system is to operate in real time, and to deliver images having sufficient detail to enable the vehicle to be manoeuvred safely. This system is described in detail in Jacka 1989.

Ultrasound is used rather than electromagnetism as the propagating energy since its lower velocity leads to a correspondingly lower operating frequency and signal bandwidth. Cheaper electronic implementation is also possible.

Resolution in the final image is dependent largely on the aperture of the imaging system. In this system, a phased array of elements is used in association with a beam forming technique to increase aperture. The electronically formed pencil beam is scanned across the region in front of the array and the responses from all parts of the region are displayed as an image of the total area. The display can be arranged as either a perspective (or 'front-on') view or a plan view.

The acoustic imaging system records 200 samples from each of 16 transducers using a carrier frequency of 25kHz, and produces an image containing 512 points every 2 seconds.

3.4 Gas Analysis System

Atmospheric concentrations of methane, carbon monoxide, carbon dioxide, oxygen, and hydrogen are measured. In addition, dust concentration, air velocity along the vehicle axis, air temperature and pressure are measured.

The sample gas stream is filtered, dried and cooled before being pumped through a system of analysers which use non-dispersive infrared and thermal conductivity measurement techniques to determine gas concentrations. A cylinder of calibration gas is carried in the vehicle to allow periodic remote calibration of the measurement system.

A retractable miniature propeller anemometer is used to measure air flow along the tunnel axis to test the state of the mine ventilation system. Since ventilation air velocity is small, the vehicle will be stopped when the anemometer is deployed and air velocity measurements are made.

The analysis systems can function continuously, but to minimise power consumption can also be operated intermittently, requiring a 10 minute warmup period. A separate analyser is used for each gas, so that useful operation is possible after partial failure of the system.

4. NUMBAT COMMUNICATIONS

The primary communication channel is a multi-mode fibre optic cable deployed from the vehicle in the manner described earlier. A single fibre forms a bi-directional channel with wavelength division multiplexing separating the 125Mbps uplink data in the 1300nm optical band from the 2Mbps downlink data in the 850nm band. This system is described in detail in Marson 1989.

The optical communication technology used in NUMBAT departs from that used in previous well known remote vehicles of this type such as the Echidna and the Three Mile Island robots (CMU 1988), which use co-axial cable dispensed and retrieved from the vehicle. Radio communication has been used successfully in mine communications, but with low capacity. The bandwidth required for NUMBAT would necessitate the use of microwave radio which is limited to line of sight propagation. This would require the use of repeaters which would have to be carried on the vehicle. Provision would also need to be provided to dispense and retrieve the repeaters. Radio was discarded because of complexity, leaving some form of cable as the physical link. The long design range of the vehicle meant that coaxial cable was unsuitable because of size and weight, leaving optical fibre as the default choice. Fibre also has the advantage that it is non metallic, and thus is intrinsically safe, but to detract from this it is relatively fragile.

4.1 Wideband Communications System

The uplink data consists of two CCIR standard video channels, digitised at 7.8125 Msamples/s, acoustic imaging data at 115kbytes/s, audio at 8kbytes/s, and sensor data at 1.6kbytes/s which are multiplexed onto a 125Mbps serial data stream.

The downlink carries the command data for vehicle control and a voice channel and operates at 2.048Mbps. This link employs coding for forward error control to maintain integrity of control information.

4.2 Backup Communications

Full vehicle operation requires a wideband communications link which, as described above,in the underground environment can be realistically supplied only by the fibre optic system. Unfortunately the optical fibre cable is susceptible to damage which would render the vehicle useless. Because of this possibility, a backup communications system in the form of a low frequency radio link has been developed (Bunton 1989). Electromagnetic energy at this frequency propagates downlink directly through the rock between the surface and the vehicle. Communications uplink can propagate either back through the rock or via a coal seam acting as a waveguide to an antenna situated at a safe place in the mine. Development is continuing on this system.

Communication speed on the backup system is very variable, depending on local conditions, and is measured in seconds per bit rather than bits per second, so wideband communication is impossible. However, limited contact can be maintained with the vehicle to provide environmental sensing capability with retrieval of low speed data.

5. NUMBAT SURFACE STATION

5.1 Configuration

The prototype surface station has been established in a caravan measuring 4.2m by 2.2m. The driver and mission commander sit at a desk on which are mounted the vehicle and camera controls. The desk is located transversely at the centre of the long axis of the van, which allows space in front of the desk to project the video display, and allows other observers to stand behind the operators. The control desk also houses the uplink data display screen which is in front of the mission commander, and an auxiliary display screen for the uplink video for viewing by the driver.

5.2 Video Displays

The NUMBAT vehicle carries three video cameras. Two form a stereo pair, which are operated in fixed focus mode. Mechanical convergence is possible to provide optimal three dimensional viewing. Images from these cameras are displayed using R-G colour separation in a colour projection monitor. The display is viewed using filtered glasses and adequate depth perception is achieved.

A third camera, mounted with the first two in a pan-tilt head, is equipped with remote focus and zoom controls to allow close inspection of items of interest. Video switching allows a choice of video feed for the display devices.

If the backup communications system is

used, a method has been devised to transmit video images of the mine environment efficiently using reduced bandwidth. A frame grabber card in the vehicle computer digitises the output from any camera. A compression algorithm is used to reduce the volume of data used to represent the image, which is then transmitted over the radio link. On reception at the surface, the reverse process is followed, and the reconstructed image is displayed.

The frame grabber system in the surface computer also makes it possible to display the acoustic imagery and other computer generated information on the large screen.

6. NUMBAT COMPUTING

The NUMBAT vehicle is controlled by distributed computers within separate system segments. On board, the vehicle computing engine is an 80286 machine, while the cable reeler is controlled by a special purpose 80C552 based microprocessor system, and the gas analysis package employs a single board 8088 computer.

At the surface station, a 80286 based PC is used to process the control and status information, and the acoustic imaging data is processed and displayed using an 80386 platform.

7. DEPLOYMENT

The NUMBAT system should have ready access to mines so it can commence operations within a few hours of a mine emergency occurring. It will precede Mine Rescue Brigades into workings and ensure that they are not placing themselves at unnecessary risk. It is normal for the rescue teams to commence rehabilitating the mine as soon as possible, with ventilation circuits being set up with temporary bratice, and fresh air bases established as soon as possible. The NUMBAT can be deployed for a kilometre in front of these fresh air bases.

If a circumstance arises where it is no longer deemed safe for rescue parties to proceed further, the NUMBAT can be sent up to 2 km into dangerous conditions, to obtain information is required on the circumstances of lost miners, or seeking evidence of the cause of the emergency.

Although it is possible that the NUMBAT could reach miners and supply life saving assistance, it is considered that this is likely to be a rare occurrence, given the catastrophic nature of coal mine disasters. It is primarily designed as a tool for use by rescue brigades.

It has a role in non-emergency settings also. Areas of mine which have been abandoned or not inspected for a period could be evaluated by the NUMBAT prior to re-entry. Closed areas of a mine with suspected heating problems could also be remotely monitored. There are other non-mine situations in which a remotely controlled sensing vehicle has applications.

8. CONCLUSIONS

The NUMBAT is one of only two post-emergency coal mining survey vehicles known to be under development world wide. The other is being produced by the Coal Mining Research Centre Japan. Details are as yet unreported.

The normal problems of communication, control and sensing in the underground environment have been increased by the possibility of operation in explosive or opaque atmospheres, as well as encountering roof falls and water inflow. These problems have been addressed and workable solutions found.

Improved vision, navigation, and communication systems will result directly from this project, and areas for future work, particularly in the realm of autonomous vehicle operation have been identified.

The achievement of the main purpose of the vehicle; the provision of real time data on the atmospheric conditions and physical state of a mine without danger to rescue teams will hopefully assist in rescue and mine rehabilitation, with social and economic benefits to the mining industry.

9. ACKNOWLEDGMENTS

This project has been developed by CSIRO Division of Geomechanics, with help of a NERDDC grant. A number of companies and research groups have been responsible for specific system components.

CSIRO Radiophysics - Communications and Acoustic imaging.
CSIRO Coal Technology - Environmental sensing.
Evans Deakin Industries - Vehicle construction.
KEL Aerospace - Fibre optic cable system.
Queensland Uni of Technology - System Integration/Electronic design.

The initial specifications for NUMBAT were achieved by consultation with rescue staff, unions, management, and government authorities (Leach et al. 1988).

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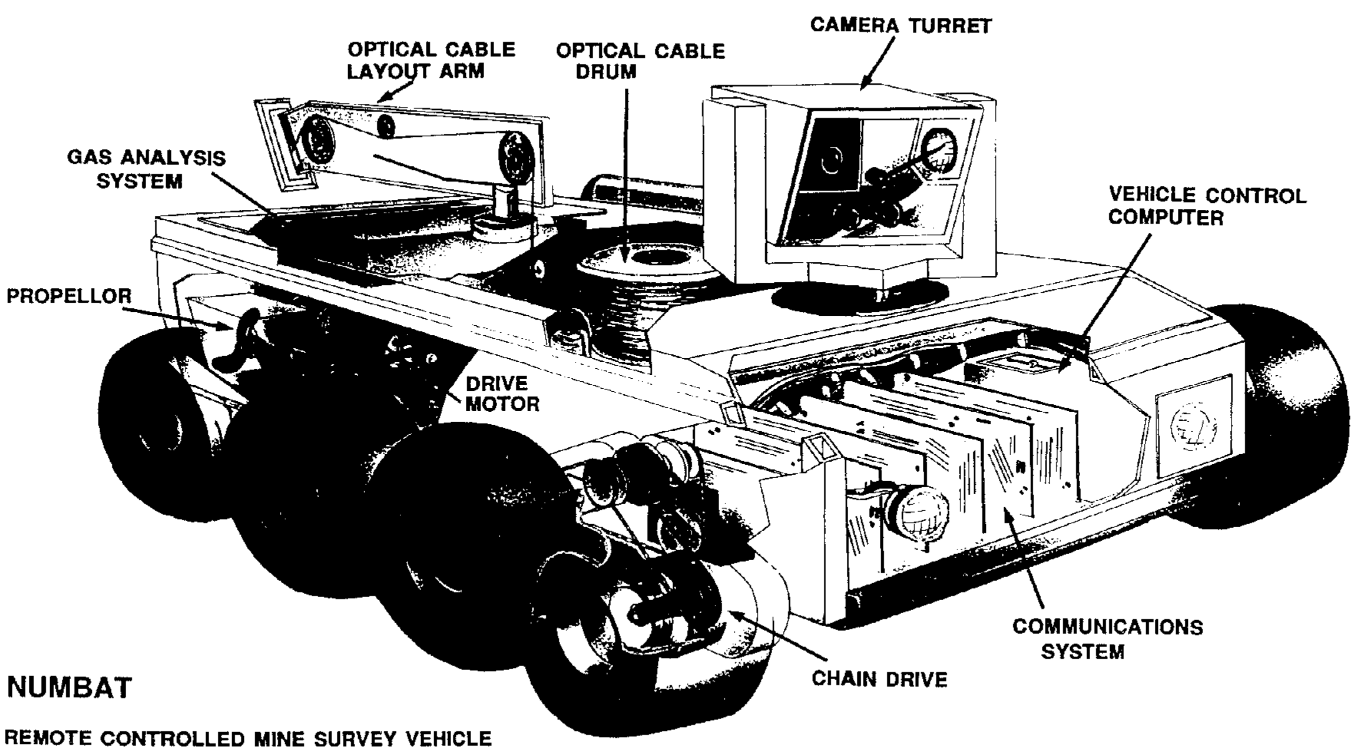

NUMBAT

REMOTE CONTROLLED MINE SURVEY VEHICLE

Automatic Computerised Jig Control

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ABSTRACT

A computerised control system was developed for a commercial Batac jig that required less operator attention for routine operation, and produced more stable operation than the original control system. A patented nucleonic-based density measurement instrument provides an on-line signal of bulk density variations in the jig bed near the refuse discharge mechanism to the control system. The combination of this new instrument and the digital computer control system is responsible for a reduction in down-time and an indicative performance gain of 1% yield for the jig.

This paper describes the control system and the density measuring instrument and sampling techniques used to measure the control system performance. Results from these investigations are presented.

The work was funded by the National Energy Research Development and Demonstration Program of Australia over a two year period.

INTRODUCTION

The project objectives were to develop an understanding of how jig operating variables influence jig bed stratification and then construct a computerised control system for the regulation of jig cut point and improvement of separation efficiency. A new nucleonic-based system for measurement of jig bed density was to be used as the primary sensor in the system.

The project was carried out in two stages; the first stage involved extensive metallurgical testing of the jig to determine its response to changes in operating variables such as pulsation frequency, air valve opening and closing times, underbed water flow rate, and weir bar height. Samples of feed, product and reject streams were taken to carry out size-by-size material balances and bed samples were taken to determine the density stratification of coarse and fine particles. The second stage of the work involved the installation of the nucleonics equipment in the jig bed and the interfacing of the jig to the process control computer followed by commissioning and testing of the control system. After simple metallurgical testing had indicated the approximate relation between control system set point and jig cut point, a series of metallurgical tests were carried out to compare the operation of the jig under computer and conventional control.

The control system design is based on a model of coal transport in the jig bed. All functions in the jig are considered in terms of the flow of coal and water along the jig bed.

Raw coal is fed on to a perforated bed plate through which a pulsating water current flows, and progresses to the end of the jig. The pulsating water current is created by admitting and exhausting air from chambers under the jig, and additional water is supplied under the bed plate to assist in the transport of the coal bed along the length of the jig.

The pulsating water (jigging) action results broadly in the separation of the raw coal bed into a shale layer on the bed plate, covered by a layer of cleaner coal. These two layers are separated by a refuse gate mechanism and weir bar; the shale passes through the gate into the hutch below the bed plate, and the clean coal flows over the weir bar into the next section of the jig or to the clean coal product. The reject gates must be controlled to regulate the relative rates of flow of the refuse and product streams. Some small coal or shale particles may be drawn through the bed plate during the suction phase of the pulsation.

One way to control the reject gate is to insert a float in the jig bed that measures the position of the top of the shale layer. A feed back loop between the device signal and the reject gates, controls the depth of the shale layer to the desired set point value. Other jig designs control the movement of coarse shale into the hutch based on the peak water pressure beneath the bed plate. The peak water pressure is assumed to be related to the average density of the bed which increase both with thickness of the total bed and shale content of the bed. The passage of coal or shale particles through the bed plate is never automatically controlled, but is considered to be controlled by increasing the underbed water flow in order to mitigate the water velocity during the suction part of the stroke. Recent research (Rong and Lyman, 1991) has shown that suction velocity cannot be changed by changing underbed water flow; instead, it has been recognised (Lyman *et al.* 1990) that an increase in underbed water flow decreases passage of fines through the bed plate by reducing the residence time of fines in the jig bed due to the higher horizontal water velocities in the bed that result.

The initial development of a control method using a density gauge was by Bartelt (1962); he measured the mean wet bulk density of the bed over the entire jig cycle. A 200 mCi. (7.4 GBq) radiation source was used. However, for safety reasons and due to the climate in the German coal industry at the time, this system did not come into general use.

Modern high count-rate electronics for NaI(Tl) scintillation detectors permit the use of a much smaller source, and count-rates can be collected over precise consecutive time intervals in the jig cycle, so that the variation of wet bulk density during the jig cycle can be determined. Control based on such time-varying signals has been patented. The control system described in this paper is based on this new technology.

CONTROL SYSTEM DESCRIPTION

The new control system (JIGSCAN) illustrated in Figure 1. consists of a control computer, an interface to the jig, the nucleonic density gauges, and a personal computer used as an operator interface.

Original instrumentation and actuators on the jig were electrically connected to the hard-wired relay-based (Batac) controller before the development of JIGSCAN. The only extra instrumentation added to the jig was the installation of the nucleonic density gauges to measure the wet bulk density of the jig bed. These gauges will be described later in the paper.

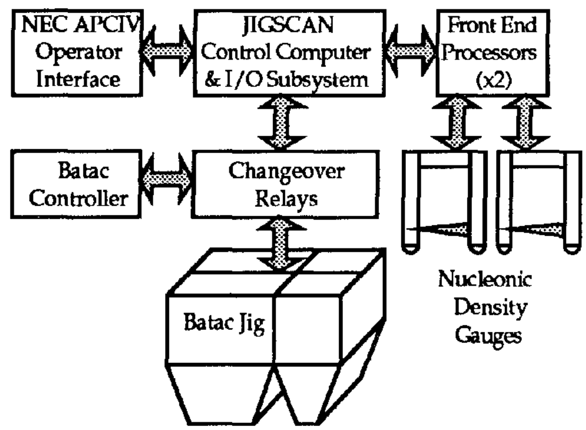

Figure 1. JIGSCAN Overview

Interfacing to the jig was a straightforward matter of providing relays to switch the electrical signals connecting the jig to the Batac controller to the JIGSCAN controller. This manual switching mechanism permitted a rapid change between the two control systems to be achieved with a minimum of downtime (typically less than 1 minute).

The JIGSCAN control computer uses standard commercially available hardware and consists of a rack based single board PDP 11/21 computer with associated support cards and appropriate analogue and digital input/output cards to transfer signals to and from the jig.

Custom-written control software running under a simple commercial multitasking operating system is used to implement all control actions. Timing of the control actions and hence the jig cycle parameters is achieved with a programmable count-down timer using a crystal clock to generate precise and repeatable intervals.

An NEC APCIV personal computer (IBM PC-AT compatible) is connected to the control computer by an RS-232 interface. The personal computer runs custom-configured commercially available software that provides an operator interface for the jig, but does not perform any control actions.

Software for the control computer was developed in two stages and was initially designed to emulate the operation of the Batac controller. By the time this first emulation stage was completed and commissioned, a number of embellishments to the standard Batac controller features had been added to improve performance, and to relieve the operator of some otherwise tedious duties. The emulation of the Batac controller, which regulated refuse extraction from signals from the jig floats, was therefore already an improved controller that found favour with the operators.

For example, a control algorithm to maintain an average water level in the under bed chambers was implemented to prevent the water pulsation from being disrupted when the level limit alarms at the top and bottom of the air chambers were tripped. These level limits on the Batac controller prevent escape of air up through the bed or entry of water into the pipes connecting the air chambers to the air valves. Previously, level control in the air chambers was implemented by the operator manually adjusting the closing time of the exhaust valves; this was time consuming and could not be carried out more frequently than on a two hour basis.

Further, an algorithm for refuse gate control was implemented that was more appropriate to the sampled control signal from the float. The algorithm provides substantially smoother start-up characteristics. In the course of improving control using the float signal, a simple mechanical modification to the float was made to improve the linearity of the float position measurement.

The second stage of software development implemented the software to collect the information received from the nucleonic density gauges and to turn them on and off. Jig control algorithms were implemented based on the information contained in this signal and on the previous improvements to jig control.

NUCLEONIC DENSITY GAUGES

The gauges consist of a U-shaped stainless steel frame with two legs, one containing a 15 mCi (740 MBq) ^{60}Co source and a pneumatically actuated fail-safe shutter and shielding assembly, while the other leg contains a NaI(Tl) scintillation detector, and appropriate power and pulse shaping circuitry. The design complies with National Health and Medical Research Council guidelines for the safe use of radiation gauges. The leg diameter is 145 mm and the two legs are approximately 500 mm apart. Each gauge is held in the jig bed by a lifting mechanism which permits manual positioning to a specific beam horizon (distance between beam axis and bed plate) in the jig bed.

A total of four gauges were installed in the jig bed; a pair of gauges was located immediately upstream of the first pair of reject gates which allow removal of coarse shale from the jig and the second pair was located at the end of the second section of the jig. The second section of the jig removes only fine shale through the bed plate and the third section of the jig makes no separation at all.

The positioning of the gauge with respect to the jig bed, floats, and refuse mechanism is illustrated in Figure 2. The rate of refuse removal is controlled by varying the refuse slot dimension by raising or lowering a bar of triangular cross-section (shown) using an hydraulic ram (not shown).

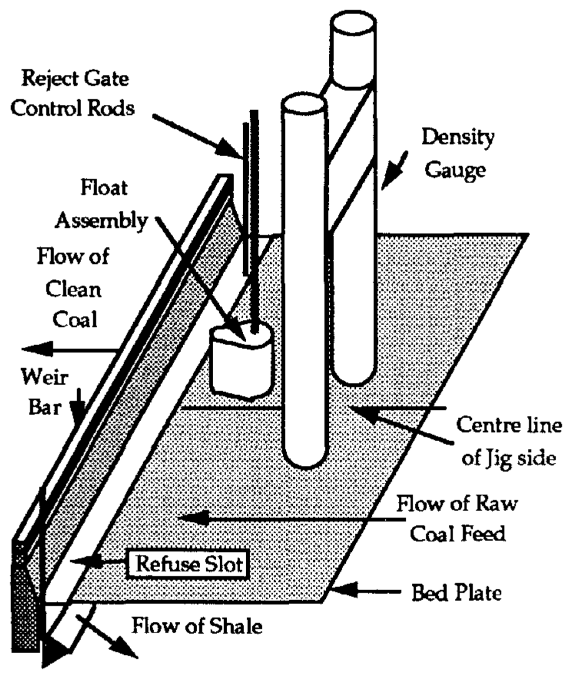

Figure 2. Arrangement of Gauge in the Jig Bed

The pulse counting and gauge safety interlock functions are performed by a computer system in the front end processor (FEP). The FEP cumulates count rates from the gauges for each of sixteen time 'windows' in the jig cycle, averages the value for each window over a number of jig cycles, converts these values to densities and transmits the results at regular intervals over an RS-232 link to the JIGSCAN control computer. The JIGSCAN control computer in turn is responsible for sending a signal to the FEP when the jig cycle starts, and when the gauges are required to be turned on.

The density gauge measures the wet bulk density of the jig bed using the familiar radiation absorption equation:

$$\frac{I}{I_0} = \exp(-\rho\mu L) \qquad (1)$$

where

ρ	$\equiv$	density
μ	$\equiv$	the mass attenuation coefficient
L	$\equiv$	path length through the jig bed
I_0	$\equiv$	effective source intensity
I	$\equiv$	measured intensity

The effective source intensity decreases over time due to source decay, however a simple correction equation can be used to correct for this effect if the elapsed time since calibration is known.

It is important to note that the wet bulk density is a function of both bed voidage (fraction water in the bed) and average coal particle density as shown in equation (2).

$$\rho_b = \rho_s (1-\varepsilon) + \varepsilon\rho_w \qquad (2)$$

where

ρ_b	$\equiv$	wet bulk density
ρ_s	$\equiv$	coal density
ρ_w	$\equiv$	density of water
ε	$\equiv$	volume fraction of water in bed

DENSITY GAUGE RESULTS

The gauges were installed in the jig bed and calibrated using $ZnCl_2$(aq.) solutions of various concentrations and a special trough the fit over the ends of the gauge legs.

With the jig in operation, and controlled by the floats, the density signal from the gauges was collected at various horizons in the jig bed. The signal at each horizon was resolved into sixteen 60 msec increments during the 1000 msec jig cycle. The result of this experiment is presented in Figure 3. as a three dimensional graph of wet bulk density of the coal bed (vertical axis) with respect to height above bed plate (increasing from back [160 mm] to front [500 mm] of the graph) and time within the jig cycle (left [30 msec] to right [930 msec]).

Three regimes of behaviour can be identified in the jig bed motion and dilation. At the top of the bed, as the jig cycle progresses, the clean coal lifts into the beam increasing the apparent bed density. Towards the end of the cycle, the coal drops out of the radiation beam leaving the radiation beam in the black water.

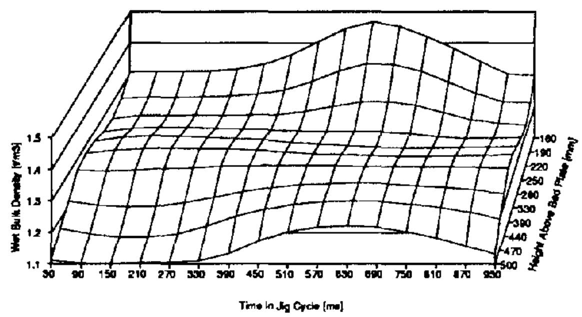

Figure 3 Typical Jig Bed Density Signal

Somewhat deeper in the bed, the radiation beam is completely immersed in the coal throughout the jig cycle, and there is almost no change in signal with time. It would seem that the variation in bed voidage and particle density with time almost exactly compensate each other. This regime extends to just below the weir bar which was nominally 300 mm above the bed plate under the operating conditions used while collecting these data. The bed sampling undertaken during the metallurgical test-work phase of this project confirms that little change in wet bulk density is apparent in the upper layers of the jig bed. Figure 4 shows a bed wet bulk density profile back-calculated from data on dry mass per unit area of the bed and average particle density for layers removed from the jig bed.

Below the weir bar, a progressively stronger cyclical effect is measured; density changes of 0.1 $t\text{-}m^{-3}$ within the cycle are measured. This substantial bed density change is caused by high density shale being lifted into the measurement beam as the jig cycle progresses.

The density signals at various heights in the jig bed show a distinctive phase relationship. For example, it appears that the point in the cycle at which the measured density begins to rise (about 330 msec into the cycle) is the same at all heights in the bed. This indicates that the bed is lifting as a whole. However, the point in the cycle at which the density begins to decrease is delayed at higher levels in the bed. This effect would appear to indicate that the lower shale layers in the bed fall away relatively quickly, while the upper layers of the bed remain in a state of suspension.

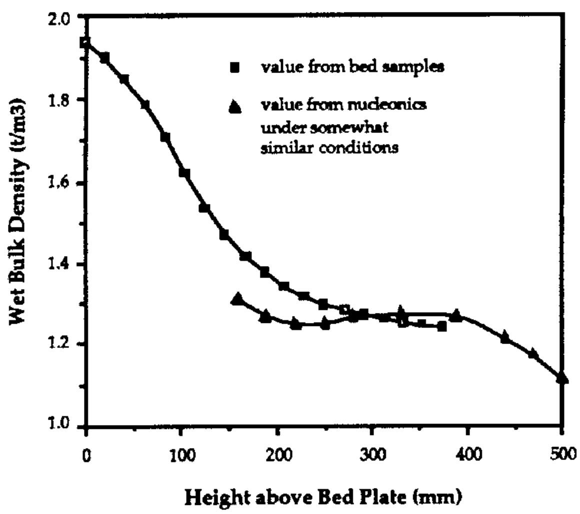

Figure 4 Wet Bulk Density of Jig Bed (calculated from bed layer mass per unit area and density analysis and compared with values from nucleonics)

The total effect is consistent with the idea that the bed first lifts as a whole and is followed by a 'voidage wave' travelling up through the bed. The term, 'voidage wave' is meant to describe the propagation of a zone of higher local voidage up through the bed. This mechanism of bed movement and dilation during the jig cycle is confirmed by observations of a pilot scale jig at the JKMRC.

The signal behaviour in the second section is qualitatively the same as that measured in the first section of the jig but exhibits a lower minimum density, a smaller density variation close to the bed plate and indicates that the bed is thinner. This is due to removal of the bulk of the high density shale in the previous section.

PERFORMANCE EVALUATION

A variety of tests were performed to evaluate the overall performance of the JIGSCAN control system, and, in particular, the performance of the nucleonic density gauges. The original implementation of JIGSCAN is still used at the test site two years after installation and is used as the system of choice by the operators of the jig. To date the system has proven to be very reliable, in spite of the use of some non-industrial standard components in the system.

Apart from reducing the amount of time the operator has to spend working with the control system, the other major advantage of the computer controller is in reducing the start-up fluctuations after a short shut-down. This effect is illustrated below in Figure 5.

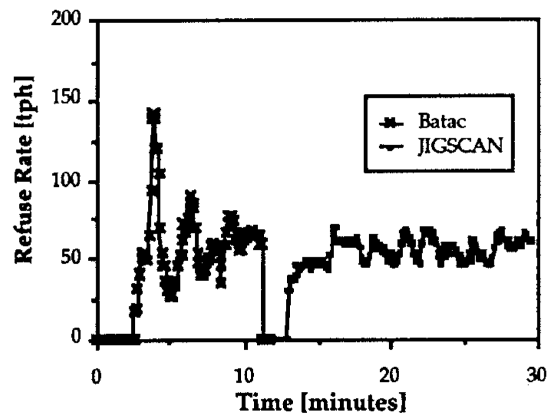

Figure 5 Controller Start-up Comparison

The use of a density gauge addresses a number of recognised problems with float systems in the determination of the condition of the jig bed. The gauge has no moving parts other than the support frame which may be adjusted initially. The density gauge system also measures density over a much wider section of the bed at a better-defined horizon in the bed. The substantial height of the float means that it responds to the average wet bulk density of the bed over a relatively thick horizontal slice of the bed, which is not desirable. Floats also wear or develop leaks, changing their effective calibration with regard to specific gravity. A density gauge calibration is extremely reliable and drift-free, when source decay compensation is included in the software. All of these points are good reasons for density gauge to provide a better control signal than floats.

The ultimate aim of the refuse gate controller is to control the jig to a constant cut-point which, with proper scheduling of washing of various coal types, permits maximum jig efficiency to be achieved.

The metallurgical performance of the jig was measured in this study both conventionally by taking samples of feed, product and reject streams for analysis and less conventionally using 32 mm density tracers. Tracer tests were used exclusively to define the relation between jig cut point and the density gauge signal in the series of tests carried out to study this problem. The cost and time delay involved with conventional sampling for such testwork was unacceptable.

The objective of the tests was to demonstrate that the density gauge produces a signal that permits positive control of the cut-point of the jig. It was expected that both the height of the beam in the bed, and the density control set-point figure would affect the cut-point of the jig. The tracer tests were carried out over a wide range of these variables. Figure 6 shows that the gauge does indeed provide positive control of jig cut-point. The predicted cut point in Figure 6 is a linear function of density gauge signal and beam position. Thus, with the beam at a fixed height in the bed, a feed-back loop that maintains the density signal from the bed at a set value holds the cut point of the jig at a constant value. Changing the set point for the density signal value to a different value will produce a corresponding change the cut point of the jig.

Note that the Batac jig involved in this study is such that two independent flows of coal progress through each half of the jig which is divided down the middle above the bed plate. Cut points were thus measured for both the 'A' and 'B' sides of the jig.

The horizontal error bars on the data values indicate a 95% confidence interval for the tracer test result. The means of determining confidence intervals for tracer test results is dealt with by Lyman *et al.* (1991). The approximate magnitude of the standard deviation of the measured cut point is 0.013 $t\text{-}m^{-3}$. The vertical error bars are determined from the goodness of fit of the linear relationship to the data (Jonkers, 1990).

It should be emphasised that these figures relate to the cut point for 32 mm cubical density tracers. There was evidence from other data collected in the program that cubical tracer cut points tend to be lower that cut points determined from a metallurgical balance on the jig. The discrepancy between tracer cut points and 'coal' cut points is thought to be related to particle shape factor. Since particles tend to become more platey at higher densities, the cut point discrepancy may increase at higher apparent cut points.

The control software for using the gauges to control the jig was completed, and a full set of plant trials involving sampling of the jig feed product and refuse streams was undertaken. A series of sixteen trials alternating between Batac and JIGSCAN control using coal from one seam was undertaken.

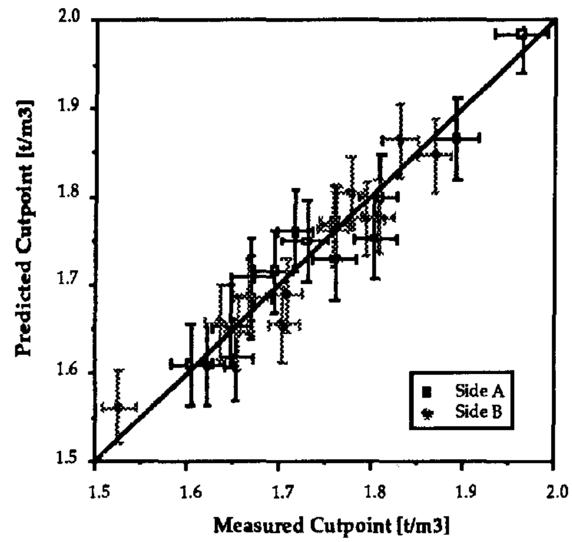

Figure 6 Tracer Test Evaluation of JIGSCAN

The samples were sized, and analysed for density distribution. The results were mass-balanced to produce raw partition numbers, to which the Armstrong or modified Gaussian partition curve was fitted (Armstrong 1959, Lyman *et al.* 1990).

The cut-point and separation efficiency (E_p) parameters of this curve are presented in Table 1.

Considerable effort was made in the analysis of the results to make accurate estimates of the standard deviation of the cut point and the E_p determined from the total processes of sampling of the jig feed, product and reject streams, statistical material balancing of the assays and fitting of partition curves to the balanced data (see Lyman *et al.* 1990 or 1991 for details of this method).

The results indicate that no difference between the performance of the controllers was detected within measurement error levels. Even though large samples of coal were collected and analysed with all possible care, conventional sampling of the jig cannot provide a determination of total coal E_p with a standard deviation lower than about 0.005; similarly, the cut point cannot be determined with a standard deviation lower than about 0.017. Such levels of uncertainty in the performance evaluation are an unavoidable consequence of fundamental sampling error (in the sense of Gy, 1982) and the accuracy of standard density fractionation methods using heavy liquids. These levels of error preclude the detection of comparative yield benefits within the range of 2-3%.

Table 1 Control Test Results (Partition Curve Parameters for Whole Coal)

Test No.	E_p [t m^{-3}]	SD [t m^{-3}]	CP [t m^{-3}]	SD [t m^{-3}]
Batac Control				
1	0.1465	0.0066	1.965	0.019
3	0.1383	0.0049	1.928	0.015
5	0.1490	0.0056	1.931	0.016
7	0.1460	0.0057	1.943	0.022
9	0.1525	0.0073	1.858	0.018
11	0.1361	0.0057	1.916	0.020
13	0.1213	0.0044	1.886	0.014
15	0.1348	0.0047	1.920	0.016
Average	0.1406		1.918	
SD	0.0094		0.031	
JIGSCAN Control				
2	0.1362	0.0053	1.933	0.018
4	0.1504	0.0053	1.891	0.017
6	0.1331	0.0041	1.918	0.015
8	0.1560	0.0064	1.910	0.028
10	0.1339	0.0050	1.952	0.017
12	0.1270	0.0039	1.907	0.013
14	0.1348	0.0048	1.902	0.012
16	0.1351	0.0050	1.961	0.016
Average	0.1383		1.922	
SD	0.0091		0.023	

CP = Cut Point [t m^{-3}]
E_p = Separation Efficiency [t m^{-3}]
SD = Standard Deviation [t m^{-3}]

Statistically, it was possible to determine that the variation in the cut-point of the jig was significantly less under JIGSCAN control than under Batac control. This result confirmed the expectation that the density gauges provide a more positive and direct signal of local density in the jig bed and provide positive cut point control.

To test for a higher yield from the jig under JIGSCAN control, a second type of measurement had to be considered. Because the jig feed was sampled for each of the 16 tests carried out, it was possible to ascertain that the feed coal characteristics did not change significantly during the trials. Nor were the operating condition of the jig changed as the type of control was alternated during the trials. The refuse weightometer records were logged during the trials could therefore also be used to indicate differences in yield from the jig under the two control systems. The refuse weightometer results are presented in Table 2.

Table 2 Refuse Rates in Performance Trials

Test Number	Average Refuse Rate [t hr^{-1}]	Standard Deviation of Rate over Test [t hr^{-1}]
Batac Control		
7	57	21
9	88	33
11	68	17
13	67	23
15	61	19
Average	68	23
JIGSCAN Control		
8	77	14
10	58	7
12	57	11
14	67	12
16	58	9
Average	63	11

Note: The results from tests 1-6 were lost due to a malfunction in the data collection routine.

The data show that the average refuse rate is lower under JIGSCAN control. Since the average product ash values operating with either control system were statistically indistinguishable, the lower refuse rate may be directly interpreted as a yield gain by the JIGSCAN controller. At the 600 tonnes per hour nominal feed rate this corresponds to a yield advantage of one percent.

The conclusion that the JIGSCAN system provides a one percent yield advantage is not absolutely certain, but it is statistically consistent with the results achieved from the sampling trials.

It can also be seen that the variation in refuse rate during a test is significantly less for the JIGSCAN controller indicating that more stable operation of the jig is being achieved. This is confirmed from visual inspection of the refuse gate operation, with the gates under JIGSCAN control being adjusted by smaller amounts, and on a much less frequent basis than under Batac control.

The performance comparison between the two systems presented here was made more difficult to interpret by the the fact that the cut point for the jig was very high during the trials, meaning that there was little near-gravity material involved in the separation. Testing the system at such a high cut point was not intentional (see Lyman *et al.* 1991 for further explanation).

Had the systems been compared at a lower cut point, it is the authors' opinion that yield differences would have been significant and that the improved stability of operation provided by the JIGSCAN system would have resulted in that system providing the higher yield.

CONCLUSIONS

This project has demonstrated that it is possible to control the cut point of a jig using nucleonic instrumentation and a single board computer of modest power. The performance data collected suggest that the control system developed may lead to increases in jig efficiency; the control system produces a clear advantage in stability of operation and significantly reduces the amount of operator attention required. Increases in stability of operation are particularly noticeable at jig start-up. The system is also popular with the operators.

The project has incidentally provided valuable insight into the problem of measuring the metallurgical performance of a jig. The detailed statistical analysis of the process data indicates that there are limits to the precision of measurement of jig cut point and E_p of approximately 0.017 and 0.005 t-m^{-3} (1 standard deviation), respectively when a jig treating a -50 mm coal is considered. The existence of such limits of precision have particular relevance to acceptance testing of jigs. Even the precision for cut point determination achieved with density tracers is limited to approximately the same value, namely 0.013 t-m^{-3}.

The JIGSCAN system has the potential to be developed into a full 'intelligent' controller for a jig. Although the PDP11/21 computer used in this first version of the system was working absolutely to capacity to control the Batac jig which had 6 pairs of air valves to control, future versions of the system can be supplied with almost arbitrarily large control and computing capacity at relatively low cost. The existing JIGSCAN system, despite being a prototype, has proved to be highly reliable offering reduced operating costs relative to the standard control system.

A jig is generally considered to be a relatively simple device and the attempts to understand the physics of its operation, with the notable exception of the work of Jinnouchi and co-workers in Japan (Jinnouchi and Kawashima 1979, Jinnouchi *et al.* 1984, Jinnouchi 1988, Tanaka *et al.* 1990), have been at best simplistic. The role of the supply of underbed water has been misunderstood until recently because of the failure to apply modern engineering modelling principles to the jig and the fact that incorrect statements have been preserved in the literature for long periods of time.

Jig research is continuing at the JKMRC with the objectives of providing more comprehensive mathematical models of the jig water and jig bed motions as well as additional instrumentation for the closer control of the jig. The mathematical models of the jig operation will provide particularly powerful design tools which will eventually permit the design of better jigs and jigging cycles for specific raw coal characteristics.

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U.S. BUREAU OF MINES RESPIRABLE DUST PROGRAM: AN OVERVIEW OF ACCOMPLISHMENTS AND FUTURE RESEARCH NEEDS

by

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ABSTRACT

Exposure to respirable coal mine dusts has long been recognized as a severe health hazard to coal mine workers. To address this problem, the U.S. Bureau of Mines' Respirable Dust Research Program is conducting research to achieve a fundamental understanding of dust hazards, and develop new and advanced research and control technologies.

Initial Bureau efforts aimed at compliance with the 2.0 mg/m^3 Federal dust standard resulted in improved dust sampling and measurement instrumentation, machine-mounted water spray systems and dust scrubbing devices. The second major thrust was the control of dust levels on longwall mining systems; including improved cutting and advanced methods of ventilation and water application. The third thrust has been the control of quartz dust exposure of mine workers; this has again meant the development of improved cutting and drilling concepts, and advanced methods of ventilation, water application, and improved scrubber designs.

Although modest gains in dust control technology have been made during the past few years, they have been far overshadowed by the large increases in coal extraction rates. As more coal is mined, more dust is generated. This continually increasing level of coal extraction has meant that far more dust is being produced. It is apparent that only through a more basic and fundamental understanding of the sources and methods of dust generation can the current level of control technology be advanced to adequately address the problems associated with increasing coal extraction rates.

This overview identifies some of the major advances in respirable dust technology, and provides some insight into current and future approaches to remove the remaining obstacles. Significant benefits to mine worker health have resulted and should continue to result from this program.

INTRODUCTION

Following passage of the Coal Mine Health and Safety Act of 1969 (Public Law 911173), the Bureau of Mines initiated a research program aimed at controlling respirable dust exposures of coal mine workers. As used here the term "respirable dust" refers to the coal mine dust that gets into, and interacts with, the lungs of those who inhale it. It has long been recognized as a severe health hazard to mine workers. This program has been implemented by a team effort consisting of the Bureau's in-house capabilities, the Generic Center for Respirable Dust, and contractors, as necessary. Over the years, Bureau research has addressed principally three areas:

- o Compliance with the Federal 2.0 mg/m^3 dust standard (1970-76).

- o Dust control for longwall mining (1976-1983).
- o More stringent respirable dust standards due to quartz dust (1983-1989).

In addition, fundamental studies have been conducted by the Generic Center for Respirable Dust, with emphasis on penetration of dust into the lung. Accomplishments have been significant, but problems remain, as noted later.

COMPLIANCE WITH THE 2.0 MG/M^3 DUST STANDARD

The Coal Mine Health and Safety Act of 1969, established a 2.0 mg/m^3 dust standard for all coal mining operations, underground as well as surface. At the time of enactment of this legislation, the industry was averaging approximately 4.0 mg/m^3. The Bureau of Mines respirable dust research program played a significant role in identifying and developing effective technology to allow better compliance with this new standard, thanks to industry implementation and Federal enforcement.

Improved Dust Sampling Methods and Devices

The respirable dust standard is based on mass (2.0 mg of respirable dust per cubic meter of air). The traditional gravimetric instrumentation used to determine compliance involves a sampling pump, size pre-classifier, and a pre-weighed filter. Over a working shift, the mine atmosphere is drawn through the pre-classifier and the respirable dust accumulates on the filter. At the end of the shift, the weight difference is measured and the degree of respirable dust exposure is determined. However, this form of measurement was not adequate when, for example, a rapid determination of the effectiveness of different dust control measures was needed for research purposes, or by mine operators or inspectors. To meet these needs, the Bureau has developed an instantaneous, portable continuous respirable dust monitor based on light scattering (fig. 1). This instrument has now become standard throughout the industry for rapid dust measurements; it is commercially available.

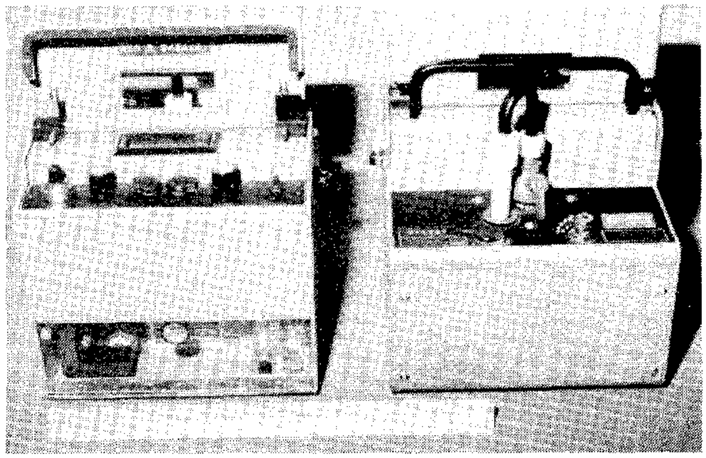

Figure 1. Bureau of Mines Portable, Instantaneous "Real-Time Aerosol Monitor", RAM-1.

Design and Development of an Inseam Tester

To limit personal respirable dust exposure, more extensive knowledge was required of the characteristics of different coal seams, as they relate to the generation of respirable dust. To address this need, the Bureau developed an inseam tester which has provided valuable data on the cutability and friability of different coals. These data cannot be obtained in a laboratory, because of the fracture and cleat structure found in most coal seams. Using this device in the actual underground mine environment has yielded valuable information that has led to alternative cutting techniques and new designs for cutting heads. Data acquired with the inseam tester can be used to tailor the cutting system to the specific physical characteristics of individual mining operations.

Improved Water Spray Systems

One of the most widely used and effective dust control techniques is the application of sprayed water. However, the establishment and maintenance of satisfactory water sprays proved difficult in the adverse conditions encountered in operating mines. Principal problems related to the need for fine atomization, and the clogging of water spray nozzles by rust scale and other contaminants typically found in an industrial water supply. Bureau research has found a method that maintains water sprays in effective operating condition; this filtration system, which uses commercially available components, is a cost-effective assembly now employed extensively throughout the industry to prevent nozzle clogging(Divers, 1976).

Dust Scrubber Systems

While the concept of scrubbers to purify dust laden air underground was attractive from the early days of the program, there were numerous obstacles to be overcome before scrubbers could be utilized successfully in operating mines. The first problem was scrubber efficiency for the fine coal particles (less than 10 microns) present in respirable dust. The Bureau-developed flooded-bed scrubber has proven to be an effective tool in this regard; collection efficiency for respirable dust from flooded-bed scrubbers exceeds 95 pct. In addition, there were some significant engineering problems involved in integrating scrubbers into equipment such as the continuous miner. However, working in close cooperation with the equipment manufacturers, such integration has been successfully accomplished. At this time, over 350 such installations are in use in the U.S.

Accomplishments - 1970-1976, 2.0 mg/m^3 Dust Standard

When the 1969 Act was promulgated, average respirable dust exposure of the continuous miner operator was in excess of 4.0 mg/m^3 (versus a standard of 2.0 mg/m^3). Thanks to Bureau research, the cooperation of the industry, and work by Federal and State agencies, average dust exposure on continuous miner sections is now below 2.0 mg/m^3. Due to new concerns raised by quartz dust found in respirable dust samples, additional problems are now being addressed, as discussed later.

DUST CONTROL FOR LONGWALL MINING

The second major thrust has been towards longwall mines. In 1976, over 70 pct of the longwall shearer faces in the U.S. were consistently out of compliance. Through an aggressive program, the Bureau has been able to identify alternative technologies to control respirable dust exposure on longwall faces.

BuMines Shearer Clearer Water Spray System

Water sprays have been used extensively by mine operators to control respirable dust. A typical water spray captures about 25 pct of the respirable dust which becomes airborne, the remaining dust is moved about by the air-moving action of the water sprays, and boils out over the equipment operators. Figure 2-A shows the primary airflow moving from right to left, and the secondary air currents caused by water sprays mounted on the shearer body. In actual mining situations, the exposure of the shearer operator can be increased by as much as 50 pct due to this air-moving action. Bureau research has shown that by simply re-orienting the existing water sprays their air-moving capability can be effectively utilized to reduce dust exposure. Re-oriented water sprays are used to divert the dust laden air toward the face and away from the shearer operator (fig. 2-B). The shearer clearer concept lowers shearer operator dust exposure by an average of 50 pct (Jayaraman, 1985). Today, over 80 pct of longwall shearers in the U.S. utilize the shearer clearer system, and the concept has been exported to Canada and Australia. A conventional water spray system causes significant dust to boil-out into the walkway, contaminating the face workers' environment; the shearer clearer effectively keeps the dust away from the face workers.

Improved Localized Ventilation Control

Uncontrolled loss and misapplication of face ventilation can significantly affect the

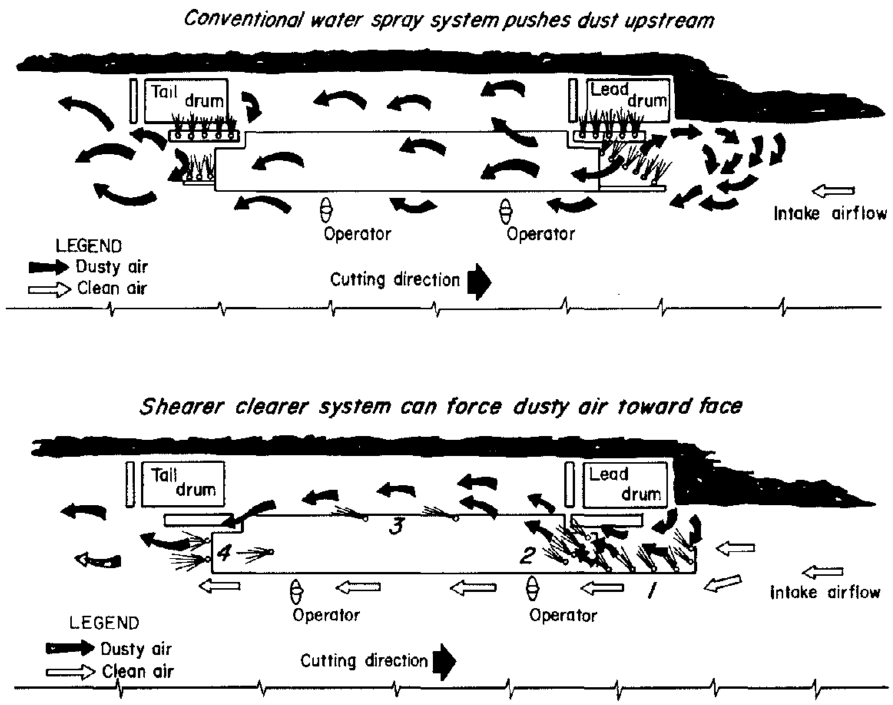

Figure 2. - "A": Dust boil-out caused by improperly oriented machine water sprays; "B": Re-oriented machine water sprays divert dust-laden air toward the face, away from machine operators.

respirable dust exposure of longwall face personnel. Examples include the amount of air which leaks into the gob or waste behind the longwall supports in the headgate, as well as how the airflow is directed over the shearer cutting drums when the shearer reaches the headgate. A simple gob curtain is used to direct the primary airflow across the longwall face, minimizing the amount of leakage into the gob. Bureau studies have shown that gob curtains can improve average face airflow by over 30 pct (Jankowski, 1983), and can significantly increase airflow along the entire face. Almost all U.S. longwalls now use gob curtains to manage the primary airflow more effectively and reduce face workers' respirable dust exposure.

Modified Cutting Sequence

Currently, over 50 pct of double-drum shearers in operation in the U.S. employ a uni-directional cutting sequence. Typically, the primary cut is taken in the same direction as the face ventilation. The primary source of the shearer operators' dust exposure is dust from the upwind drum which spreads out into the walkway, increasing respirable dust exposure of both operators. If the upwind drum is raised and the trailing drum is used to cut the remaining bottom coal during the clean-up pass (modified uni-directional cutting), both operators can work on the intake (clean) air side of the primary dust generating source, significantly reducing their exposure to dust generated during cutting. While uni-directional cutting may affect overall productivity, it has been shown to be an effective tool in helping to maintain compliance with dust regulations.

Deep Cutting to Reduce Dust Generation

With deep cutting, larger fragments of coal are removed and fewer coal surfaces are exposed, resulting in less airborne dust. Extensive evaluation of deep cutting shearers has clearly shown that doubling the depth of the cut can reduce airborne dust levels by as much as 60 pct(Ludlow, 1982). While there are some limitations in terms of implementing this technique on existing shearers, with new equipment and/or appropriate modification of existing equipment this has proven to be an effective and well utilized means to promote dust compliance.

Control of Dust Generation During Coal Transport

Assuring a supply of clean intake air to the longwall face area is critical in minimizing face workers' dust exposure. On most longwall operations this is difficult to achieve because of dust generated by the coal crusher and at transfer points outby the face (located in the intake). The Bureau has demonstrated that by enclosing the stageloader/crusher unit and installing water sprays at strategic locations along the unit (fig. 3), the intake dust levels can be reduced by as much as 60 pct(BuMines, 1985).

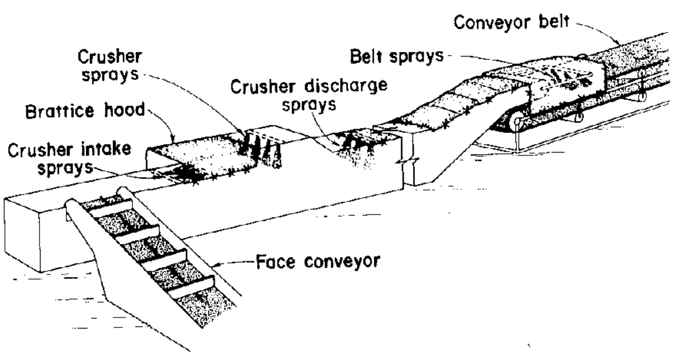

Figure 3. - Enclosed stageloader/crusher reduces intake-air dust contamination.

Accomplishments - 1976-1983, Longwall Dust Control

Respirable dust levels on longwall faces in 1976 averaged approximately 6.8 mg/m^3. Through combined efforts of the Bureau, industry, and inspectorates, the average dust level in 1983 was reduced to approximately 2.0 mg/m^3. Compliance levels have risen from 30 pct in 1976, to 85 pct in 1986. However, increasing productivity on longwall faces continues to make compliance a difficult problem; work is currently underway to identify future research needs in this area.

MORE STRINGENT RESPIRABLE DUST STANDARDS

The third major thrust in the Bureau's respirable dust program pertains to quartz dust control. Whenever the quartz content of respirable dust exceeds 5 pct, regulations require the 2.0 mg/m^3 dust standard to be reduced further. With sections being placed on more stringent dust standards (below 2.0 mg/m^3), approximately 35 pct of the industry is now affected. Two major sources of quartz dust from underground mining operations are the continuous miner, when cutting floor and roof rock or rock partings within the seam, and the roof bolting machine, while drilling the roof.

Half-Curtain Face Ventilation System

In sections with marginal intake air velocity, the half-curtain can be used to decrease the cross-sectional area of the mine entry, and hence, increase the intake velocity over the miner operator, helping to confine the dust to the face area. Figure 4 illustrates the basic concept. With a half-curtain, dust reductions at the continuous miner operator are on the order of 50 pct on mining sections where there is marginal intake air velocity(Jayaraman, 1986).

Modified Cutting Sequence Reduces Quartz Dust Generation

One primary source of quartz dust is the continuous mining machine when cutting roof rock. A modified cutting sequence has been successfully implemented, the top coal/rock is undercut, and then the coal/rock material near the roof is cut to a free face. This sequence, which generates less dust, also helps to confine the dust cloud under the machine where it can be effectively suppressed by the water sprays before it can enter into the main airstream. The modified cutting sequence has

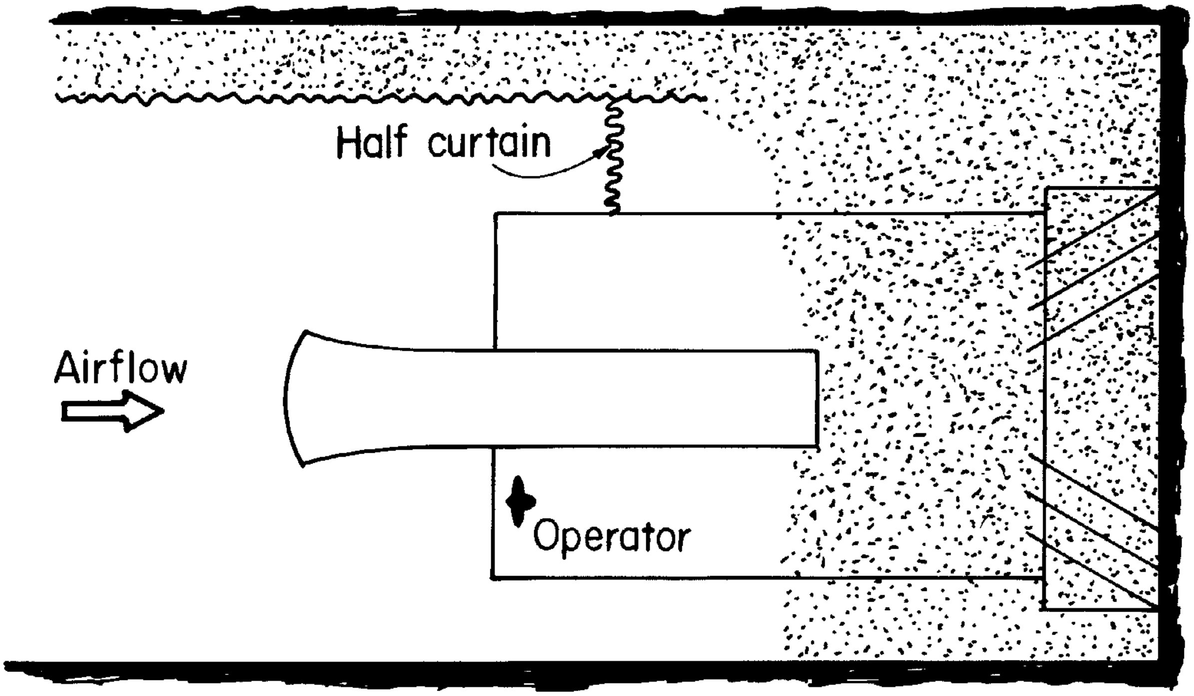

Figure 4. - Half-curtain face ventilation technique increases air velocity over the miner operator.

been shown to eliminate operator quartz dust exposure, while reducing quartz dust levels in the return by as much as 65 pct(BuMines, 1985).

Water Sprays for Improved Ventilation Control

One primary factor affecting the miner operator's dust exposure is dust rollback from the face. It is usually caused by low primary airflow, and a poorly designed machine water spray system. Water sprays are effective air movers; depending on the specific circumstances, that movement of dust-laden air by water sprays may be advantageous or deleterious. Water sprays which travel a long distance before impacting a solid surface of the machine are effective air movers; the water sprays that only travel a short distance before impacting the cutterhead or another part of the machine are more effective in suppressing dust, and do not exhibit the air movement features of the other spray positions. When the sprays do move the dust-laden air, it tends to rollback toward the continuous miner operator. Marginal air velocity from the principal air system will cause the localized air movement induced by the water sprays to overpower the primary ventilation system. The Bureau's anti-rollback system and guidelines for its installation have been effective in reducing machine operator dust exposure by as much as 40 pct (Jayaraman, 1984).

Control of Quartz Dust During Roof Bolting

The second major source of quartz is the roof bolting machine, when drilling into roof rock. The Bureau has evaluated various bit types available to the industry and found a 5:1 difference in the amount of airborne dust generated by different types (fig. 5). Based on Bureau studies, most manufacturers and operators have now adopted the dust hog bit design.

Other Bureau studies have shown that maintenance, especially of the dust collector system, on roof bolters is critical for proper dust control. According to an independent study by the Mine Safety and Health Administration, 90 pct of the sections surveyed have achieved compliance by implementing the Bureau's recommendations(Thaxton, 1984).

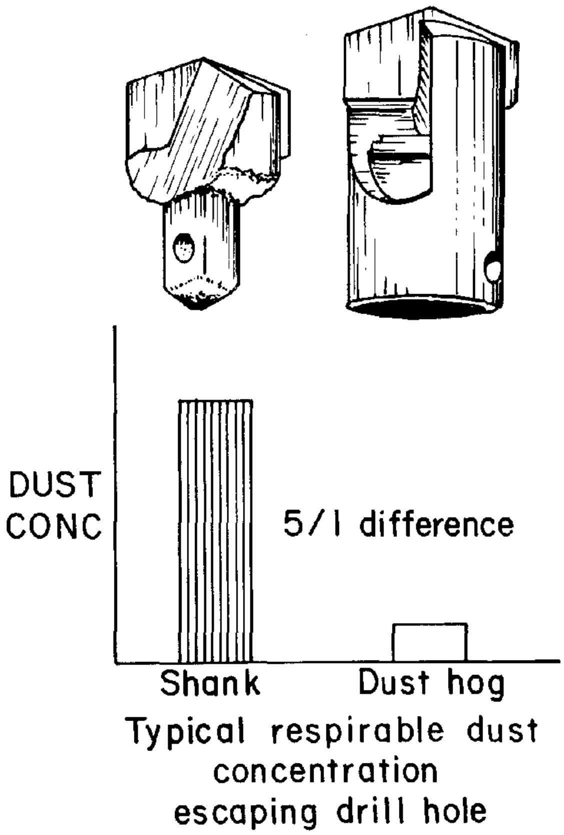

Figure 5. - Airborne dust levels generated by various roof bolt drill bit types.

Scrubbers for Improved Quartz Dust Control

Although 90 pct effective for removing respirable coal dust, the conventional flooded-bed scrubbers described earlier are less than 50 pct effective in removing quartz dust particles which are typically 1/10 the diameter of respirable dust particles. This means that the quartz dust collection efficiency of flooded-bed scrubbers is unacceptable. The Bureau has investigated methods to correct this. Studies indicate that random-weave, synthetic collection bed media can increase the quartz collection efficiency to 97 pct. The Bureau has also identified and tested a high-pressure water-powered scrubber (fig. 6) for continuous mining machines. Initial results indicate that the system is capable of improving quartz dust removal by approximately 40 pct, compared to flooded-bed units(Jayaraman, 1990). Additional field evaluation is underway.

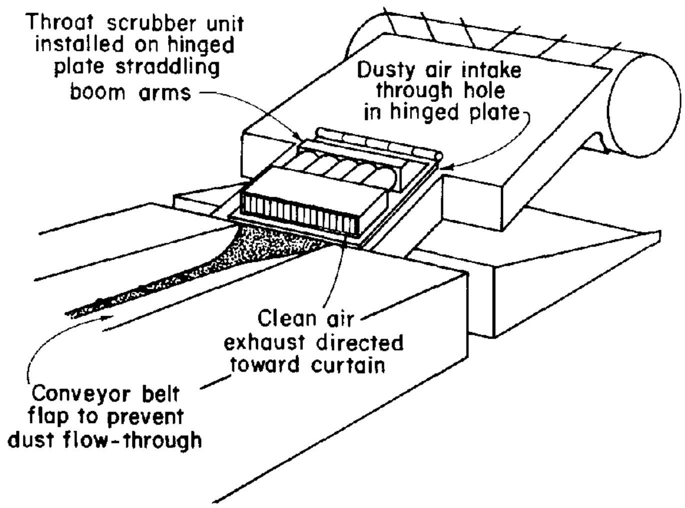

Figure 6. - High-pressure water-powered scrubber for continuous mining machines.

Proper Miner Bit Selection

Recent studies have resulted in guidelines for the selection of continuous miner bit types to reduce quartz generation. These studies have shown that slender profile bits with large tungsten-carbide tips generate the least amount of respirable quartz dust (fig. 7). Mining companies and equipment manufactures are now making this transition.

Expert Systems

While progress has been made in dealing with the more stringent dust standards, additional work, now underway, offers significant promise of further improvements. The Bureau has developed expert systems for both continuous and longwall mining(Kissell, 1987). Expert systems provide guidance to the mine operator in all areas of respirable dust control from water sprays and machine design to ventilation concepts. They are operated on the desktop computers, now found in most mining companies. Preliminary field evaluation has been most encouraging, and further expansion and utilization of this technology is anticipated. This will enhance the accuracy and rapidity of Bureau technology transfer.

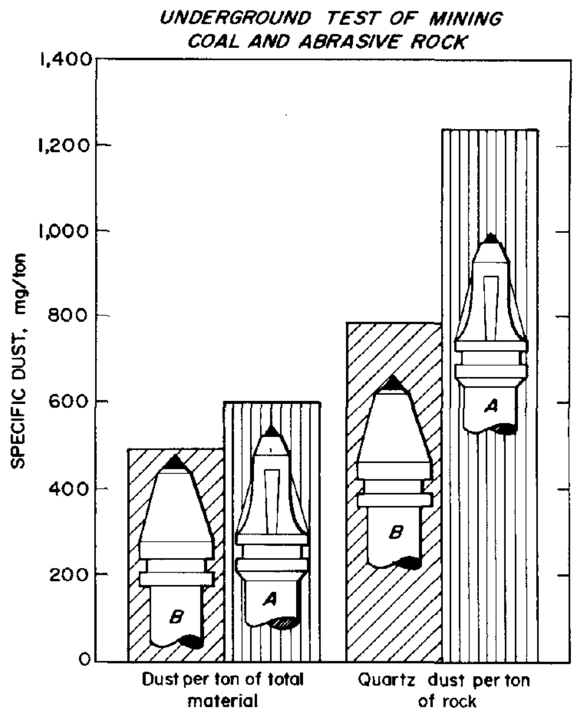

Figure 7. - Comparison of dust levels generated by various continuous miner bit types.

Water and Air Guidelines

Laboratory tests were conducted to determine the respirable dust reduction effectiveness of, and interaction between, face airflow and water sprays, when applied at various operating levels on a continuous miner. Testing was conducted in a full-scale model mine entry where air and water application could be easily monitored and controlled. Exhausting face ventilation was varied from 1.4 to 4.2 m^3/s (3000 to 9000 cfm), miner spray-water-flow varied from 57 to 132 l/m (15 to 35 gpm), and nozzle operating pressure varied from 550 to 1,380 kPa (80 to 200 psi).

Interactions between dust control parameters were found to be significant and often, would define the level of application for a control parameter at which further increases in that control parameter did not produce continued reductions in dust concentrations (Colinet, 1991). Regression modeling indicated that increases in airflow to 3.9 m^3/s (8400 cfm), in water flow to 95 l/m (25 gpm), and in water pressure to 965 kPa (140 psi) could typically be used with beneficial results.

Accomplishments - 1983-1989, More Stringent Dust Standards

Over 35 pct of underground mining operations are currently under more stringent (below 2.0 mg/m^3) dust standards. Whereas in 1983, less than 20 pct were able to maintain compliance with these reduced standards, today over 50 pct of sections are able to operate at these reduced dust levels. Through Bureau research and industry implementation, quartz dust generation during roof bolting has been almost eliminated. A fundamental, as well as practical, understanding of quartz dust generation and behavior has been achieved. With continued efforts by the Bureau, industry, and Federal enforcement agents, further improvements in this area are expected.

ONGOING RESEARCH - FUTURE PROBLEM AREAS

The problem of more stringent dust standards will continue to grow. The formula for determining reduced standards is as follows:

Dust standard = 10/% quartz

Based on this standard, the formula for more stringent standards has resulted in many mine operators being required to operate at or below 0.8 mg/m^3. To date, approximately 8,850 work places have been placed on more stringent dust standards due to quartz (Jankowski, 1987). Control techniques must be improved if mandated levels are to be met.

As longwall production increases, dust levels will also increase (Jankowski, 1987). Average longwall production at the end of the 1980's was 1,900 tps, with an average dust level of 2 mg/m^3; the 6 top U.S. longwalls produce an average of 4,200 tps, with an average dust level of 3.8 mg/m^3. However, much of the current successful compliance with respirable dust has been accompanied by a significant reduction in productivity of U.S. mining sections. In light of the industry trend toward longwall mining, if no new control technology is available, the Federal dust standard will act as a constraint on future output per hour. This is especially pertinent to longwall mining where the average dust level is already 2.0 mg/m^3. Although it is imperative that industry meet the required dust standards, the United States must also remain competitive on the international energy market.

It is apparent that only through a more basic and fundamental understanding of the sources and methods of dust generation can the current level of control technology be advanced to adequately address the longwall dust problem. Research under this program will concentrate on obtaining an elemental analysis of dust generation mechanisms from stageloader/crusher operations, auxiliary beltline and face ventilation systems, face sloughage, and airborne respirable quartz. Research efforts will then utilize these findings to identify and evaluate state-of-the-art dust control technology required on high production longwall faces

The development of a total longwall dust simulator should prove invaluable from both the standpoint of a research tool, as well as an application tool for the longwall mining industry. A computer simulator that would be able to predict what impact productivity or panel design changes would have on ambient dust levels, along with estimating the impact of changes in dust control implementation, would allow research to concentrate its limited resources in the most critical areas while allowing the industry to estimate changes in dust levels as a result of operational changes from a cost-benefit standpoint. This may enable a total systems approach to control of longwall dust, and provide an expanded database for estimating dust levels and control procedures.

Silica dust control research will focus on technologies that enhance suppression efficiency of smaller sized silica dust, improve the energy efficiency of two-phase fluid transfer systems, investigate preconditioning seam processes applied before mining, and study air curtain concepts. Increasing the efficiency of water application will be directed towards investigating technologies that increase the probability of water capture and/or agglomeration of smaller sized silica particles. This will encompass studying several alternative technologies to generate smaller water droplets and the effect of water droplet size on silica capture efficiency. Other water application technology will focus on intensifying momentum transfer induction systems. This work will involve vector analysis of water and air systems to amplify the constructive transfer of kinetic energy between the two fluids. Mechanisms to stimulate fluid flow through coal seams (permeability) will also be studied to provide effective fluid preconditioning processes of coal seams for airborne dust prevention. Fundamental coanda effects of air movement will be explored to identify potential localized ventilation applications for worker protection. Bureau studies have identified the nature and character of airborne particulate generated by diesel engines. There is a significant difference in the size of respirable coal dust and that of diesel exhaust particulate. On-going Bureau studies are addressing means to more exactly characterize the chemical nature of these particulates and to keep them from becoming airborne.

A detailed research evaluation of each of these concepts is needed to determine their potential benefits, and to understand the basic theory of operation and potential application.

GENERIC MINERAL TECHNOLOGY CENTER ON RESPIRABLE DUST

The Generic Mineral Technology Center on Respirable Dust (Center) was established in August 1983, at the request of the Bureau of Mines, to conduct fundamental research that affords "...each miner the opportunity to work underground during the period of (his/her) adult working life without incurring any disability from pneumoconiosis or any other occupational disease." The Center consists of the Mining and Mineral Resources Research Institutes (MRI's) of The Pennsylvania State University (PSU), and West Virginia University (WVU), in association with the MRI's of the Massachusetts Institute of technology (MIT), and the University of Minnesota (UMN).

The Center brings together experts concerned with particles causing potentially disabling or fatal diseases, including pneumoconiosis ("black lung"), silicosis, and asbestosis, the last of deep concern not only to workers in the mineral sector but also to the general public. The primary goal of the Center is to control the respirable dust disease through a better understanding of the respirable dust generated by mining and milling, and its interaction with the lungs. The Center's work concentrates on: (1) the dust-lung interaction; (2) dust particle characterization; (3) the relationship of mine environment, geology, and seam to dust generation and mobility; (4) the dilution, dispersion and collection of dust in mine airways; and (5) the control of dust generation. The fundamental aspects of this work are applicable to respirable dust problems in both hard rock mines and coal mines, and to other dusts, such as those generated by diesel equipment. The Center's interdisciplinary activities involve the training of engineers and scientists, graduate students, and undergraduate students through their respective institutions, and technology transfer to the industry. The Center research is fully compatible and complementary with the existing and ongoing Bureau of Mines activities and integrated into the Bureau's research on dust generation, transport and suppression.

CONCLUSION

Health standards in the U.S. are among the highest in the world. Achieving these standards have often had an impact on productivity, slowing output, and raising prices to levels that make it difficult to compete with many foreign industries. The answer to many of these problems lies in the development of new and advanced control techniques. This overview has identified some of the major respirable dust technological hurdles that have been overcome, and has provided some insight into current and future approaches underway to remove these obstacles and to provide the United States with the most advanced state-of-the-art mining industry in the world from a respirable dust standpoint. The necessary developmental research is costly and time-consuming. The long-term, high-risk aspects of this effort are being addressed by the Bureau and the Generic Center on Respirable Dust, with support by industry (fig. 8). This should be recognized as one of the principal agents through which the great mineral potential of this Nation can be realized, and our international status as a mining power be assured without compromising the health and welfare of those who ensure it.

The problem of more stringent dust standards will continue to grow. To date, approximately 40 pct of the coal mining industry has been placed on more stringent dust standards due to quartz. Control techniques must be improved if mandated levels are to be met. As longwall production increases, dust levels will also increase. In light of the industry trend toward longwall mining, if no new control technology is available, the Federal dust standard will act as a constraint on future output per hour.

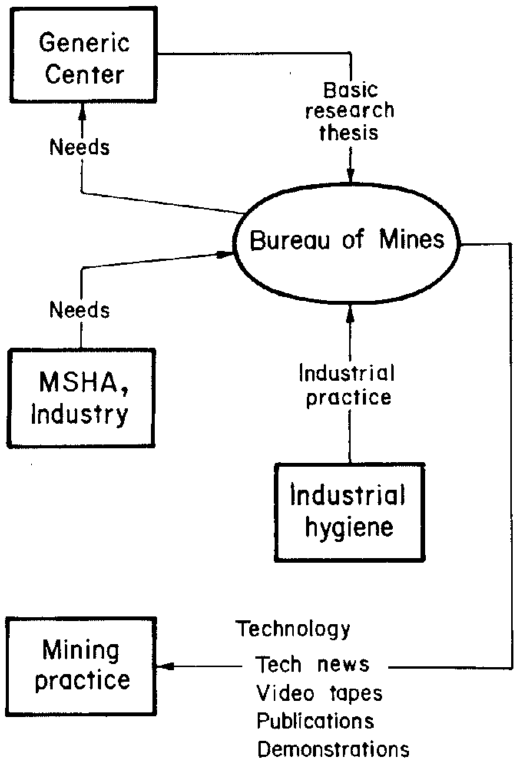

Figure 8. - Interaction between the U.S. Bureau of Mines, the Generic Technology Center on Respirable Dust, and the U.S. Mining Industry.

In sum, significant benefits to mine worker health have resulted, and should continue to result, from the synergistic scientific, engineering, and medical research being conducted jointly by the Bureau and the Generic Mineral Technology Center for Respirable Dust.

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THE EVOLUTION OF ENVIRONMENTAL R&D FOR COAL UTILISATION IN BRITISH COAL

by

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ABSTRACT

As part of British Coal's statutory duties as the chief supplier of coal in the UK, the Corporation recognises its responsibilities to respond to society's rising environmental aspirations. Therefore, for over 30 years British Coal has directed increasing R&D resources aimed at reducing the environmental impact of coal use.

This paper describes the environmental R&D programme which has evolved since the early activities aimed at developing smokeless fuel production and more efficient combustion techniques following the introduction of the 1956 Clean Air Act. There has been the continuing emphasis towards achieving further improvements in performance and amenity with associated environmental benefits for the range of combustion equipment used in the domestic, commercial and industrial market sectors.

Much of the R&D has focused directly on environmental issues, including the measurement and control of gaseous and particulate emissions. A key feature of this work is concerned with improving the understanding of basic science behind the formation and control of pollutants such as SO_2 and NO_x.

The paper also reviews research aimed at addressing the important requirement that arising waste residues need to be disposed of in an environmentally acceptable manner. This research also examines the opportunities for utilisation of such wastes.

At the same time as developing low cost means for reducing emissions from conventional plant, substantial research resources are being directed towards developing advanced coal combustion systems, aimed at improving the efficiency of power generation as well as minimising pollution. The need for such improvements has become more pressing in view of the recent international developments concerning the CO_2 and Greenhouse issues.

INTRODUCTION

The British Coal Corporation has statutory duties for the extraction and marketing of the indigenous solid fuel resources within the United Kingdom, as well as for matters concerning the environment. Since the mid-fifties, British Coal has been actively involved in the development of "clean coal technology" to reduce the impact of coal utilisation on the environment. In that time the emphasis has changed from local to international, and most recently, to a global dimension. Furthermore, to satisfy the environmental aspirations of an increasingly concerned public, the Corporation has transformed its mining techniques to reduce the environmental impact of its principal business operations.

R&D in the UK Coal Industry: An Historical Perspective

Coal production in the United Kingdom, pre-1947, was centred on about 900 independent mines. Following the depression of the 1920's, demand for coal declined and there was a reluctance on the part of mineowners to invest in the industry, and industrial unrest was rife[1]. Following a number of Commissions of Enquiry into its structure and operation[2], the coal industry was nationalised in 1946[3]. The official transfer to public ownership, Vesting Day 1st January 1947, established the National Coal Board (NCB). Subsequently, as a result of the Coal Industry Act of 1987, its name was changed to the British Coal Corporation (BCC) in order to reflect the more commercial environment as the UK nationalised industries move towards privatisation.

From its inception there was a strong awareness of the need for scientific R&D to support the mining activities of the NCB[4]. Under the first NCB Board Member for Science, Sir Charles Ellis, F.R.S., a Central Research Establishment, C.R.E.1, was set up in 1948 at Stoke Orchard, near Cheltenham in Gloucestershire. Its function was to undertake scientific R&D into aspects of coal mining and utilisation. Scientists of international renown who worked at CRE in the early days include Dr. Jacob Bronowski, Dr. W. Idris Jones and Dr. D.C. Rhys Jones. As the workload increased, an additional site, C.R.E.2, was established in 1952 at Isleworth, near London[5]. Efforts at Stoke Orchard, subsequently renamed the Coal Research Establishment, then concentrated on coal preparation, smokeless fuels production and fundamental studies into coal properties, while Isleworth dealt with mining, coal transport, mining environment and safety issues. During this period mining related R&D was also carried out at the new Central Engineering Laboratory at Bretby, near Burton on Trent. Subsequently in 1969, the responsibilities for mining, including coal preparation, were centralised at Bretby, and it became known as the Mining Research and Development Establishment (MRDE).

Coincident with these developments, another organisation, the British Coal Utilisation Research Association (BCURA), was also concerned with "promoting research and other scientific work in connection with the utilisation of coal and its derivatives"[6]. Formed originally in 1938, it became established in its eventual home at Leatherhead, near London, in 1948. The majority of the financial support for the Association was supplied by the N.C.B., who were strongly represented by Sir Charles Ellis (President of the Council) and the NCB's Director General of Scientific Services, Dr. W. Idris Jones (Chairman of the Research Sub-committee). In 1971 the main BCURA laboratories closed, though research work continued under contract with outside bodies[7], and the establishment was renamed NCB-Coal Utilisation Research Laboratories (NCB-CURL).

BCURA had a remit to improve the efficiency and reliability of coal-fired boilers and achieved this by collaborating with organisations engaged in the design and construction of appliances, encouraging collaboration between manufacturers and coal users, and most importantly, by bridging the gap between scientific advance and industrial practice. In addition to its work on appliance development, BCURA was also responsible for some of the most important advances in the understanding of coal science. Among its respected scientists were such eminent names as D.W. Van Krevelin, I.G.C. Dryden and C.A. Seyler.

In more recent years, coal utilisation R&D has been concentrated at CRE, and in response to mounting environmental pressures, there has been an increasing emphasis on these issues within the Establishment's programme. CRE continues to play a leading role in the development of clean coal technology to support the continued use of coal in the industrialised world. Furthermore, it has forged strong links with certain international agencies in the identification, and transfer of appropriate coal-firing technologies to third-world countries. Because of its extensive background knowledge of the environmental effects of coal utilisation, British Coal has found itself increasingly involved in the national and international debate on pollutant emissions regulations and legislation. From this informed position, British Coal has been able to influence decisions which would otherwise result in unreasonable and expensive measures being applied to coal combustion systems.

January 1990 saw the publication of its Framework Policy on the Environment which outlined environmental policies in connection with deep mines, opencast, coal products and coal in use. Under coal in use, "British Coal's objective is to promote clean coal technology and energy conservation as a means of minimising the environmental impact of coal handling and use; in particular to assist customers to achieve, and ensure that coal burned at its own sites conforms with, good environmental practice".

The Development of Environmental Legislation in the United Kingdom

One of the reasons for nationalising the coal industry in the UK was to seek improvements with regard to health and safety in the mines. Another reason, which became increasingly important, was the concern over poor air quality in urban areas. This environmental concern arose as a result of the infamous "pea souper" smogs and their associated adverse health effects; the chief culprits being domestic and industrial coal firing.

Prior to 1956, general smoke abatement legislation in England and Wales was based on smoke nuisance sections in the Public Health Act, 1875; modified by the Public Health (Smoke Abatement) Act, 1926, and consolidated in the Public Health Act, 1936, and the corresponding Act for London[8]. Legislation was solely concerned with the imposition of penalties following the occurrence of nuisance. Private dwellings were exempt, and no action could be taken that "interferes with or obstructs" the efficient working of mines or metallurgical processes. After 1946 there were a number of local Acts passed which necessitated a modified form of "prior approval" of fuel burning installations. Some of these Acts included provisions for smokeless zones, but it was not until March 1951, in Coventry, that the first of these came into operation.

In March 1946 the Fuel and Power Advisory Council, under the chairmanship of Lord Simon, issued a report on "Domestic Fuel Policy"[9] to the Minister of Fuel and Power. Included in the report were two very significant recommendations;

> the need to develop appliances to burn efficiently and as smokelessly as possible both bituminous coal and smokeless solid fuels

and

> the Government should encourage the largest practicable increase in the production of smokeless solid fuels suitable for domestic purposes

Both were to have a profound effect on the direction of the R&D objectives of the newly-formed NCB.

However, matters came to a head in December 1952 when the infamous London smog disaster occurred. As a result of the adverse atmospheric conditions (persistent fog, absolute calm and a temperature inversion) particularly high smoke and SO_2 ambient ground level concentrations were experienced for 4 days. The number of excess deaths caused by the fog, during the following two weeks were estimated as about 4,000 for Greater London[10].

As a result of the 1952 smog, the following year the Government appointed a Committee on Air Pollution, under Lord Beaver, to investigate the causes and make recommendations for future policy changes. One of the principal conclusions of the Beaver Report[11] was the need for new legislation to minimise the emission of smoke to the atmosphere - a "Clean Air Act". The report endorsed several of the recommendations of the earlier Simon Report, ie the need for smokeless zones which would preclude the use of bituminous coal in conventional appliances, prior approval of new domestic heating appliance designs and increased use of smokeless fuels. The report also introduced the concept of "best practicable means" to the prevention of emissions of dark smoke, grit or harmful gases. A need to accelerate research and development work into tackling the technical problems of air pollution was also highlighted.

This led to legislation being introduced in the form of the Clean Air Act, 1956[12]. As a consequence of the Act, Smoke Control Areas were established in most large urban areas which necessitated the use of approved smokeless fuels or exempted appliances capable of burning bituminous coal smokelessly.

The impetus given by the introduction of Clean Air legislation had a marked effect on the R&D policy of the NCB.

CLEAN AIR DEVELOPMENTS AND NCB RESPONSES

Smokeless Fuels

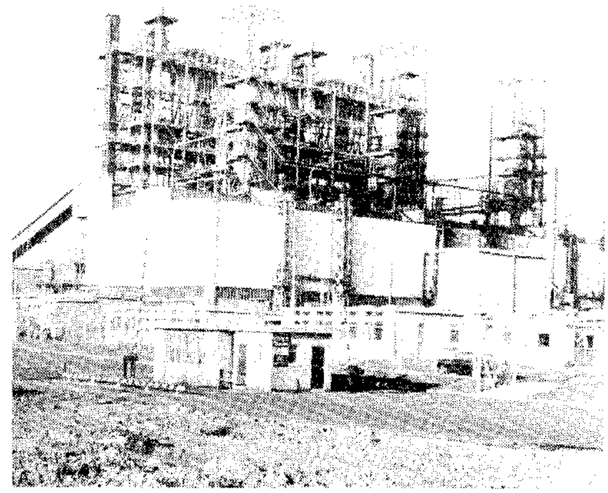
Smokeless fuels had been made for domestic purposes since the beginning of the twentieth century. However, at this time the emphasis was on reactivity rather than "smokelessness", and the economics were determined by the value of the oil recovered as a byproduct[13]. The fuels were manufactured by means of a low temperature carbonisation process at between 400 and 700 °C, because the highest yield of oil occurred in this temperature range. However, there were problems carrying out carbonisation in conventional ovens and retorts at these temperatures. Few processes overcame these difficulties and only the Coalite and Rexco processes survived.

The advent of the Clean Air Act of 1956, and the establishment of smoke control zones, brought an increased demand for domestic smokeless fuels. The timing for the introduction of these zones was influenced by the availability of smokeless fuels in these areas. In 1954, the Beaver Report[11] estimated a national deficit of smokeless fuels of 11.4 million tons. In 1957, it became apparent that as a result of increasing mechanisation within the NCB, there was likely to be an increase in the availability of small-sized, low-rank coals. Furthermore, the output of large coal for burning on open-fires was falling by about 1-2 Mtonne/annum[14]. As a result, there was an incentive to utilise these fine coals in the manufacture of smokeless fuels. Naturally smokeless anthracite was available but was not being mined in sufficient quantities to meet demand. Also it was not an ideal fuel for the open-fire which was in widespread use at that time.

Char Briquetting Developments

Work was already under way by 1956 at CRE to devise a commercial process which could produce a smokeless briquette from low-rank coals. The coal needed first to be carbonised to render it smokeless, and then agglomerated into larger pieces to enable it to be utilised in domestic heating appliances. It was opportune that the temperature at which the coal becomes smokeless is the temperature at which the coal exhibits its maximum plasticity and amenability to briquetting. Two options were available for heating the fine coal particles, dilute (disperse) phase or dense phase in a fluidised bed: the latter appeared to be the more suitable.

Using a 1 ton/hour pilot plant at CRE, data was obtained to allow the design of a large scale commercial unit. Subsequent work[13] confirmed the suitability of the fluidised bed approach, and demonstrated that a single reactor, fluidised by air would provide the level of control required. Further pilot plant studies at Birch Coppice led to the commercialisation of the process in 1964 with the advent of the "Homefire" and "Roomheat" smokeless char briquettes. The "Homefire" plant near Coventry is still in operation producing some 180,000 tonnes of briquettes per year.



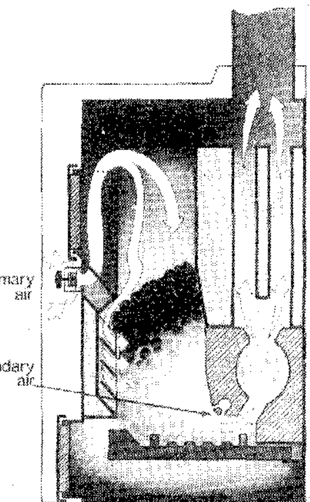
'Homefire' Briquetting Plant, Coventry

The Development of Low-Polluting Appliances

Along with developments in the field of smokeless fuels, CRE has made many significant advances in the design of domestic combustion appliances. In the early days the impetus was to reduce the smoke emitted[15]. Subsequently, greater attention was directed towards increasing their efficiency[16].

When considering the common open-grate domestic fire, a fundamental design difficulty is immediately apparent. Air, required to support the combustion of the fuel on the grate, is supplied from below. As the coal heats up, the volatile tars and gases are released and swept away from the embers of the fire to regions of lower temperature. Consequently, these volatiles are incompletely burnt and are emitted from the flue as smoke. This effect is particularly marked immediately after refuelling of the fire, when maximum smoke emissions are observed. As a consequence, to use such an appliance in a Smoke Control Zone, would require a smokeless fuel to be used with a low volatile matter content, viz less than ~12%. Whilst naturally-occurring anthracite meets this requirement, insufficient was being mined to meet demand. On the other hand, high volatile, low rank coals were in good supply at relatively low cost.

Having established an understanding of the causes of smoke formation in domestic open-fires, workers at CRE, in conjunction with appliance manufacturers, set about to devise new designs to overcome the problem. One approach was to alter the combustion air distribution so that it entered from above the firebed[17]. In this way, the volatile tars and gases, formed when the coal is heated, are drawn through the embers of the fire and virtually consumed in the process. Subsequent developments[18] resulted in further refinement of the air distribution to provide primary and secondary air which improved the control of the combustion conditions. This type of appliance effectively reduces smoke emissions by some 90% compared to a conventional open-fire, and meant that high volatile bituminous coals could be burned in Smoke Control Zones.



Domestic Boiler Designed to Burn Coal Smokelessly

Another approach concentrated on the development of appliances which could utilise the naturally smokeless fuels, anthracite and low-volatile steam coals, that were produced in the Welsh coalfields. However, these coals suffer from the major disadvantage of low reactivity which makes them less suitable for burning on open fires. Consequently, there was a need to design a new type of appliance which could take advantage of their natural smokelessness, yet overcome their low reactivity. Subsequently, a range of gravity feed, or magazine boilers, was developed and introduced to the market place[19].

The incorporation of a boiler into the domestic combustion system, to provide central heating to the home, greatly increases the overall efficiency of the appliance. The typical efficiency of an open-fire without boiler, and burning smokeless fuel, is about 40%, whereas the incorporation of a boiler can increase that figure to about 50%[20]. This increase in efficiency not only benefits the household with lower fuel bills, but is environmentally beneficial as it reduces the amount of pollution per useful unit of energy extracted from the coal. With exempted appliances such as a roomheater with integral boiler, appliance efficiencies up to 75% are achievable.

A more recent development at CRE has been the application of underfeed stoker technology to the domestic and commercial size coal burning appliances[21]. To enable this to be achieved on the small scale necessary for domestic applications, British Coal has introduced a new size grading of coal called "Coalflow Pearls"; sized between 14 and 6mm, and prepared from a high calorific value, low-ash content coal. These Coalflow appliances combine low smoke emissions with a high amenity value, due to their high turndown capability (15:1) and automatic coal feed and ash removal, which makes them suitable for unattended operation. With an efficiency of up to 70%, the new range of Coalflow boilers is seen as continuing the advances made in the 60's and 70's, and contributing to future domestic coal burning, well into the next century.

THE DEVELOPMENT OF MORE EFFICIENT PLANT

In the 1960's and 70's the coal industry in the UK was faced with competition from cheap oil from the Middle East, and later, natural gas from the North Sea. R&D efforts were redoubled to develop coal-firing technologies which were more efficient, cleaner, more reliable with improved coal and ash handling facilities, and also environmentally acceptable.

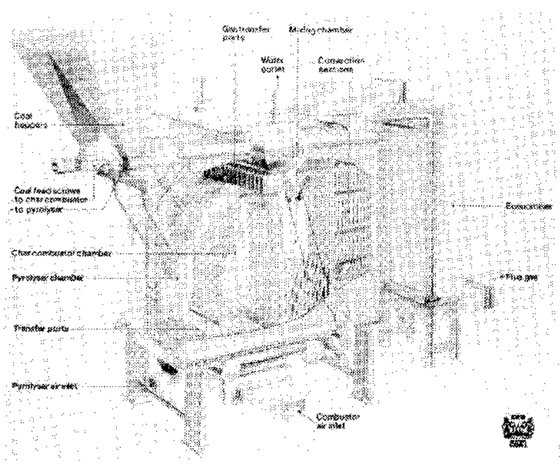
Development of FBC technology

It was considered that the technology best suited to meet all these needs would be based on the combustion of coal in fluidised beds[22]. There was already considerable expertise within the NCB in the utilisation of fluidised beds for the heating and oxidation of coals for smokeless fuel manufacture. It was a natural extension to apply this expertise to the combustion of coal.

The new approach by the NCB resulted from collaborative work in the 1960's with the then Central Electricity Generating Board (CEGB)[23] to design large power station boilers, and BCURA to design industrial boilers. As a result of other involvements, the CEGB withdrew and the NCB and BCURA continued to develop the system. Investigations into the basic chemical, physical and engineering aspects of the technology continued at CRE, and confirmed the advantages of the system and led to the design of combustors. By 1970, experimental units had been built at both CRE and BCURA. CRE concentrated on systems operating at atmospheric pressure, while BCURA worked to develop a pressurised combustor for advanced systems of power generation with high efficiency. Following the closure of the CURL site, the work on pressurised systems was transferred to CRE where it has been successfully integrated into British Coal's Topping Cycle studies.

As a result of lower combustion temperatures than in other systems, fluidised bed combustion offers the potential for lower NO_x emissions. Another important environmental advantage of the fluidised bed approach, recognised at an early stage, was the incorporation of sorbent materials into the bed to reduce the emission of SO_2 to the atmosphere[22]. This was of particular importance to operators in the USA where there are large reserves of high sulphur content coal. Accordingly, the NCB and BCURA were able to attract funding from the Environmental Protection Agency and the Electric Power Research Institute of the USA. These studies confirmed that fluidised combustion presents no serious problems of erosion or corrosion of constructional materials.

A novel variant of the fluidised bed combustor has recently been developed by CRE. The pyrolyser-combustor twin-bed system[24] comprises sub- and super-stoichiometric combustion chambers. The combustion gases from each, when subsequently mixed and combusted, produce a high temperature gas with low NO_x emissions. The elimination of in-bed tubes and the greater turn-down also give this type of boiler further advantages over earlier fluidised bed boilers.

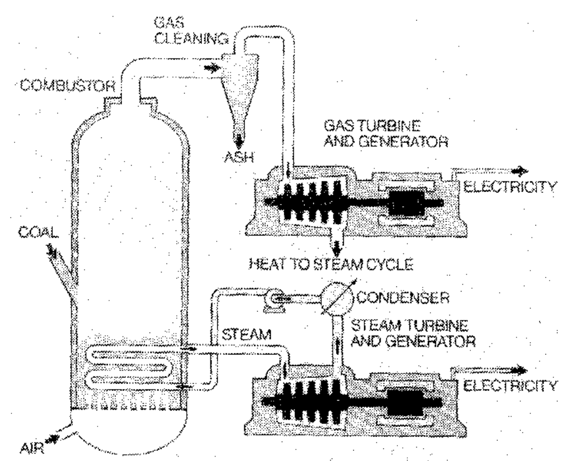


Pyrolyser/Combustor Water Tube Boiler

Fluidised bed technology has now developed to the extent that there are a wide range of appliance types available which have been successfully demonstrated on the industrial scale in several countries. Combustion Services Limited (CSL), a jointly-owned subsidiary of British Coal and BP Trading Ltd., is now charged with promoting this technology around the world.

PFBC Developments at BCURA and Grimethorpe

Although fluidised bed boilers operating at atmospheric pressure offer significant advantages over conventional coal-fired units, boiler efficiencies remain essentially unchanged. However, operation at elevated pressure allows the hot combustion gases to be used for driving a gas turbine, in addition to a conventional steam cycle. By such a "combined" cycle, the efficiency of power generation can be increased to 40% compared with 37% for the most efficient, conventional pulverised fuel-fired plant with flue gas desulphurisation. Emissions of sulphur dioxide can be reduced by the addition of limestone or dolomite to the bed material, and NO_x emissions are lower. The technology offers the prospect of cost savings over conventional systems because of reductions in both capital and operating costs.



PFBC Syatem for Power generation Using a Combined Cycle

Research began at BCURA in 1968, and an experimental combustor began operation the following year, rated at 2 MW and operating at 6 bar. The rig was used mainly for combined cycle generation studies, and attracted funding from the US Department of Energy and the Electric Power Research Institute (EPRI).

A major international development in fluidised bed technology saw the construction in 1980 of a large experimental pressurised facility at Grimethorpe, Yorkshire. Initially, jointly funded by the UK, the USA and W. Germany, the project was set up by the International Energy Agency (IEA) for larger-scale studies. More recently, a joint NCB/CEGB project[25] proceeded to demonstrate component reliability and flexibility of response, as a preliminary to demonstrating the process on a commercial scale.

The core of the Grimethorpe plant is the combustor which was designed on the basis of work at CRE and CURL. The combustor has a maximum rating of 80 MW_{th}, and operates with either a crushed coal or coal water mixture feedstock. Limestone or dolomite blended with the fuel feed enable sulphur dioxide reductions of 90% to be achieved.

Coal and Ash Handling Improvements

To facilitate the introduction of new coal-fired technology, it has been essential to address the problems of coal and ash handling. Traditionally, coal-firing was a manually-intensive practice, with the operators (stokers) manually feeding coal to, and removing ash from, boilers and furnaces. With the modern combustion systems which were becoming available, and their need for accurate control systems to maximise efficiency and minimise pollutant emissions, it was essential to develop systems which could improve on, and effectively replace, the traditional stoker's role. Accordingly, the development of improved coal and ash handling techniques has played an important part in the R&D activities of the Industrial Combustion Sections at CRE.

The controllability and amenity value of coal-fired systems has been markedly improved by the introduction of pneumatic delivery technology, and novel feeder systems based on incremental and screw conveyor principles[26]. The R&D has been carried out with the guidance of a coal and ash handling liaison committee which was set up by the NCB in 1980[27] to coordinate activities in this area. In addition to the development of new hardware, significant advances have been made in the understanding of the basic mechanics involved in the technology associated with this subject. Extensive use has been made of annular shear cells and mathematical models to predict the performance of novel handling systems and various coal characteristics.

More recently, attention has been directed towards improving the environmental impact of coal reception and storage facilities. The introduction of pneumatic delivery vehicles and coal silos has greatly reduced the dust levels normally associated with conventional open stocking arrangements. The problems associated with conventional ash removal and storage have largely been overcome with the advent of automatic, wet ash removal systems discharging into closed hoppers[26].

Changes in Clean Air Legislation

Environmental legislation comprised emissions of smoke from combustion appliances in the form of the Clean Air Act of 1956. This was subsequently revised in 1968[28] when legislation was introduced, particularly aimed at the industrial sector. The Act empowered the Minister for Power to prescribe limits on particulate emissions from commercial, industrial and power station boilers. As a consequence, CRE has been active for many years in developing more efficient, reliable and lower cost dust removal equipment, including cyclonic devices and bag filters.

The new Act also gave local authorities greater powers with regard to specifying chimney heights[29] to maximise the dispersion of emissions at ground level. This helped towards improvements in air quality near to the source of the emissions. However, this policy of dispersion from tall chimneys has come under attack in more recent years with the recognition of problems arising from Acid Rain.

This period in the history of CRE coincided with the entry of the UK into the Common Market (EEC). As a consequence, British Coal, and CRE in particular, began to take advantage of the funding that was available from Brussels. Initially the bulk of the funding was available through the European Coal and Steel Community (ECSC).

ACID RAIN, EUROPEAN CONCERNS AND DEVELOPMENT OF ENVIRONMENTAL LEGISLATION

Towards the latter half of the 1970's there was increasing concern about depletion of fish stocks and damage to forests in certain areas, including Scandinavia and Germany. Observed increases in acidity of surface waters in these regions were attributed to acidic precipitation. It was argued that the acidity of the rainfall in these areas was higher due to the presence of acidic pollutants, SO_2 and NO_X, from industrial sources several hundreds of miles away. Thus, the Acid Rain phenomenon was able to make its effect felt across national boundaries, and this escalated air pollution concerns from local to regional dimensions.

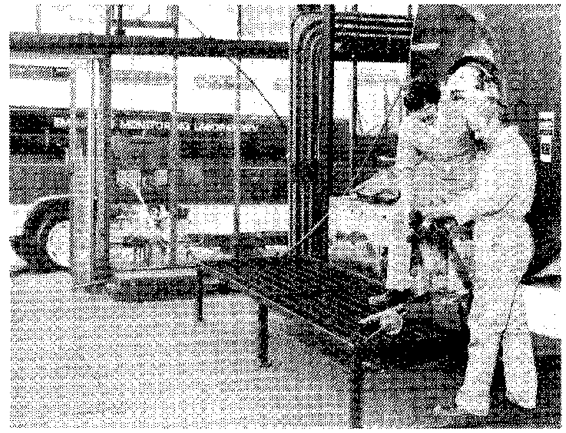
There followed intense public and scientific debate in Europe. This resulted in the introduction of EC legislation in the form of the Framework Directive (84/360/EEC) on combating of air pollution from industrial plant[30], which established the groundrules for subsequent legislation. The Large Combustion Plant Directive (88/609/EEC) on the limitation of emissions of certain pollutants into the air from large combustion plants[31], evolved from the earlier directive. It extended air pollutant emissions control to cover acidic gases (SO_2 and NO_X) as well as particulates. Limits were set for all new plant built after July 1987, and national targets were set for reducing the emissions of SO_2 and NO_X from existing large combustion plant.

British Coal's Response to Acid Rain Issues

Because the scientific evidence was not well established as to the scale and causes of alleged environmental damage, British Coal considered it important to undertake itself, and sponsor externally, paper and experimental studies in order to be able to make an informed contribution to the national and international debate. For example, British Coal with the CEGB funded a major project, managed by the Royal Society in conjunction with the Swedish and Norwegian Academies of Science. It examined the factors that influence the acidification of surface waters. Also, British Coal, in conjunction with the CEGB and the Scottish Electricity Boards, financed a study which demonstrated that the water chemistry of an acid lake can be restored by limestone treatment of the catchment.

Following concern about the possible contribution of acid deposition to the deterioration of historic buildings, such as Lincoln Cathedral, British Coal has participated in the Building Effects Review Group (BERG) set up by the UK Department of the Environment. CRE is coordinating British Coal's effort on a National Materials Exposure Programme (NMEP) within this group. This has involved the operation of five sites at which standard samples of building materials are exposed while meteorological and pollutant conditions are monitored. The CRE monitoring site has also been selected for use within a United Nations International materials monitoring programme.

British Coal's own research and development programme on the use of coal has increasingly been focused toward addressing environmental issues. Because initially, information on emissions from coal burning appliances was not sufficiently well quantified, CRE has undertaken many pollution monitoring programmes on a wide range of coal-fired appliances[32]. It now has two mobile laboratories which are used extensively throughout the UK[33].



Emissions Monitoring Using CRE's Mobile Laboratory

The emissions data obtained have proved invaluable in enabling an accurate assessment to be made of the contribution of coal combustion systems to national pollutant emission inventories. From this informed position, British Coal has been able to make significant contributions, through its consultations with the legislators, who have had the task of implementing the European legislation within the UK. Advice has been given on the cost implications of pollution control and the exact status of control technologies for the different types of coal utilisation processes.

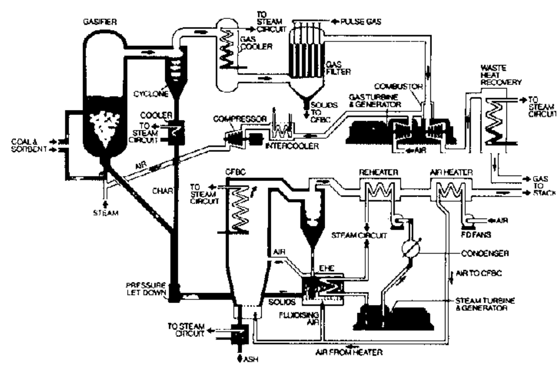
In conjunction with its emissions assessment programme, evaluation of various SO_2, NO_X and particulate control technologies, experimental studies and plant trials have been undertaken. The emphasis has been to reduce emissions by a combination of optimisation of combustion conditions and the application of low-cost abatement technology, to reduce the financial burden on coal burning technology. For industrial boilers, modest reductions (40-60%) in SO_2 emissions, at relatively low cost, can be achieved by in-furnace limestone injection in stoker-fired plant. Fluidised bed combustors offer ideal conditions for sulphur capture by the incorporation of sorbents into the bed material. Circulating FBC systems have demonstrated sulphur capture levels as high as 90%, comparable with the performance of FGD systems for large power plant. Low-cost NO_X control is most easily achieved by reducing excess air levels, NO_X emission reductions of ~20% are claimed, though combustion efficiency may be adversely affected. Low-NO_X burners offer greater NO_X reduction potential (up to 60%) but are more expensive and only applicable to pulverised fuel firing. Most expensive of all the options are the catalytic reduction techniques applied to the flue gas, with removal performances up to 80%.

Projects undertaken by CRE have demonstrated the scope for reducing NO_x formation in coal-fired boilers by modifying the combustion conditions, including the use of air staging or ammonia injection. Sorbent characterisation assessment procedures have been developed in support of the SO_2 control studies on FBC and stoker-fired plant, and have provided valuable data for a wide range of sorbents, limestones and dolomites. Technical and economic feasibility studies have also been undertaken[34,35] for the application of spray dry and alkali scrubbing FGD techniques for industrial-scale plant. Other investigations have led to significant improvements in performance and reductions in costs of particulate removal systems, including cyclonic devices, bag filters and electrostatic precipitators[36].

An important consideration of any pollutant control technology is the environmental impact of any residues emanating from the processes. Traditionally, the residues have comprised mainly coal ash, but new types of residue have resulted with the emergence of technologies to control SO_2 and NO_x. Over the years CRE has been to the forefront in developing environmentally acceptable means of disposing of residues from combustion systems. Utilisation has always featured strongly. Research continues and now concentrates on establishing utilisation prospects and environmentally acceptable disposal options for the new residues arising from control technologies.

For example, residues from FBC systems incorporating sulphur capture can contain free lime, which could influence their disposal. However, they harden when hydrated and applications such as partial cement replacement in stabilised roadbase materials, and in calcium silicate bricks have been evaluated. The environmental impact of the disposal of a wide range of FGD residues, by means of plant growth studies and physical, chemical and mineralogical characterisation, has shown that they should present no additional problems compared to conventional residues.

During this last decade there has also been significant progress in the development of advanced combustion and gasification processes, and increasingly there have been international dimensions to the work as a result of collaborations with overseas organisations. Considerable expertise has been established both in fluidised bed combustion and gasification, and this has resulted in the British Coal Topping Cycle[37] for coal-based power generation. This combined cycle approach utilises a pressurised, spouted fluidised bed gasifier to generate a low-calorific value fuel gas, which is subsequently burned for expansion through a gas turbine. The residual char from the gasifier is consumed in a fluidised bed combustor which provides heat for the steam cycle. Overall power generation efficiencies of around 45% are expected. This Topping Cycle development is being undertaken at CRE and Grimethorpe PFBC Establishment, with support from government and private sponsors. The technology is expected to be ready for commercialisation by the year 2000.



British Coal Topping Cycle With CFBC Char Combustor

GLOBAL WARMING AND INTERNATIONAL CONCERNS

The advent of the 1990's has seen international concerns over anthropogenic emissions of CO_2 and their possible contribution to enhancement of the naturally-occurring Greenhouse Effect. Suddenly this has become the priority, coal-related environmental issue because it poses a serious potential threat to coal use worldwide. Because of the apparent uncertainties regarding the extent and timing of any climatic change[38], British Coal has advocated that action needs to be taken to increase understanding of the Greenhouse Effect, and urgently develop control strategies that could be deployed should it become necessary[39]. Thus British Coal has initiated a number of in-house studies and international activities.

In view of the considerable uncertainties that exist concerning the links between emissions and climate change, British Coal's early studies have been concerned with increasing our understanding of coal's contribution to the increases in concentration of greenhouse gases in the atmosphere. British Coal is funding studies, both in the UK and overseas, to investigate how the climate has changed as greenhouse gases have built up in the atmosphere[40]. Research is also being funded which is aimed at examining the natural mechanisms involved in the absorption of CO_2 from the atmosphere, and the possibility of enhancing them to encourage nature to work a little harder in mankind's favour.

Among the short-term measures to restrict the emission of greenhouse gases, British Coal is continuing its R&D effort to improve appliance efficiencies, and encouraging the introduction of combined heat and power schemes wherever feasible. In the longer term, British Coal is making a major commitment to the development of a clean coal power generation system based on The Topping Cycle[37]. For generating capacities of around 350 MW_e, technical and economic evaluations indicate that the Topping Cycle has a substantial economic advantage over pf stations fitted with FGD or other competing technologies. Compared to a conventional pf + FGD power station, the system offers a 20% reduction in electricity generating costs, coal burned per unit of electricity produced, and emissions of CO_2. Without additional gas treatment the Topping Cycle is also expected to remove 90% of the SO_2, and 50% of the NO_X. The work has attracted substantial funding from the British government as well as the EEC.

A British Coal initiative is leading to a major International Energy Agency programme[41] being established which is aimed at developing fossil fuel-fired, power generating systems, with minimal emissions of greenhouse gases. The UK (Dept. of Energy) and about 14 other countries, including the USA, most of the EEC, and Japan are expected to participate. British Coal has been nominated to act as Operating Agent for the initial stage.

The British Coal Global Warming programme will form part of the UK contribution to the IEA Programme. Preliminary assessments of technology options are underway. It is proposed to undertake laboratory-scale work on the most promising option for generation with CO_2 removal, and to investigate means of utilising, or storing, the CO_2. The aim is to maximise the efficiency of the overall system (with CO_2 removal) and ensure that coal maintains its competitive position.

CONCLUSION

When the UK mining industry was nationalised after the last war, the emphasis was producing sufficient coal to meet the country's energy needs. Inevitably, environmental considerations were not a prime consideration. But over the years this has changed to a remarkable extent. Initially, the industry had to address environmental concerns which were local in nature, such as the adverse health effects of high SO_2 and smoke concentrations in ambient urban air. Then came strong competition from cheap Middle East oil and North Sea natural gas, and the growing requirements for cleaner and more convenient forms of energy.

In more recent years, British Coal has become increasingly active in collaborative R&D on an international scale. The Acid Rain issue introduced the European dimension at about the time when the UK entered the EEC. Now it prepares to contribute in an expanding international arena as the world addresses the concerns over Global Warming.

It is appropriate to recollect the words of Jacob Bronowski, who in 1957[14] said, "Science is the human capacity for looking ahead, for forecasting the way things will happen and will change, and for acting so as to forestall the changes of the future." This philosophy is very pertinent today, and typifies British Coal's response to environmental issues whether they be Acid Rain or Global Warming concerns.

ACKNOWLEDGEMENT

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ON-LINE ANALYSIS IN COAL-FIRED POWER STATIONS

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ABSTRACT

The performance of pulverised coal-fired boilers in power stations can be improved by adjusting combustion conditions to minimise losses due to incomplete combustion and excess air. This can be achieved by balancing the burners and then adjusting excess air to minimise losses. Two new instruments are being developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for this application. The first is a microwave gauge for the on-line determination of unburnt carbon in fly ash. A plant trial of an industrial prototype gauge has been carried out at a New South Wales power station during 1991. The second instrument is an ultrasonic gauge for the on-line determination of pulverised coal mass flow to individual burners.

1. INTRODUCTION

There has been a rapid increase in the industrial application of on-line analysis instrumentation in the coal industry over the past decade particularly for the determination of ash, moisture and elemental composition (Sowerby, 1991). The CSIRO Division of Mineral and Process Engineering has been actively involved in this field through the development and field testing of on-line instrumentation for the determination of ash in coal using dual-energy gamma-ray transmission and pair production techniques; in-stream analysis of coal slurries using nuclear techniques; and the on-line determination of moisture in coal and coke using capacitance, microwave and nuclear techniques (Cutmore et al., 1990). These techniques have been licenced to either Mineral Control Instrumentation Ltd or the Australian Mineral Development Laboratories, both of Adelaide, South Australia. These on-line gauges are used in a wide variety of applications, including mine grade control, coal sorting, coal preparation plant control, coal blending and power station feed monitoring (Sowerby, 1989).

In the combustion of pulverised coal for steam generation there are certain controllable energy losses caused by operating under non-ideal conditions. These losses are due to incomplete combustion of both solids and combustible gases and losses due to the need for excess air. Also the non-uniform distribution of pulverised coal between burner feed pipes leads to localised areas of incomplete combustion, slagging and fouling, increased NO_x emissions and a reduction in boiler efficiency.

In practice, the controllable losses due to incomplete combustion and excess air show a minimum as a function of oxygen in the flue gas (Fig. 1). These losses can be reduced by balancing the burners and then adjusting the excess air to operate near the minimum. There is therefore a clear need for reliable and accurate on-line instrumentation to measure the mass flow rate of pulverised coal in feed pipes into large coal-fired boilers and to measure the unburnt carbon in fly ash in the flue ducts. At present the few instruments which have been developed have not found widespread acceptance or use in the power generation industry.

2. UNBURNT CARBON IN FLY ASH

2.1 Introduction

Three different approaches to optimise efficiency by on-line monitoring are to determine oxygen in the flue gas, CO in the flue gas or unburnt carbon in the fly ash. Zirconium oxide based oxygen sensors are commercially available and widely used in the power generation industry. However, oxygen sensors are very sensitive to air infiltration into the boiler and ducts (Presser et al., 1982). Also it is difficult to locate the sensor(s) to representatively sample the flue gas and calibration drifts are common (Anon, 1984). Both in-situ and by-line CO monitors are commercially available, based usually on infrared absorption. Most reported CO measurements on boilers have been on oil and gas-fired units. However there is continuing debate as to the effectiveness of CO monitoring in large coal-fired boilers.

The on-line measurement of unburnt carbon in fly ash would be ideally carried out by determining the average value across the large (~4x4 m) flue ducts in a power station. However no method of doing this has yet been devised and the three previously developed instruments (Table I) all continuously extract small quantities of fly ash from the ducts. Two of these instruments determine carbon by combustion, one by measuring the CO_2 produced and the other by measuring mass loss. The third instrument measures carbon by infrared reflection. All three instruments have significant disadvantages, as outlined in Table 1.

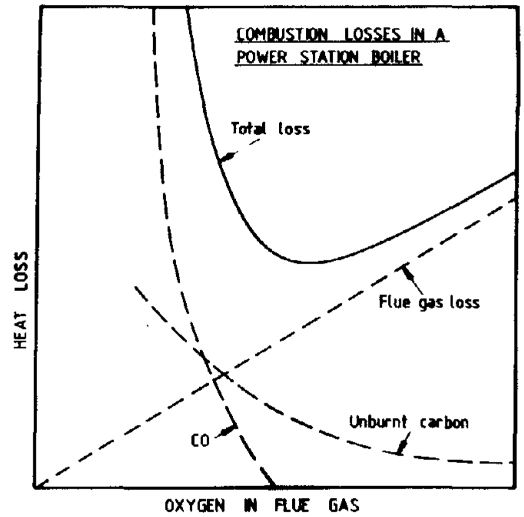

Fig. 1. Combustion losses in a coal fired boiler as a function of oxygen content of the boiler flue gas.

CSIRO have been investigating nuclear and microwave techniques for the rapid and accurate analysis of fly ash samples, which in an industrial instrument would be extracted from the duct via a cyclone, filter or similar device.

2.2 Laboratory Measurements

Nuclear and microwave techniques have been investigated for the rapid and accurate analysis of fly ash samples (Abernethy et al., 1991, Cutmore et al., 1990). Laboratory measurements have been carried out on 123 fly ash samples which were provided by six Australian power stations. These measurements have shown that carbon can be determined using either microwave or neutron inelastic scattering techniques to within an r.m.s. error of 0.08 to 0.29 wt% for individual power stations. For combined

TABLE 1. Comparison of previously developed instruments for the on-line determination of carbon in fly ash.

Instrument	Cigma Carbon-in-Ash Monitor	Anteater	Tapered Element Oscillating Microbalance (TEOM)
Manufacturer/ Marketer	Bristol Babcock Ltd, U.K.	M&W Asketeknik ApS, Denmark	Rupprecht & Patashnick Co., USA
Measurement Technique	Combustion (fluidised bed, CO_2 analysis)	Infrared reflection	Combustion, mass loss
Sample size	~2.5 g	~3 g	~35 mg
Analysis time	6 min	3 min	15 min
Accuracy (wt%C)	0.5	>0.5	>0.5
Limitations	Furnace sealing, complexity of sample handling and weighing	Inaccuracies due to variations in coal and ash properties and particle size	Small sample mass, complexity of sample handling

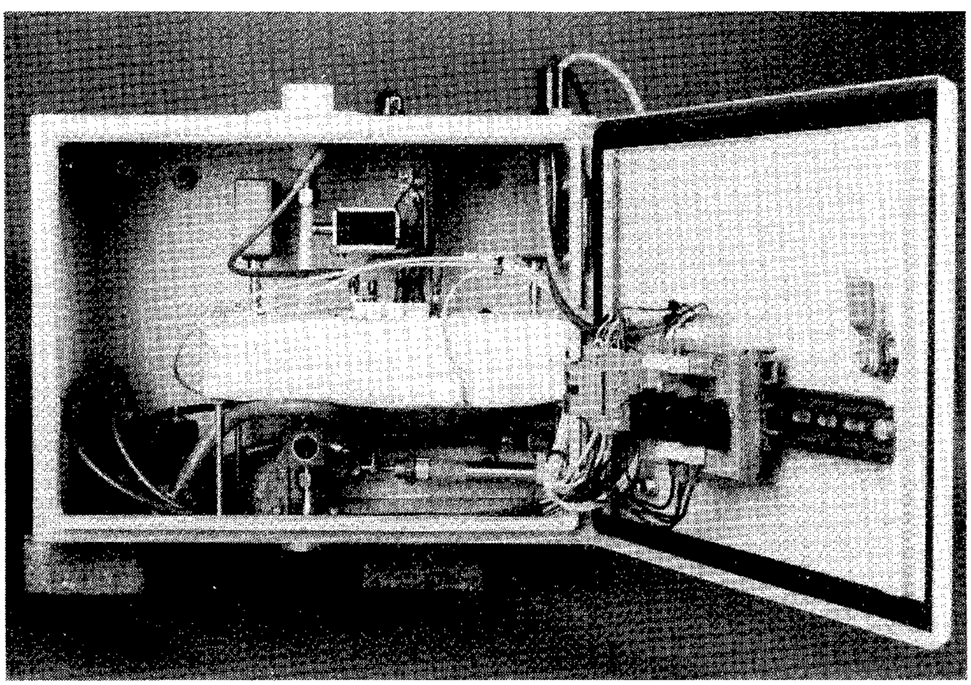

Fig. 2. Industrial prototype of the microwave gauge for determination of unburnt carbon in fly ash. The CEGRIT sampler is located directly above the microwave gauge.

data of less than 5 wt% carbon from all six power stations, the r.m.s. errors were 0.23 and 0.30 wt% carbon for the microwave and nuclear techniques respectively. The neutron inelastic scattering technique has the advantage of measuring elemental carbon directly. However, microwave techniques have the advantages of rapid analysis time, higher accuracy at low carbon content, adaptability to small sample sizes, lower cost and no requirement for bulky radiation shielding. Consequently, the microwave technique was selected as the most suitable technique for further development and field trials.

The measurement of weight percent unburnt carbon in fly ash by microwave techniques is based on the high real or imaginary part of the complex dielectric constant of unburnt carbon compared to the dielectric properties of the remaining matrix (principally oxides of silicon, aluminium and iron). The complex dielectric constant, $\varepsilon = \varepsilon' - j\varepsilon''$, is a function of the dielectric constant (ε') and the loss factor (ε'') of the fly ash/air mixture, and therefore affected by both the unburnt carbon concentration and bulk density of the fly ash. Laboratory microwave measurements were made in three geometries in which the fly ash sample was in free space, in a waveguide and in a central tube in a cylindrical microwave resonant cavity (MRC). The sample masses in these geometries were about 3 kg, 300g and 3 g respectively. In the first two geometries microwave attenuation and phase shift were measured whereas resonant frequency and Q-factor were measured in the MRC. Of the three microwave techniques developed, the MRC technique has the advantages of simplicity, small sample size and equivalent accuracy to the other microwave techniques (Abernethy et al., 1991). In practice, the small sample size makes the MRC technique suitable for use with commercial automatic dust-samplers.

2.3 Field Trial of MRC Technique

There are two main practical problems to be overcome in the application of the microwave technique to the routine on-line determination of carbon in fly ash in a power station. These are firstly to ensure a controlled flow of fly ash through the gauge, and secondly, to ensure that the sample analysed is representative of the fly ash being expelled from the boiler.

The microwave technique has been field tested using CEGRIT Automatic Dust Samplers (Mark II) to supply fly ash to the gauge. The field test commenced in April, 1991 at the Electricity Commission of New South Wales Wallerawang power station. Two gauges have been installed on separate ducts from the No.8 boiler at the station. One of these gauges (Fig. 2) analyses fly ash collected by a single CEGRIT sampling device, and the other gauge analyses fly ash collected simultaneously by three CEGRITs at different vertical positions in the duct. The fly ash from each CEGRIT will be analysed separately to allow an assessment of sampling bias. Results to date indicate that multiple sampling points are required to achieve representative sampling. Whilst the field trial is still in progress, preliminary results indicate unburnt carbon can be determined to better than 0.5 wt% over the range 7-16 wt%.

3. PULVERISED COAL MASS FLOW

3.1 Introduction

In pulverised coal-fired boilers coal is pulverised in mills and then transported pneumatically via heated primary air through burner feed pipes to burners within the boiler. A typical large coal-fired boiler will operate with about seven pulveriser mills and 40 burners. The mills pulverise the feed coal to a particle size of about 75% through a 75 micron screen. The coal-air mixture is blown out of each mill into about six burner feed pipes of diameter 300 to 600 mm at velocities of about 25 m/sec. The coal and air densities in these pipes are respectively about 1.0 and 1.2 mg/cm^3. Non-uniform distribution of pulverised coal between the burner feed pipes leads to localised areas of incomplete combustion, slagging and fouling, increased NO_x emissions and a reduction in boiler efficiency.

There is a clear need for a reliable and accurate on-line instrument to measure the mass flow rates of pulverised coal in feed pipes into large coal-fired boilers. The measurement technique should preferably be non-invasive, accurate to within about 5% relative and inexpensive. However, at present, no satisfactory method is known for the routine on-line measurement of coal mass flow rate in the harsh environment of burner feed lines in power stations.

A number of groups have previously carried out research and development into techniques for the on-line determination of pulverised coal mass flow. For example the British Coal Utilisation Research Association (BCURA) developed and field tested a pulverised coal mass flow meter comprising an ultrasonic gas velocity meter combined with a beta-particle absorption meter for coal density (Parkinson, 1967). The ultrasonic meter comprised two pairs of ultrasonic transducers with 40 kHz continuous ultrasonic waves transmitted upstream and downstream at about 45° to the flow direction. The gas velocity was derived from the phase difference between the two received signals. The BCURA pulverised fuel mass flow meter was evaluated by Loosmore (Loosmore, 1972) and, although it had some problems, it was shown to be capable of measuring the mass flow to individual burners to within about ± 10%. Six BCURA mass flow meters were field tested at a British power station (Pickering et al., 1973). However there was sufficient erosion and build-up on the sensor faces that the mass flow meter was not recommended for industrial use.

In the early 1980's, Mount Isa Mines Ltd, Australia, developed a gauge for the determination of coal mass flow in the feed to a copper reverberatory furnace (Cunningham et al., 1985). The technique involves measuring the coal density using the forward scatter of beta radiation and the velocity using the transit time of electric charge fluctuations in the dust.

In practice, the major disadvantage of the above techniques is the hazard of using radioactive beta-ray sources separated from an abrasive and hostile atmosphere by only thin windows.

More recently, Wayne State University and Available Energy Inc. have developed an ultrasonic technique in which a narrow ultrasonic beam of frequency 460 kHz is transmitted at 90° to the flow direction, and flow velocity is determined from the down stream drift of the beam which is measured by physically moving the ultrasonic receiver (Leffert and Weisman, 1987). Solids loading is measured from the mean attenuation of the transmitted ultrasonic beam. The main disadvantage of this technique is the need to constantly move the ultrasonic receiver to determine the mean signal amplitude of the highly fluctuating signal at each received location.

CSIRO is developing an ultrasonic technique for the on-line determination of the mass flow rates of solids suspended in a gas stream. The flow meter comprises pairs of broad beam ultrasonic transducers positioned on opposite sides of the pipe carrying the pulverised coal to the boiler. From measurements of the transit times of ultrasonic pulses in both directions at about 45° to the flow direction and the amplitudes of transmitted ultrasonic pulses, the following parameters are derived: the velocity of gas flow; the mass loading of solids; the mass flow rate of solids; and the gas temperature.

3.2 Laboratory Measurements

In order to evaluate mass flow techniques under realistic conditions, a large closed-loop dust rig for recirculating dust in the velocity range 10 to 30 metres per second has been installed and successfully tested at our laboratory. The rig comprises 300 mm diameter pipes, an 840 mm diameter centrifugal fan with variable speed drive and a cyclone clean-up system (Figure 3).

In order to use the closed-loop rig to evaluate flow measurement techniques, it was first necessary to understand and, to some extent, be able to manipulate the flow characteristics of the rig. A series of measurements were made with pitot tubes and ultrasonics to examine the effect on air velocity and turbulence of (a) speed controller setting; (b) the insertion of orifice plates of diameter 150, 200 and 250 mm; (c) the insertion of flow straighteners (two designs); and (d) the covering of measurement ports to ensure a smooth inside bore of the pipe.

Standard air velocity measurements were made using pitot tubes at 20 positions across horizontal and vertical diameters of the duct, according to British Standard BS1042, Part 2A, 1973. These velocity measurements were then used to calibrate the variable speed controller under various conditions (orifice plates, straighteners, etc). For a particular configuration, a linear calibration of the variable speed controller could be used to determine velocity to within about 0.07 m/s.

A comparison of the pitot tube measurements with the 45° ultrasonic technique showed that the ultrasonic technique could be used to measure air velocity to within about 0.4 m/s over the range 10 to 30 m/s.

To date, dust measurements have been made with glass microspheres and alumina dust in the rig. These materials have been chosen as they do not constitute an explosion hazard, they do not break up significantly in the rig and they are readily available in a number of size fractions.

Ultrasonic attenuation measurements of dust loading are complicated by the effects of turbulence and by window erosion and/or build-up. The ultrasonic gauge is calibrated against a ^{85}Kr beta-ray transmission gauge located adjacent to the ultrasonic gauge. Flush mounted ultrasonic probes at 90° to the flow direction were found to be most satisfactory for attenuation measurements. Results to date indicate that ultrasonic attenuation can be used to determine dust loadings to within about 10% relative over a range of velocities and dust loadings.

4. DISCUSSION

The MRC technique for determination of carbon in fly ash was licenced to Mineral Control Instrumentation Ltd (MCI) in 1990, subject to satisfactory completion of a field trial of the technique at Wallerawang. It is anticipated that commercial gauges will be available in 1992. The ultrasonic technique for coal mass flow is at an earlier stage of development and requires further testwork prior to field testing and commercialisation.

The potential benefits of improved control of coal-fired power stations resulting from the use of these gauges are increased combustion efficiency, increased unit availability, more consistent fly ash composition and reduced CO_2 per MW generated. The potential financial savings are site-specific, depending on the

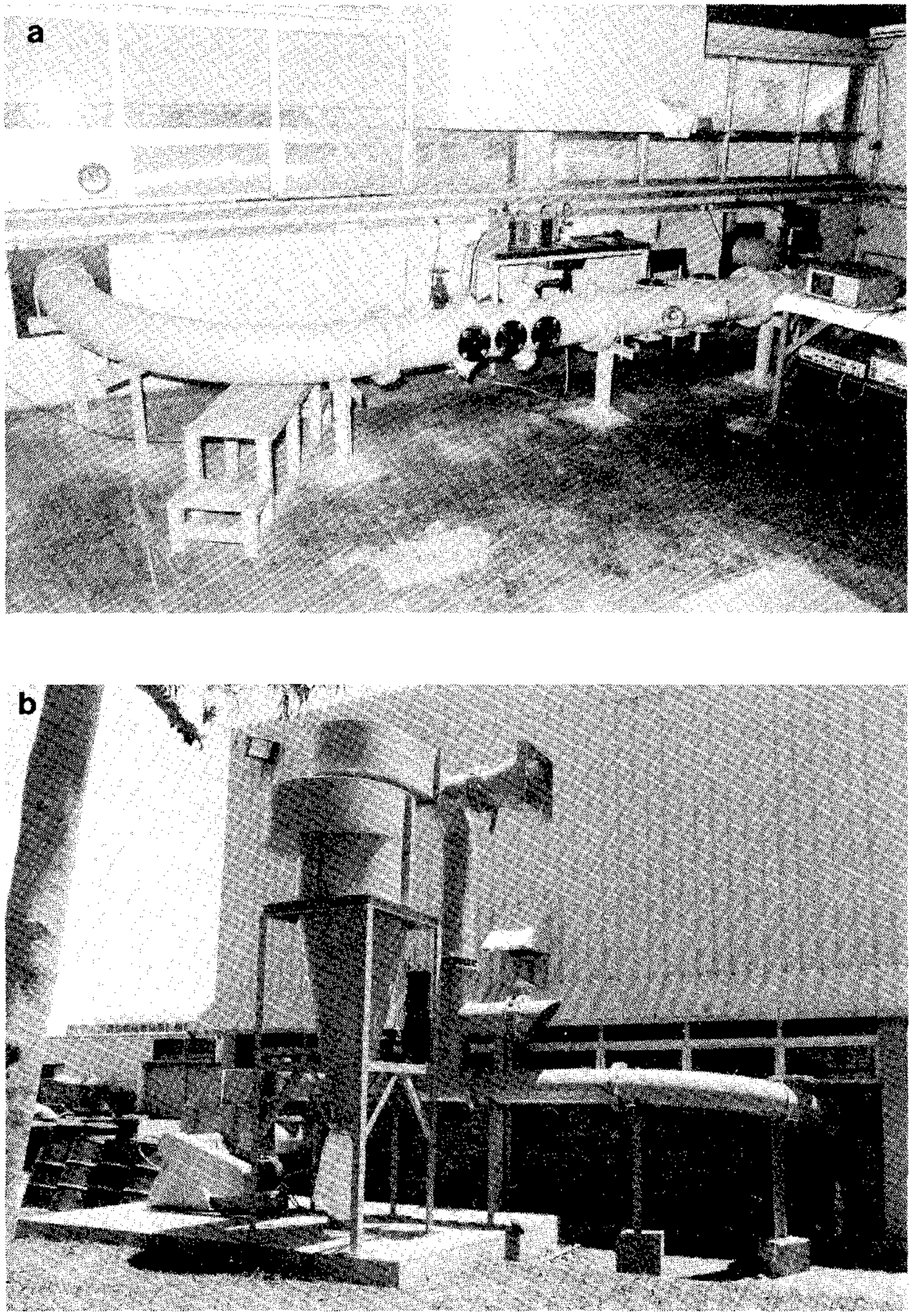

Fig. 3. The closed loop dust rig used for the development and testing of coal mass flow gauges, showing (a) the instrumented pipe sections and (b) the centrifugal fan and cyclone cleanup facility.

price of coal, capacity factor, fly ash disposal, etc. These savings have been estimated to be over US$ 1 million per year on some boilers (Sotter and Mortensen, 1990).

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CLEAN USE OF COAL VIA GASIFICATION AND LIQUEFACTION

by

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ABSTRACT

The production of gaseous and liquid fuels via coal gasification and liquefaction provides beneficial routes towards the clean use of coal. Following the major investment directed towards process development in the 1970s there was a down-turn in the overall level of activity in the 1980s. However, a number of significant developments continued and encouraging demonstrations of potential were made. Recently, environmental requirements and the possibility of oil shortages has given these developments new impetus.

The significant recent advances made in coal gasification and liquefaction, with emphasis on European activities, are described. In particular, progress made on the development of British Coal's Topping Cycle power generation system and also on its Liquid Solvent Extraction process is presented.

Significant improvements in performance and reliability of gasification and liquefaction technologies have been achieved but further improvements can be expected. Accordingly, an examination of some of these potential advances is made.

INTRODUCTION

The term clean coal technology encompasses a very wide range of technologies from coal preparation and coal handling, through retrofits and modifications to conventional combustion technology, to advanced coal combustion and coal gasification, and ultimately coal liquefaction.

Coal gasification and liquefaction in a variety of forms have been utilised at an industrial scale at various times in various locations during the twentieth century. These processes have often not been economically competitive with other fuel sources or with other coal utilisation technologies. Hence, there has long been a need for improvements in the performance of these technologies.

The energy crises of the 1970s spurred major investments in RD&D aimed at the improved process performance of gasification and liquefaction processes, in terms of availability, reduced costs, and improved efficiency. As concerns about the cost and availability of gas and oil declined in the 1980s so did the investment in technology development. However, the realisation that the environmental performance of these technologies could make a major contribution towards achieving this goal meant that a number of significant development programmes continued.

This paper concentrates on significant developmental activities within Europe and in particular on activities undertaken by the British Coal Corporation (BCC).

GASIFICATION TECHNOLOGIES

The significant contribution offered by gasification is that it provides a route to a clean gas which can either be used as an energy source for a combined cycle power plant, as a substitute for natural gas, or as a source of chemical feedstock, ie, carbon monoxide and hydrogen.

The principle activities in Europe which are based on European technology and concentrate on the use of coal gasification within combined cycle power generation systems can be summarised as follows.

Entrained Flow Technology

The Krupp Koppers Prenflo process, which is an oxygen-blown entrained system, has operated at a 48 tpd scale.

Plans are now being discussed regarding the construction of a 170MWe plant at Duisburg in Germany which will incorporate a Siemens combined cycle power island. (Makansi 1990)

Fixed Bed Technology

British Gas and Lurgi have been developing their fixed bed BGL slagging gasification process at a 500 tpd plant in Westfield, Scotland since 1984. A demonstration programme was completed in November 1990 which illustrated that gasification of conventional power station coals could be successfully achieved by producing bitumen-bound briquettes from fines and blending these with the lump coal before charging to the gasifier. In addition, it was shown that the performance of the gasifier was not significantly affected by sudden changes in coal rank or mineral matter content of the feed. (Gliddon 1991)

The BGL gasification system is now under consideration by several consortia for inclusion in a number of proposed European IGCC projects.

Fluidised Bed Technology

Based on the successful operation of the atmospheric Winkler gasification process the HTW demonstration plant has been in operation since 1986. Operating at 10 bar it processes 720 tpd of lignite. A pilot plant operating at 25 bar has been in operation since late 1989. (Energie Spektrum 1991). Some test-work has been undertaken on hard coal and also using air and steam as the gasifying agents.

RWE Energie AG plans to build a combined cycle power plant based on the gasification of lignite with air. The plant is being designed to produce 300 MWe with a Siemens combined cycle power island including a Siemens, type 94.3, gas turbine.

Topping Cycle Technology

The processes described above have a number of common features when operating on hard coal; specifically they use oxygen and steam as the gasifying agents and employ conventional low temperature 'sulphur' capture and particulate removal downstream of the gasifier. The combination of these features results in significant capital cost and efficiency penalties.

British Coal are undertaking a programme to develop a hybrid gasification/combustion system for hard coal which incorporates an air-blown spouted fluidised bed gasifier. This scheme produces a low calorific value gas for combustion in a gas turbine. This feature of the scheme is not unique since it is worth noting that in many of the proposed conventional integrated combined cycle schemes, nitrogen separated in the oxygen plant is recombined with the medium calorific value gas, forming a low calorific value gas prior to use in the gas turbine.

Unconverted char from the BCC gasification system is burned in a combustion system that forms part of the steam cycle. The advantages are that air-blown partial gasifiers can be used which are of simple design and tolerant to a wide range of coal properties. The use of a separate solids combustor means that high temperature heat is available in an oxidising environment to ensure that state of the art steam conditions can be used.

British Coal has assessed the options available and has established a preferred system for commercial development. Figure 1 shows a schematic of the Topping Cycle selected by British Coal. Coal is gasified in an air-blown spouted bed gasifier operated at elevated pressure (typically 18 bar) and temperatures up to 1000°C. Sorbent is also injected into the gasifier to retain sulphur which would otherwise be released in the gas. The fuel gas from the gasifier undergoes an initial stage of cleaning in a cyclone. The raw gas leaving the cyclone, at close to 1000°C, is then cooled to about 600°C via a heat exchanger; it still contains some fine particulate material which is then removed using ceramic candle filters. At this temperature almost all the volatile alkali salts condense out from the flue gas onto the particulate matter collected by the filter medium. The clean fuel gas is burned in the gas turbine combustor, producing hot combustion products at about 1380°C corresponding to a turbine entry temperature of 1260°C. These are passed to the turbine expander stages which drive the turbine compressor and an electric power generator. The exhaust gases pass to a waste heat boiler and then via a stack to atmosphere.

Between 70 and 80% of the coal is converted into a low calorific value fuel gas. The 20-30% of the gasifier coal feed which remains unconverted is removed from the gasifier mainly as fines collected by the cyclones and hot gas filters. These fines are transferred to the circulating fluidised bed combustor (CFBC) where, together with any residual gasifier material removed from the base of the gasifier, they are burned to raise heat for the steam turbine cycle, thereby resulting in further power being generated. The sulphided sorbent in this material is converted to calcium sulphate. Additional sorbent can be fed to the combustor to complete the sulphur retention process.

The predicted efficiency for a commercial power plant based on such a Topping Cycle system using a typical UK power station coal is around 46-47%. This assumes the use of a commercially available gas turbine and a sub-critical steam cycle with turbine inlet conditions of 160 bar, 538°C, and reheat to 538°C. There should also be significant capital savings compared to conventional pulverised fuel power stations with flue gas desulphurisation and other advanced technologies. The British Coal Topping Cycle will have a lower generating cost than the other options and has the potential for significant improvement in efficiency. The development of advanced super-critical steam turbines will mean that supercritical steam cycles can readily be introduced (for which the CFBC system is particularly well suited). There should also be benefit from future developments in gas turbines that could be retrofitted to the system. Such advances are predicted to raise the cycle efficiency to around 52% or more.

Environmental Performance

Sulphur

The British Coal Topping Cycle makes use of the ability of limestone to capture sulphur in both the fluidised bed gasifier and fluidised bed combustor. Sorbent is injected into the gasifier where hydrogen sulphide, which would otherwise have been released with the fuel gas, is captured as calcium sulphide. This material is transferred along with the unconverted coal char to the combustor where it is converted to calcium sulphate, an environmentally acceptable material. Tests so far carried out in the gasification process, have shown that up to 95% of the sulphur can be captured in the coal ash and added limestone at atmospheric pressure. Work is in progress, on a plant which processes 12 tpd coal, to investigate the effects of pressure on this process and to demonstrate that the oxidation process is completed in the combustor without unacceptable release of sulphur dioxide. Should further reduction in sulphur emissions become necessary, polishing systems such as the use of zinc ferrite are under development. Such a system is intended for demonstration as a sidestream on the plant being constructed by Demkolec for SEP the Dutch utility, based on the Shell gasification process.

NO_x

The use of air-blown gasification systems enable combustion systems to produce low levels of NO_x emissions. Fuel gas which has been cleaned in dry systems, such as those using ceramic candles, still contain quantities of fuel-bound nitrogen. Tests have been carried out, by AIT under contract to British Coal, using synthetic gas mixtures in a 1MW combustor. These tests have shown that conversion of molecular nitrogen to NO_x is very low (less than 5 ppm) while conversion of ammonia is less than 50%, leading to acceptable NO_x levels for fuel nitrogen contents expected from the gasification stage of the British Coal Topping Cycle. Development will continue with tests using synthetic fuel gas preheated to 600°C and by the addition of a gas cleaning system and gas combustor to the pressurised fluidised bed gasifier at the Coal Research Establishment.

Estimated emissions from a Topping Cycle plant, using a typical UK power station coal, are given in Table 1. Environmental impact data, including comparisons with other power generation technologies, is given in Table 2.

LIQUEFACTION TECHNOLOGIES

Referring to the previous section, it is interesting to note that coal gasification has a role to play in process routes from coal to liquid products. It is either used as a prime operation in the indirect route (gasification plus synthesis) or for the provision of hydrogen, an essential part of the direct liquefaction route.

There has been a long history of coal liquefaction development and exploitation in Europe. During the recent developments since the late 1960s the emphasis has clearly been placed on the production of transport fuels. Process development has been undertaken on both single and two stage processes.

Single Stage Liquefaction

Two processes have been under development in Germany since the early

1970s. Both are single stage processes in which coal solubilisation and primary hydrogenation are carried out in the same processing step, although both include an integrated downstream refining step.

In the Kohleöl process developed by Ruhrkohle, coal is slurried with a distillate recycle solvent at a ratio of about 1:1. Primary hydrogenation is carried out with a disposal 'red mud' (FE_2O_3) catalyst at 300 bar and at temperatures around 475°C. The reactor products are flashed, the flash bottoms being vacuum distilled to separate residual solids. The vacuum column overheads are recombined with the flash overheads and are further hydrogenated in a fixed bed reactor, the products from which are again flashed. The bottoms from this second flash are recycled as solvent, whilst the overheads are further hydrogenated in a second fixed bed reactor. There is no pressure let-down between the first stage and the hydrogenation reactors, which therefore also operate at 300 bar although at lower temperatures. The distillate product is refined, although further processing is still required to produce acceptable transport fuels. Distillate yields as high as 61% by weight on dry, mineral matter free coal have been reported; this is associated with a hydrogen consumption of approximately 9% of the coal feed.

The initial processing stage of the Pyrosol process developed at Saarbergwerke is very similar. Again, a red mud catalyst is used, although the recycle solvent is heavier and the solvent:coal ratio is 1.5:1. Reactor conditions are significantly less severe than those of the Kohleöl process, the reactor pressure being 200 bar and the temperature also being lower. The liquid products from the reactor, however, pass to an uncatalysed hydropyrolysis reactor, producing additional distillate, gas, and coke. The overall distillate product is relatively unrefined, but yields of up to 55% by weight have been reported at a hydrogen consumption as low as 3% of the coal feed.

Two Stage Liquefaction

The British Coal Corporation Liquid Solvent Extraction (LSE) process is an example of a modern two stage liquefaction process. The process was developed on a small integrated recycle plant at the Coal Research Establishment (CRE) where development work on an advanced solids filtration system was also performed. A 2.5 tpd coal feed plant has recently begun operation at the Point of Ayr Liquefaction Facility. A simple process flow diagram is given in Figure 2 and a process description presented below.

Coal is dried, crushed and slurried with a hydrogen donor solvent. This solvent, a mixture of aromatic and hydroaromatic hydrocarbons, is produced within the process and recycled indefinitely. The coal slurry is pressurised to approximately 20 bar, preheated to 410°C and then fed a digester in which up to 95 per cent of the coal is dissolved. No catalyst or added hydrogen is used in this step, the use of elevated pressure being simply to prevent undue vaporisation of the solvent. During the digestion process, hydrogen is donated from the solvent to the coal structure as it breaks up, thus preventing retrograde coking reactions. The resulting digest contains dissolved coal ('extract'), residual coal solids and, of course, the mineral matter originally present in the coal since this is insoluble.

The digest is cooled to 300°C, depressurised and filtered to remove the mineral matter and the undissolved coal. The filtrate, which is solids free and has a very low ash content, is known as 'coal extract solution'. The filter cake is washed with a low boiling fraction of the solvent, produced by distillation from the coal extract solution, which displaces the coal extract solution trapped within the voidage of the cake. The residual wash oil is, in turn, recovered by vacuum drying the filter cake. This washing and drying procedure minimises the loss of extract and solvent with the filter cake. It is the use of filtration for solids removal, together with the low pressure first stage, which distinguishes the LSE process from other two stage liquefaction processes.

The coal extract solution is pressurised, typically to 210 bar, mixed with hydrogen gas and preheated before being fed to the hydrocracking reactors. These reactors contain catalysts which are similar to those used in the oil industry for the desulphurisation of heavy petroleum residue. The catalyst bed is fluidised by a high flow of recycled hydrocracker product, which heats the fresh feed to the operating temperature of 400-450°C. This recycle flow also allows the hydrocracker temperature to be controlled by transferring to the incoming feed the heat liberated by the hydrogenation and hydrocracking reactions taking place in the reactor. These reactions result in a proportion of the gaseous hydrogen combining chemically with the coal extract, breaking down its structure and yielding relatively low boiling products.

The product from the hydrocracking stage is distilled to recover the recycle solvent and to give three main products:- LPG (propane and butane), naphtha (boiling below 180°C), and middle distillate (boiling range 180-300°C). In some circumstances a by-product pitch stream, nominally boiling above 500°C, is taken off, although most of the material in this boiling range is recycled to the digestion stage as part of the solvent. The remaining by-product streams consist of light hydrocarbon gases, predominantly methane and ethane, and heterogases such as ammonia and hydrogen sulphide which are formed from the nitrogen and sulphur present in the coal.

Since no gaseous hydrogen is used in the digestion stage, it is important to ensure that the solvent retains its hydrogen donor ability on repeated recycle. Within the hydrocracker it is, therefore, necessary to rehydrogenate the solvent to replace the hydrogen donated to the coal during digestion, as well as to hydrocrack the coal extract. The overall hydrogen consumption is 6% of the coal feed.

The distillate products from the core of the process described above, unlike other liquefaction processes, require little further upgrading before they are suitable for use as transport fuels. A conceptual refinery block flow diagram is shown as Figure 3.

Naphtha is hydrotreated to remove residual sulphur and nitrogen and then fractionated to give an isomerisation unit feed a cut which is 60 per cent or more cyclohexane and a reformer feed. This cut by-passes the reformer since the cyclohexane would otherwise dehydrogenate to benzene, an environmentally undesirable gasoline component. Reformer conditions need only be very mild in comparison with those used for petroleum naphthas. A Research Octane Number of 100 is readily achievable at a liquid yield approaching 95 per cent. As a result, an overall octane number of 98 can be achieved in the gasoline pool, giving it a premium value as a high octane blendstock.

The production of diesel fuels of acceptable quality from direct coal liquefaction primary products is more challenging. The middle distillate must essentially be completely saturated, increasing its hydrogen content as far as possible, principally because of the correlations between hydrogen content, specific gravity and cetane number. Even then, the cyclic structure inherited from the coal limits the maximum cetane number which can be obtained.

Environmental Performance

The overall performance of a liquefaction process will depend not only on the performance of the process itself but also on the configuration of the total plant in terms of the provision of process heat, power, steam and hydrogen. A conceptual commercial LSE plant is shown in Figure 4.

The sulphur contained in the coal fed to the LSE process is largely removed as hydrogen sulphide in the digestion and hydrocracking stages. Most of the remainder is contained in the gasifier feed. All gas streams are cleaned as an integral part of the process, since this allows gas recycle and minimises the need to produce fresh hydrogen. Gas desulphurisation is essentially 100% effective, giving a solid sulphur product. As a result, only those streams which are burnt on site, together with the transport fuel products, are potential generators of sulphur dioxide.

The bulk of the nitrogen contained in the coal feed is removed during hydrocracking as ammonia. Most of the remainder passes through to the gasifier. There are small amounts of ammonia in other gas streams, notably in the secondary refining area. As part of the gas cleaning referred to above, ammonia is removed in aqueous solution and recovered as a by-product. Residual nitrogen levels in the process fuel gases, LPG, gasoline and diesel are very low . The only fuel-derived source of nitrogen oxides is, therefore, the pitch product used in the fired process heaters, and in steam raising.

The quantity of the 'coal-bound' sulphur and nitrogen reporting in the liquid products and the gaseous emissions from the plant are given in Table 3. It can be seen that in excess of 98% of the 'fuel' sulphur and 89% of the 'fuel' nitrogen is removed.

Improved Process Performance

The separation of inert solids associated with the coal feed is a necessary step within all direct coal liquefaction processes. In general, the lower the mineral matter content of the coal, the lower will be the capital and operating costs of the solids separation stage. Hot, pressurised filtration is the solids separation method used within the LSE process. It is considered to be the most efficient of the methods available, since it rejects the smallest proportion of coal liquids with the solids. Nevertheless, there is scope for reducing this rejection still further by reducing the total amount of solids which must be removed. Cleaning the coal prior to processing is an obvious means of achieving this.

Cleaning the feed coal may, however, have other effects on the economics of coal liquefaction. Some methods of coal cleaning, for example dense medium centrifugal separation, preferentially reject unreactive coal macerals with the mineral matter. This could increase the extent to which the coal could be dissolved in the extraction stage, which in turn could change the filtration properties of the residual solids. The behaviour of the dissolved coal 'extract' in the subsequent hydrocracking step could also be affected.

Recent work (Moore 1991) has shown that dense medium centrifugal separation techniques can readily produce a clean coal fraction of 2-3% ash content and a fraction of less than 10% ash, from raw coals containing up to 50% ash. The combined energy content of these fractions can represent over 98% of that of the raw coal fed to the separator.

This technique produces a significant degree of maceral separation, the clean fraction being enriched in vitrinite and depleted in inertinite. This maceral separation is found in all size fractions from -1mm to 8-25mm.

The clean fraction was more readily soluble in the extraction stage of the LSE process, as would be expected from the well established correlation between coal inertinite contents and undissolved coal yields. Although filter cake resistivities for the clean fraction were higher, the reduced solids loading when processing clean coal would lead to higher overall filtration rates in continuous operation.

Concentrated coal solutions prepared from clean coal were more reactive in hydrocracking with product distributions weighted towards lighter products.

Overall, it appears that there would be small but significant advantages in processing only the clean fraction, routing the higher ash fraction which is depleted in vitrinite and enriched with inertinite to utility sections of the plant such as power generation. These improvements suggest the coal energy reporting to the main products could reach 70%.

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TABLE 1

ESTIMATED TOPPING CYCLE GASEOUS EMISSIONS* AND EMISSIONS STANDARDS

SPECIES	ITGC	ITGC WITH SULPHUR POLISHING	UK EMISSIONS STANDARDS
SO_2	390	100	400
SO_3	50	15	
NO_x	200	200	650
N_2O	28	28	
HCl	390	5	
Particulates	20	20	50

* All values expressed as mg/m^3 at 6% O_2

ITGC - Intermediate temperature gas clean up, see Section 2 of the text.

TABLE 2

ENVIRONMENTAL IMPACT DATA

TECHNOLOGY	CO_2 (KG/KwH)	SOx RETENTION %	NOx (mg/m^3 @ 6% O_2)	PARTICULATES (mg/m^3 @ 6% O_2)
PG + FGD	0.87	90	500-650	50*
CFBC	0.86	90	100-300	~30**
PFBC	0.82	90	150-300	~10***
IGCC	0.78	99	120-300	Negligible emission
BCC Topping Cycle (CFBC Option)	0.72	90	200-300	~30**
BCC Topping Cycle (PFBC Option)	0.73	90	200-300	~5***
ECC Emission Standard		90	650	50

* (HMIP Inspectorate, 1986)

** Filter bag house

*** Ceramic filters

TABLE 3

EMISSIONS OF SULPHUR AND NITROGEN FROM CONCEPTUAL COMMERCIAL LSE PLANT

	COAL CONTENT %	REFINED LIQUID CONTENT %	% EMITTED AS SO_x* and NO_x**	REMOVAL %
SULPHUR	2.00	0.005	0.03	98
NITROGEN	1.50	0.005	0.16	89

* SO_x emitted from:-

(1) combustion of process derived fuels for process heating purposes

(2) sulphur recovery plant

(3) coal combustion for process steam and power

** NO_x emitted from:-

(1) combustion of process derived fuels for process heating purposes

(2) coal combustion for process steam and power

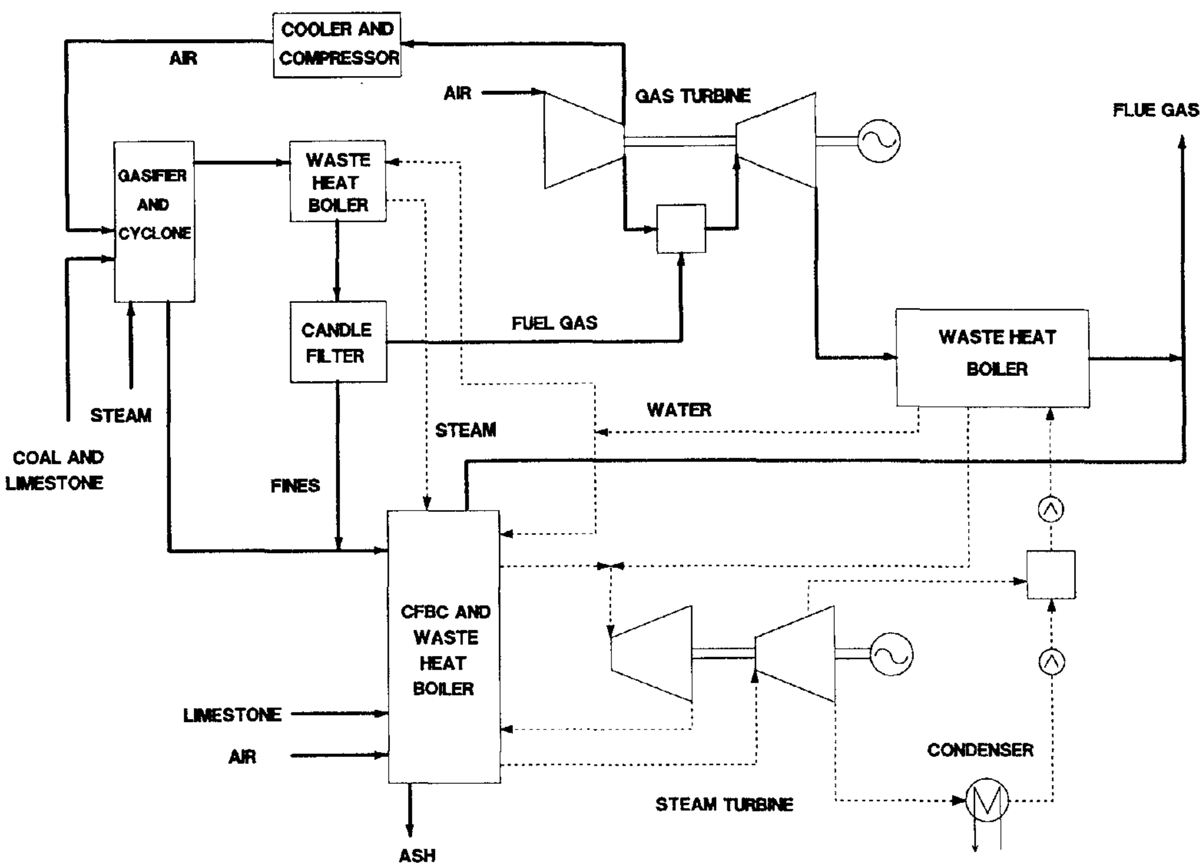

Figure 1 The British Coal Topping Cycle

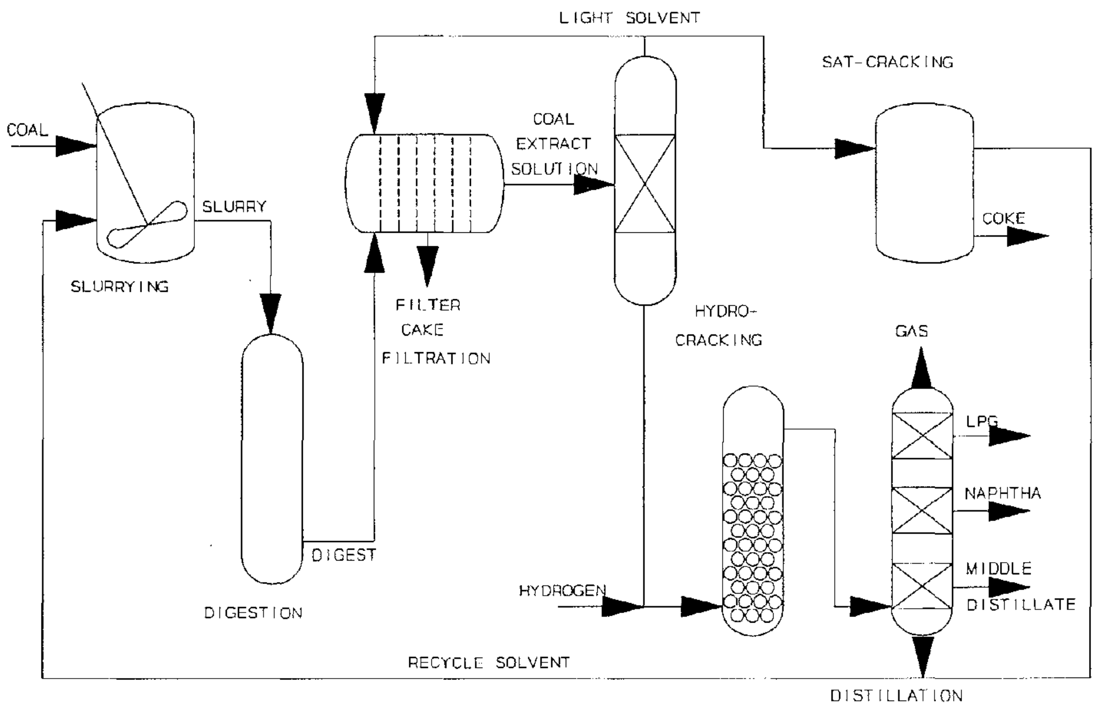

Figure 2 Simplified process flow diagram for the liquid solvent extraction process

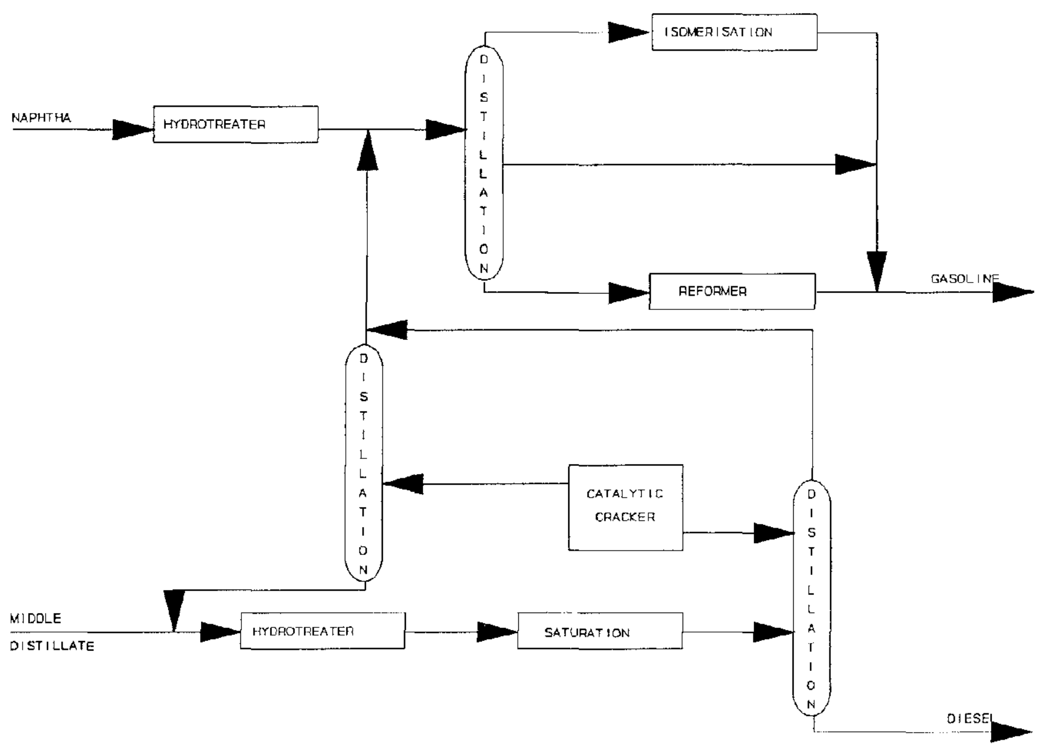

Figure 3 Conceptual block flow diagram for upgrading primary liquefaction products

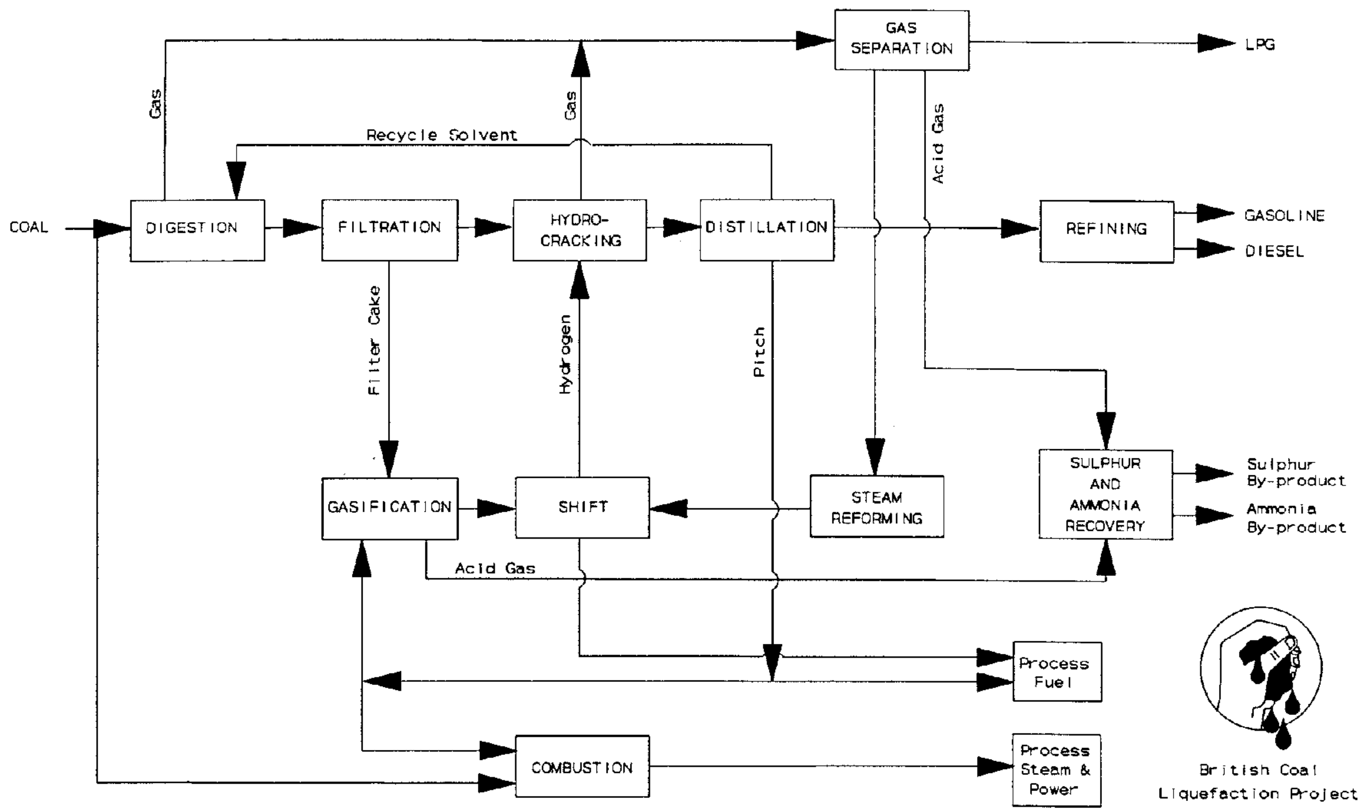

Figure 4 Conceptual Commercial LSE Plant

THE NEW TECHNIQUES IN COAL UTILISATION FOR ELECTRICITY GENERATION

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ABSTRACT

This paper presents a short review of the status of the four major technologies commercially available for power generation : pulverised fuel combustion (PF), atmospheric circulating fluidized beds (CFBC), pressurised fluidized beds (PFBC), gasification (GCC). These two last are considered to be associated with a combined cycle. In this comparison, a special attention will be paid to environment issue. PF, associated with wet de-SOx and SCR de-NOx, is a well established technology, but suffers from heavy investment cost and low thermal efficiency. CFBC may be considered as appropriate technology in certain conditions (poor solid fuels, cycling or medium size units). PFBC allows, by integration in a combined cycle, to increase thermal efficiency, and according to promotors to scale-up more easily. Its availaibility and maintenance costs remain main challenge. For both, CFBC and PFBC very large amount of solid waste results from de-SOx, for which industrial uses need to be developed. The main advantages of GCC is to provide high efficiency associated with very low environmental impact. Owing to its high capital cost and moderate flexibility, this technology appears mostly suited for base load units.

INTRODUCTION

The primary use of coal is in the production of electricity. Because production units are large, it is possible to economically surmont the specific difficulties of using coal, such as handling of solids, combustion of an ashy fuel, need for flue gas cleaning.

The capacity of the power plants in service throughout the world in 1987, and capable of working with solid fuels, has been estimated to be 815 GW. These consumed more than 1 550 million metric tons of coal, which is about half of the total world production. In the industrial countries with market economies, the proportion of electricity generation in the total consumption of coal is even greater, corresponding to more than 75%. The electricity produced from solid fuels accounts for about 40% of the world production.

Total of coal reserves, estimated at 700 billion tons, are much larger than those of other fossil fuel. Moreover, their distribution among different countries is more favourable : in rough figures, 30% in Northern America, 20% in China, 30% in USSR and Europe, 15% in Australia and South Africa. International trade represents only 10% of world production. In such a situation, experts predict for the future that the price of coal will remain stable, and slightly or not affected by an increase in price of other fuels.

Owing to a predictable increase in the demand for electricity, conditions could be favorable for significant development in the use of coal for electricity production.

This development however, is not a foregone conclusion and the future consumption of coal will not be the result of a simple extrapolation of the past. Indeed, given the evolution of the world economic system, the context in which industrial and energy decisions are made, is in the process of changing. The place which coal will take in the production of electricity will depend on factors, such as :

- the increasing demand for environmental protection,

- the increasing demand for financing investments on a world level, resulting in high costs for financial resources ; this aspects leads one to favour these energy sources that do not call for high capital costs, especially natural gas.

- the growing complexity of technico-economic systems and the difficulty of the forecasting, which induces many decision-makers to opt for the most flexible technical solutions.

Within the context of competition with other sources of primary energy, we may ask the following questions : are these new expectations fulfilled at best by the traditional methods of converting solid fuel to electricity, or by techniques that are developed at present ? How do recent trends in research allow for these expectations ? Knowing that the natural evolution of technology has its own peculiar logic and rhythm, it seems to us that these questions merit examination at a time when the development of the economic situation is very rapid.

With this point of view, the objective of this paper is to present a short review of the status of the four major technologies commercially available for power generation, in order to highlight their respective advantages and draw-backs. Then, I shall focuse attention on research and development that could give answers to current limitations of these technologies. But, first of all, it seems to us useful to briefly consider environmental issue since emission reduction is probably the main driving force behind development of several processes

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Environmental issue include several distinct aspects. Basically, we may divide it into different concerns :
- acid rain effect,
- greenhouse effect,
- ozone layer depletion,
- protection of soil and water ressources.

The acid rain effect relates to sulphur oxides (SO_2 and SO_3) and nitrogen oxides (NO and NO_2). Although mechanisms are not clearly elucidated, these compounds are considered to contribute, through acid rain, to soil acidification and tree declines. In many countries, attention has been paid firstly to sulphur oxides. However, at present, nitrogen oxide has become a bigger issue. In almost all industrial countries, regulation limits the emissions of these gases. As a general trend, northern European countries have adopted the most stringent emission standards. They are followed more or less quickly by other industrial countries.

The greenhouse issue is currently at the top of agenda. Some scientists consider indeed that increasing concentrations of CO_2, CH_4 and other gases in atmosphere could induce climate warming. Predictions of mean temperature increase for the middle of next century range from 0.1 °C to 5 °C or even more. The most pessimistic forecast that climatic conditions could dramatically change in the next century, with severe consequences for some countries. At first glance, coal could appear to be the only "culprit": its emission factor of 0.75 Gigatons per tera-watt-year Gt/TWy being substantially higher than those for oil, 0.62 Gt/TWy, and gas, 0.43 Gt/TWy. Emission of CO_2 from coal combustion accounts for about 30% of human production, and 15% of the greenhouse effect (CO_2 emission represents half of total greenhouse effect) A careful analysis oriented on seeking realistic solutions reveals that nearly half of overall CO_2 emissions could be reduced by energy conservation measures and technological improvements at end-user level, especially in the residential/commercial sector, industry and transportation. In this view, one can mention that a more widespread use of cogeneration would, at low or moderate cost, result in a very efficient use of fuels, with no need for technological development. Another point to take into account is that about 60% of the overall coal production is consumed in USSR, China, Eastern Europe, and developing countries where old combustion devices and more generally the entire production system offer only poor performance. It has been showed that severe taxation of fossil fuels could not achieve significant results : for example, even a 100% tax on coal, like currently in Sweden, would reduce the annual growth rate of CO_2 only by 0,2% or 0,5% to the years 2050 and 2100 respectively. As a solution, it has been suggested to remove CO_2 from flue gas, then use it in chemical industry, or for enhanced oil recovery, or store it in oceans or geological cavities. Even though technical improvements would reduce their cost, these ultimate solutions could not be extensively applied. However, improvements in efficiency by 20% achieved by new means of electricity generation can be considered as interesting regarding CO_2 concern and more generally energy conservation.

Greenhouse and ozone depletion effects are often grouped under the rubric "climatic change", since some compounds are involved in both effects, like CFC or nitrous oxide N_2O. The latter is found in flue gas. Although sampling and analysis methods are still in progress, first results suggest that some low temperature furnaces could produce significant quantities of this gas.

In fact, this concern seems today much more complex than we thought previously. It has been indeed shown that, at ambiant temperature, nitrous oxide can be produced from nitrogen oxide in presence of vapor and sulphur oxide, this same reaction which was responsible for "artifact N2O" which caused errors in early measurements. Nitrogen oxide emitted from stacks is scrubbed by rain, and thus returns to soil where it may also form again nitrous oxide by bacteria action. If confirmed, these presumptions could re-inforce noxious characteristics of nitrogen oxides.

The solid fuels industry also affects soil and water in different ways. Startling examples are given by the huge heaps found in some mining regions, still in place long after closure of mines. Most of industrial countries, especially those of high population density like The Netherlands, have taken or are going to take stringent measures to protect landscape, soil and aquifer quality. As a result, disposal of wastes or extraction of minerals will be strictly limited (sometimes forbidden) and also very costly. Another concern is that the continuous increase in water demand for domestic and industrial uses is more and more difficult to satisfy. Thus, industries consuming high quantities of water like power plants could be affected when hot and dry conditions would occur, like in France during the summer of 1990.

To finish this short overview, I would like to emphasize that environmental protection, despite mediatic exageration, does not be considered only as a concept in fashion, but must be took into account carefully for developement of new processes.

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The traditional coal power plant, burning pulverised fuel equipped with a steam cycle, is a well-developed system but seems to have already reached its technical maturity. The investment costs per kW are high compared with units running on natural gas ; they can be lowered only by economies of scale, which involves the construction of large units having a high utilization factor. From this point of view, the studies dealing with a sharp increase in severity of the steam conditions (pressure, temperature), the use of several fluids with steam cycles in series, or even the insertion of a magneto-hydrodynamic device above the steam cycle, do not tend to significantly reduce the capital cost.

With the reinforcement of environmental protection restrictions, traditional techniques have had to face up to a new problem. It is becoming necessary, following combustion, not only to remove dust, but also to reduce sulphur and nitrogen oxides emissions. Sulphur abatment may be carried out by different means, including in-furnace dry sorbent injection, wet Flue Gas Desulphurisation (FGD). The latter, widely used in Germany, ensures high capture (95% or more) with very low sorbent consumption and produces marketable gypsum as by-product. Fly ash collected beforehand is unaffected by wet FGD process, and can still be sold to cement industry. The main draw-backs of wet FGD processes are its heavy investment cost and large energy consumption. Dry sorbent injection, lower in investment costs, may achieve moderate sulphur capture of about 50% typically.

Much research has been and is still being carried out to improve the process by in-duct steam or water injection and solids recycling. Under certain conditions, suphur capture of 90% have been achieved, but generally at the expense of high sorbent consumption. High rates of sulphur capture produce large amounts of solid wastes, a mixture of ash, unreacted lime, sulfated lime with sometimes presence of leachable compounds. These products have not yet found industrial use, are difficult to handle, and problematic for disposal. Nitrogen oxides control also stimulated numerous technological development, some oriented towards combustion modifications (low-NOx burners, air or fuel staging, flue gas recycling), some on flue gas treatment with Selective Catalytic Reduction by ammonia (SCR), and some towards non-catalytic injection of ammonia or urea, this latter being at an earlier stage of development. Combustion modifications, still under commercial demonstration, might be efficient enough to comply with regulations currently in use certain countries, but further increase in efficiency could be limited by unacceptable degradation of ash quality. Thus, if future regulations adopt emission standards similar to those already in-use in certain countries (Germany, Austria,...), SCR which provides 80% of NOx reduction, will be necessary. SCR is well proven in Japan for low-sulphur fuels and base-load units. German experience, where SCR has been recently under development, will provide useful information on the availaibility of this technique in more difficult conditions, as found in cycling units.

From above developments, we can conclude that current and future regulations on air quality as well as on soil and water protection, will require PF units to be equipped with highly efficient SO2/NOx control processes. This will result in heavier capital and operating costs. Moreover, the net electric efficiency will fall from 38% to about 35%, and flexibility to load variations will probably suffer from this.

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This situation has opened up a new field of development for atmospheric fluidized combustion, in dense or circulating conditions, which appeared as a low investment solution for the acid rain issue. Formerly used for low-grade or low-reactivity fuels, this technique operates at low-temperature and high solids recycling rate, and thus allows desulphurisation actually in the furnace itself through the addition of limestone. Typical sulphur captures of 90% are reached at the expense of sorbent consumption 2 or 3 times greater than with wet FGD. Fluidized combustors, of circulating or deep bubbling bed type, produce less nitrogen oxides NO/NO2 than PF furnaces even after combustion modifications. With ammonia or urea injection, they could reach, without catalyst, levels similar to those produced in PF units equipped with SCR. However, emission figures must be scrutinized carefully, since an increase in calcium injection in order to improve sulphur capture generally enhances nitrogen oxides production. It has been also shown that some fluidised combustors produce significant amounts of nitrous oxide suspected to contribute to ozone layer depletion.

Owing to lower combustion temperatures, ash from fluidized bed units is different in quality from that produced by PF boilers. Consequently, it cannot be used in the same way as an additive for cement making. Large quantities of sorbent are added for desulphurization, so the solid wastes contain high proportion of quick-lime that makes them useless, unless they are treated.

Difficulties found in scaling up dense fluidized beds have limited the development of this technique to units smaller than those generally used for power generation. Circulating fluidised boilers took their place in this market and units of 200-400 MWth are already in use. Two of 500-600 MWth are planned and utility boilers of 250 MWe appear to be faesible. However, scale up to 600 MWe remains at present a challenge.

Another solution to overcome scale-up problems consists of increasing operating pressure. It is also expected that the reduced size of pressurised units would reduce their cost as well. This might make it possible to extend the economic advantages of fluidised bed combustion to larger plants. After hot dust removal, flue gas at 800-850 °C may drive a gas turbine, and then be used for steam raising. This kind of combined-cycle configuration improves the efficiency of the power plant from 38% for an atmospheric unit to about 43%. Sulphur and nitrogen oxides emissions for pressurised fluidisation are close to those for atmospheric fluidised processes, with similar problems for management.of residues Another important point is that pressurised processes are more complex, for instance feeding and extraction devices, and materials operate in severe conditions. The most advanced process operates in dense conditions. Several commercial demonstration units ranging from 73 MWe to 135 MWe are currently under construction or strart-up.

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The advantages of industrial techniques for coal gasification and gas turbines have opened the way to another process for converting coal to electricity. It consists of gasifying the coal by making it react with steam and oxygen, cold-washing the gas generated in a solvent, then burning this fuel of medium calorific value to produce the hot gases supplying a combined-cycle. New gas turbines accept inlet temperatures of up to 1260 °C. Their use in combined-cycles for power generation will ensure efficiency levels ranging from 42% to 45%.

The total cost of the equipement may be higher in a plant of this type than in the traditional type of power plant, at least at the present stage of technology and for current emissions limits. Reasons for this are method of producing oxygen, size of industrial gas generators,... On the other hand, the time for which the capital for the construction is tied up should be shorter. In effect, such a plant can be designed in the form of several power units ; the length of the construction time for each unit is short and the plans for the successive installations can be more closely adapted to the predicted demand for electricity.

An important point in this scheme is its flexibility. On one hand, the shortening of the construction time reduce financial risks. On the other hand, in certain fuel market conditions one can start by investing in just a combined-cycle supplied by natural gas, while retaining the possibility of changing to coal when price of premium fuels justifies this step.

Another important point in this type of power plant relates to its environmental performance. The gas cleaning processes used produce a fuel of extremely low suphur and solids content, which is, additionally, an attractive benefit for protecting the gas turbine from maintenance problem

The availability of combined-cycle with coal gasification is regarded as more likely than for pressurised fluidized bed combustion, since the various components of such an unit have all been seperately proven at an industrial scale for a long time. Several commercial demonstration units, including EPRI and Texaco's Cool Water facility, Dow's Plaquemine plant, and Shell's SCGP1 plant, have demonstated the industrial validity of this scheme. A 250 MWe unit is planned for the next future in The Netherlands.

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The four main technologies we have considered are competing on the power plant market. My purpose here is not to predict the chance of every challenger, but to point out their relevent features. For this, it will be necessary in some cases, to define more strictly than previously the process under consideration.

<u>Pulverised fuel combustion with low NOx burners, Ammonia injection for Selective Catalytic Reduction of NOx, wet Flue Gas Desulphurization</u>. This traditional technology renewed to reduce acid gases emissions has been proven at large scale in Japan and Germany. It may comply with the tightest regulations currently in use for SO_2 and NOx emissions. Provided that the desulfurisation by-product is converted into gypsum, solid wastes management does not appear as a potential limitation for this technology. It suffers mainly from heavy investment cost and low efficiency of about 35%. From an economic point of view, these two disavantages, when associated, must be considered as a strong limitation for future development for power generation. What is well established is that this technology, if maintained, will be limited to large units.

<u>Atmospheric Circulating Fluidized Bed Combustion</u>. Recent development of this technology has been driven by acid gas control. If SO_2 emission standards are stringent, very large amounts of sorbent are required. Huge quantities of the solid produced, a mixture of ash and unreacted lime, have not yet found large industrial use. Although NO/NO_2 emissions are modest, recent measurements showed that N_2O could be an issue for this technology. Owing to their relatively low capital costs, circulating fluidized bed may be considered as appropriate technology in certain special conditions : poor solid fuels (for instance, coal washeries waste products), cycling units, or medium size units (< 300 MWe).

Pressurised Dense Fluidized Bed Combustion with Combined Cycle. Compared to preceeding techniques, this one offers higher efficiency for power generation. Since units are more compact, pressurisation is also presented by its promotors as a solution to scale up more easily fluidized units and to reduce investment costs for large units. Its situation about gazeous emissions and solid residues seems today rather similar as described for atmospheric fluidisation. Its availability and maintenance costs remain the main challenge for this technology. Success or failure of industrial demonstration projects in progress could be decisive for further development of this technology.

Coal Gasification by steam and oxygen with slagging gasifier, Combined cycle with high efficiency gas turbine (inlet temperature of 1260 °C). The main advantages of this technology are to provide high efficiency (similar to PFBC) along with very low environmental impact. Very high levels of sulphur and nitrogen oxides abatment are achieved, and solid wastes as slag are inert. However, owing to its high capital cost and moderate load flexibility, this technology appears mostly suited for base load units.

An interesting feature of combined-cycle is their reduced water consumption, which could be useful in many cases.

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Along previous sections, we mentioned that current technologies are far from being perfect. For this reason, a great number of research and development projects are in progress. It would be impossible to mention all of them. One may at least identify their different orientations :

1 - specific developments needed to overcome technological bottle-necks which limit the development of one technique.

2 - medium or long-term development programs oriented to improve one technology in terms of efficiency, cost or emission control.

3 - more general-purpose research and development tasks that could provide results useful for every technology.

A great number of research activities belongs to the first category. For example, for flue gas treatment, one can mention works carried out on SCR catalysts to increase their life-time, their resistance to temperature changes and also their specific activity in order to avoid formation of deposits resulting from oxidation of SO2 into SO3 enhanced by catalyst. Improvements of high temperature (800 °C) gas filters could be of great benefit for pressurised fluidised bed units as well as for gasifiers with combined-cycle, since gas turbine availability is a critical point. Owing to numerous mechanical failures encountered with fluidized units, a lot of effort have also been devoted to improve tube design and arrangements.

Several medium and long term programs relate to gasification combined-cycle schemes. A great number of variants are at present being studied. The main objective is to reduce investment costs by process simplification and greater integration of the power plant. The conversion efficiency should be increased at the same time.

One can try to avoid the use of oxygen in coal gasification, for the cryogenic production of oxygen is costly in terms of investment as well as in the energy for running the system. One may resort to allothermic gasification, that is to say, appling external heat source to provide the energy necessary for the reaction of the coal with steam. But the technical conditions for providing this heat is difficult. One tends, rather, towards gasification with air, producing a gas of low calorific value. But the interchangeability of this fuel with natural gas is, then not guaranteed.

Another trend, often complementary to the preceding one, is to simplify the operations for cleaning the combustible gas. The desulphurisation can take place in the gasifier itself, if it is a fluidised bed ; or else downstream of the gas generator, but by simple hot absorption of the hydrogen sulphur on a bed of metal oxide. One may also opt for only partial gasification of the coal, burn the residue in a fluidised bed and use this fluidised bed for desulphurising the emitted gases as a whole.

In this latter case of partial gasification, one may also use the exhaust from the fluidised bed combustor in order to reheat, in an exchanger, the combustion air supplying the gas turbine or else opt for pressurised combustion (topping cycle ...).

If technical problems raised are solved, certain of these processes could result in plans for a gasification combined cycle power plant offering a lower investment cost per kW. It is still possible, however, that this objective can be achieved only at the expense of poorer environmental performances and/or less flexibility.

Since different technologies are concerned, research on ash and solid wastes could be put in the third category. On the one hand, their purpose is development of processes to stabilize these residues to allow their use or disposal without problems. On the other hand, experiments are under progress to demonstrate their possible use in industrial applications for road making or in the building industry for instance.

One can also mention development of advanced monitoring and diagnosis systems. Processes for power generation become more complex. They frequently work in severe conditions of temperature and pressure. One wants to change fuel quality if needed for economic reasons. Emissions must be kept within statutory limits. As a result, they are more and more difficult to operate in optimized or even in normal conditions. A small equipement failure if not early detected, may induce deviation from the designed point, which results in significant economic penalties. Sometimes the deviation is such that it brings the plant to an unsafe situation, requiring the plant to shut down and imposing an even greater economic penalty.

In such conditions, automatic tools that could assist operators are very helpful for conventional as well as for advanced processes. On-line diagnostic systems generally include an expert-system module linked with a static or dynamic mathematic model describing normal behaviour of the process. Significant deviations between actual and calculated figures are interpreted as symptoms of an abnormal situation. In this case, expertise process takes place to find out the cause of the default. The operator is soon informed of this cause and measures are suggested to return to normal conditions. Presently, these systems use temperature, pressure, flow rate sensors already used for traditional control systems. In the near future, new methods could appear, some based upon enhanced interpretation of signals delivered by traditional sensors for instance pressure fluctuations, others involving complelely new sensors. Diagnostic tools could also be used to improve the life expectancy of power generation units. This aim is of great interest since capital costs represent a large share of total cost of electricity produced from fossil fuels.

I would like to finish this short review with a special mention for environmental research. Many studies are being conducted on several aspects of environmental protection, especially mechanisms of pollutant formation, in order to determine operating conditions that reduce their formation. But, considering the complexity of environmental effects, more global studies are needed. They should highlight and assess main trends for the future, not only about CO2 or other gases, but also for other aspects of environmental impact. Moreover, great effort must be devoted to find out possible consequences on the coal industry and on process development. This task is not at all easy, because of the diversity of aspects which must be taken into account, and also because it is very difficult to guard the needed objectivity.

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Many avenues at present being explored in the developement of techniques for converting coal to electricity. Certain of these approaches present points of uncertainty or points where progress is necessary. But several offer real advantages and could play a part in future markets. We consider it important that the development of the principal processes be pursued to the industrial stage. Given the stake represented by the power plant market for the effective use of the world resources of coal, an even considering the high cost of developing these processes, it would be very desirable if it were the subject of international cooperative research effort.

ADVANCED COAL BURNING SYSTEMS FOR POWER GENERATION

by

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ABSTRACT

The privatisation of the Electricity Supply Industry in the UK is likely to result in the use of smaller power stations (up to 500MW) which can be built more quickly than the 2GW power stations previously built by the CEGB. At these smaller sizes new technologies may be favoured over the pulverised fuel stations which previously formed the backbone of the CEGB system. Pressures for new high efficiency technologies also come from the increasing environmental concern associated with emissions of SO_2, NOx and CO_2.

Coal-fired power stations accounted for 82% of the total units generated in the UK in 1987/88. It is a prime objective of British Coal's R&D programme to ensure that advanced, clean and efficient coal-fired power generating technologies are available to enable the continuation of coal's share of the electricity market in the future.

The Topping Cycle, which is a combined cycle based on partial coal gasification with combustion of the char residue, is described and progress with the development programme is detailed.

An economic assessment of a number of advanced coal-fired options has been updated. The results of this study are presented which identify the substantial advantages that advanced Topping Cycles have over the alternatives.

INTRODUCTION

Energy demand is rising worldwide but this is coupled to increased concern about the environmental impact of power generation systems and need to obtain an assured quick return on investment. The situation in the UK is a good example, where power demand is forecast to rise from 308 TWh in 1988 to 366 TWh in year 2000 (IEA, 1986). Emission regulations are tightening on particulates, oxides of sulphur and nitrogen while 'greenhouse gases' such as carbon dioxide are receiving much attention. Privatisation of the electricity supply industry will probably require a reduction in power plant size from the previously proposed 2 x 900MWe coal fired steam plant and 1200 MWe nuclear stations. This is because gains achieved by increased scale are rendered uneconomic by the payback time and rate of return expected on capital investment in the private sector. In future most new utility plants are expected to be sized up to 400MW with short build times to provide the necessary quick return on investment. The ability to gradually increase installed capacity in step with demand is attractive.

Gas turbines are an essential component of the efficient, environmentally friendly power plants of the future. Clean hot gases can be produced using innovative technologies and expanded through this advanced heat engine exploiting the inherent efficiency advantage given by its relatively high firing temperature, before heat is recovered from the exhaust generating steam for a steam turbogenerator. They are available as compact modules in sizes ranging from about 1 to 150MWe (soon 200MWe). The standard design facilitates short delivery times and incremental addition of capacity as demand grows.

Coal is the natural choice of fuel for power generation because it is the most abundant fossil fuel in the world. Reserves in the UK are estimated to be sufficient for 400 years at the current rate of usage (IEA 1989). As an indigenous resource it is subjected to similar inflation and exchange rate forces as the consuming utility, presenting a lower risk than reliance on imported fuels. Coal fired gas turbine power systems would satisfy the stated UK strategic policy requirement to avoid dependence on one fuel because of the back-up capability of alternative fuels. (This capability will also enhance plant availability.) It is also in the national interest to preserve premium fuels, such as natural gas, for applications fully exploiting their advantages eg in chemicals production.

SYSTEM OPTIONS

Current Technologies

Pulverised Fuel Plant with Flue gas Desulphurisation (PF + FGD)

In these plant, power is produced by a condensing steam turbogenerator, using heat released by combustion of finely pulverised coal in a high temperature flame. The boiler flue gases are cleaned to remove particulates and treated in a flue gas desulphurisation plant to remove most of the sulphur dioxide before release via the stack. A reheat steam cycle is generally used for units of 100MWe and above to maximise efficiency.

Circulating Fluidised Bed Combustion Plant (CFBC)

In these systems, coal is burned in a bed of solids fluidised by a high velocity air stream. The off-gases and entrained solids are separated in a high efficiency cyclone and the solids are returned to the bed. Heat is extracted from the combustor and from a waste heat boiler which cools the combustion gases before final clean-up. Limestone may be added with the coal to reduce sulphur dioxide emissions. Superheated steam raised in the boiler systems drives a conventional condensing steam turbine which generates power.

Natural Gas Combined Cycles (NGCC)

In these plant, natural gas is used to fire a gas turbine and the hot exhaust gases are cooled in a waste heat boiler, generating superheated steam for a steam turbine. To maximise efficiency, it is necessary in the waste heat boiler to use steam production at more than one pressure or to use supplementary firing (Knizia 1989). NGCC are a popular choice in the world at the moment but only a medium term solution for power generation.

A typical natural gas combined cycle plant consists of two gas turbines and one steam turbine.

Steam Injected Gas Turbines (STIG)

Addition of steam to the working fluid of a gas turbine to increase mass flow allows extra power to be generated. The steam may be used as coolant for the turbine blades and is raised by cooling the turbine exhaust in a waste heat boiler. Turbine modifications are required.

Coal-fired Technologies At Introductory Commercial Stage

Pressurised Fluidised Bed Combustion (PFBC)

In PFBC combined cycles coal is burnt in a bubbling fluidised bed at typically 10-15 bar and 850°C (see Figure 1). Air for combustion is provided by the compressor section of a gas turbine. Off-gases from the PFBC are passed through cyclones and then advanced to the turboexpander inlet. The turbine exit gases are fed to a waste heat boiler, final gas clean-up and finally the stack. Heat from the waste heat boiler and combustor heat exchangers is used to raise superheated steam for a reheat steam cycle. Sulphur dioxide emissions are controlled by feeding limestone to the combustor.

Commercial PFBC systems are currently either operating or commissioning, built by ABB Carbon at Stockholm, Escatron (Spain) and Tidd (USA). A 330MWe scheme, partly funded by the US DoE, is planned at the Philip Sporn Plant, West Virginia (Redman 1989). An order has been placed for a unit in Japan.

Integrated Gasification Combined Cycles (IGCC)

In Integrated Gasification Combined Cycles, shown in Figure 2, the coal is first fed to a gasifier operating at elevated pressure, where the coal reacts with oxygen and steam or water to produce a raw fuel gas. The raw gas is subsequently cleaned to remove particulates and gaseous pollutants (eg hydrogen sulphide) before firing in a gas turbine to generate power. Hot exhaust from the gas turbine is passed through a waste heat boiler to raise all or part of the steam for a conventional condensing steam turbine, which produces additional power.

For IGCC systems to achieve efficient performance, a high degree of carbon utilisation in the gasifier is essential. This can have implications on reactor size, fuel flexibility, control, etc. Gasifiers proposed for IGCC have included members of the three generic types - entrained bed (eg Shell, Dow and Texaco), fixed bed (eg BG/Lurgi) and fluidised bed (eg IGT and

KRW). The optimum cycle configuration depends on the particular gasification system chosen. The entrained bed gasifiers generally produce high pressure steam (superheated in the case of Shell) for use in the steam cycle. Fluid bed gasifiers have the advantage of greater fuel flexibility than fixed bed systems and the facility for sulphur control by limestone addition.

These attractive features of fluidised bed gasifiers have led British Coal to develop their fluidised bed gasifier for use in a more advanced combined cycle known as the topping cycle, described later.

The Texaco gasifier has been well proven technically in the 100MWe IGCC demonstration facility at Cool Water, California, although economic operation was not achieved. Two 100MWe gas turbines have been operated successfully on gas from Dow's gasification process at Plaquemine, Louisiana. The BG/Lurgi gasifier has been demonstrated at up to 550 tonnes/day and used to power a Rolls Royce SK30 gas turbine, though not in combined cycle arrangement. An order has been placed for a 250MWe unit using Shell technology in Buggenum, Holland.

Integrated Gasification Steam Injected Gas Turbines (IGSTIG)

Steam injected gas turbines can be fed with coal-derived fuel gases in variants of IGCC systems. If the gasifier produces high pressure steam, a steam turbine is still required but the proportion of gross power produced by the gas turbine is higher than for conventional IGCC.

Hybrid Systems

Natural gas/coal based systems

A combination of gaseous and solid fuels may be used in combined cycles and different schemes have been proposed. One way is to use the exhaust gas from a natural gas fired turbine to provide hot combustion 'air' for a PF-FGD unit (GT/PF-FGD, see Figure 3). Such a system could be achieved by modifying an existing coal fired station.

British Coal's Topping Cycle

Of particular interest to British Coal in the medium term are Topping Cycles, which incorporates coal gasification and combustion in their configurations. In the British Coal topping cycle (Figure 4) coal is gasified in an air-blown spouted bed gasifier operated at elevated pressure and temperatures up to 1000°C. Sorbent (ie, limestone or dolomite) is also injected into the gasifier to retain sulphur which would otherwise be released in the gas. The fuel gas from the gasifier undergoes an initial stage of cleaning in a cyclone. The raw gas leaving the cyclone, at close to 1000°C, is then cooled to about 600°C via a heat exchanger; it still contains some fine particulate material which is then removed using ceramic candle filters. At this temperature almost all the volatile alkali salts condense out from the flue gas onto the filter medium. The clean fuel gas is finally advanced to the gas turbine combustor. The combustion of the fuel gas in the gas turbine combustor produces hot combustion products at about 1380°C corresponding to a turbine entry temperature of 1260°C. These products are passed to the turbine expander stages which drive the turbine compressor and an electric power generator. The exhaust gases pass to a waste heat boiler and then via a stack to atmosphere. The gas turbine used in this application is a state-of-the-art machine although there are developments required for the fuel gas valve and gas combustion system.

Between 70 and 80% of the coal is converted into a low calorific value fuel gas. The 20-30% of the gasifier coal feed which remains unconverted is removed from the gasifier mainly as fines collected by the cyclones and hot gas filters. The residual gasifier material removed from the base of the gasifier together with the fines are transferred to the circulating fluidised bed combustor (CFBC) where they are burned to raise heat from the steam turbine cycle, thereby resulting in further power being generated. The sulphided sorbent is converted to calcium sulphate. Sorbent can also be fed to the char combustor to complete the sulphur retention process. In this way 90% of the sulphur can be removed at source.

The main advantage of the Topping Cycle is that it can exploit the potential of high inlet temperature gas turbines while minimising the energy losses incurred in the production of fuel gas. No oxygen production plant is required and 90% sulphur gases removal is achieved by addition of limestone to the gasifier and combustor, so avoiding the need to cool and scrub the gases before they are burnt. A key requirement to take advantage of this is a system for medium to high temperature filtration and alkali removal from the gasifier product gas to meet the gas turbine's requirements. The gasifier has been proved at atmospheric pressure in tests on a variety of coals at 12 tonnes/day scale and a pressurised version has been operational since 1990.

Direct Coal-fired Gas Turbines

Direct firing of gas turbine on micronised coal or coal-water mixtures with heat recovery for a steam cycle could ultimately provide an efficient means of generating power (Diehl 1989).

The requirement is principally for a combustion system that yields a hot product gas that is sufficiently low in alkalis and contains sufficiently few damaging particulates to pass through a gas turbine without causing excessive corrosion, erosion or deposition. A high degree of ash rejection by use of slagging systems and associated particulate removal equipment is one means being investigated for cogeneration applications in the USA (Cowell 1989).

COMPARISON OF SYSTEMS PERFORMANCE

Performance

Table 1 gives indicative plant size and efficiency data for examples of some the technologies described in **SYSTEM OPTIONS**. Currently commercial coal-fired plant have net efficiencies of about 39% LHV. However, units built in Denmark reach 42% with super-critical steam cycles and lower condenser temperatures.

PFBC and IGCC, at about 41-43% (LHV basis) offer an advantage of up to four percentage points over the standard steam cycle only plant. This is because the use of gas turbines as well as steam turbines allows higher upper cycle temperatures. The PFBC cycle operates at lower turbine entry temperatures (ca.800°C) than the other examples - hence its smaller efficiency advantage.

The predicted efficiency for a commercial power plant based on a Topping Cycle system is around 47% (lower heating value basis). This assumes the use of a commercially available gas turbine and a sub-critical steam cycle. There will be scope for significant improvement on this efficiency value in due course. Thus the development of advanced super-critical steam turbines will mean that super-critical steam cycles can readily be introduced (for which the FBC system is particularly well suited). There should also be benefit from future developments in gas turbines that could be retrofitted to the system. Such advances are predicted to raise the cycle efficiency to around 52% LHV.

The efficiency of natural gas fired combined cycle plant is higher than those of IGCC systems operating at similar turbine entry temperatures because oxygen separation is not required, there are no conversion losses in gasification and there are no solids handling energy requirements.

Economics

Also included in Table 1 are indicative specific capital costs (1991 money) for the technologies. Specific costs for utility-scale direct coal-fired gas turbine combined cycle systems are too uncertain to quote. For the plants with steam cycles only, the CFBC option is lower in specific capital costs, largely as no FGD plant is required. The combined cycle plant are all comparatively low in specific capital cost because part of the power is generated by gas turbines, which are relatively inexpensive and result in higher station efficiencies. Natural gas combined cycle plant have much lower capital costs than the coal technologies because there is no solid fuel processing or waste stream handling equipment associated with this fuel.

Estimated power generation costs are shown in Figure 5, in terms of contributions from capital charges and fuel costs. The capital charges are based on a discount rate of 10% and an assumed plant life of 25 years for coal, 15 years for gas with an average load factor of 85%. The fuel costs are based on a coal price of £1.90/nGJ and natural gas at 22.1p/therm (HHV). The O & M costs include labour, maintenance, rates, insurance, water, chemicals, ash disposal and, where relevant, limestone costs.

Figure 5 shows how the lower capital charges and fuel costs for the coal-fired technologies incorporating gas turbines generally are predicted to result in considerably cheaper electricity costs compared with the steam cycle only plants. This is especially true for the topping cycle, with its high generation efficiency. The effect of the very low capital and O & M charges for natural gas combined cycle plant on electricity cost from these systems is also evident. However, the future price of natural gas is likely to be linked to the price of oil. Any investor in power generation will be looking at projects of at least 25 years life. British Coal, in particular, is able to offer long term contracts for coal with the fuel price linked to the Retail Price Index. This gives the provider of capital greater assurance in the future rate of return if coal is chosen as the fuel.

Environmental Impact

The impurities in coal put it at a disadvantage with its chief competitor natural gas but these can be removed, to particular advantage in gasification based technologies where clean-up of the fuel gas has economic and technical advantages over flue gas clean-up. Table 2 compares predicted emissions of CO_2, SO_x, NO_x and particulates for the systems considered earlier. It shows a trend of reducing environmental impact with advancing coal fired technology, with IGCC and Topping Cycles demonstrating substantial superiority over PF based technology.

KEY DEVELOPMENT AREAS

The advanced technologies covered in this paper enable exploitation of state-of-the-art gas turbines whose performance rests simply on maintaining the subtle blading profiles with minimal levels of erosion, deposition and corrosion. The tasks needed to implement technologies at the introductory commercial stage of development are moderate. They concern amassing reliability data, as commercial demonstration rather than proving the science, in order to generate the confidence for utilities to order such plant. The key development areas for these and the most advanced technologies are described.

Hot gas clean-up

This offers potential thermal efficiency and capital cost benefits while easing the turbine duty when replacing a conventional flue gas system.

Ceramic filters

Ceramic filters can remove virtually all particulates sized bigger than 1 micron, with the concentration of circa 10 ppm remaining in the gas reflecting performance of the element seals. Ceramic filter candles have been demonstrated at 810°C in the 130 element EPRI unit on the Grimethorpe PFBC (Tassicker 1989) and 33 elements at 570°C on the KRW gasifier at Waltz Mill (Cherish 1988). A number of tests are being planned to prove their performance over extended periods, ie beyond the current experience which is approaching 1000 h in any one test series.

Alkali metal control

If fuel gas is maintained above the dew point of alkali metal salts in IGCC and Topping Cycle plants then alkali control is probably necessary. The Coal Research Establishment and the University of Surrey have developed a clay sorbent system for alkali control at about 950°C in laboratory work and larger scale demonstration is planned. 600°C cooling on Topping Cycle will probably eliminate the need for this technology.

Sulphur control

The US Department of Energy have pioneered a sulphur polishing process using zinc ferrite which is capable of reducing H_2S concentration to a few ppm at about 600°C. GE Environmental Systems plan to demonstrate a moving bed version on a 1 t/h fixed bed gasifier at Schenectady (Gal 1988). This could be applied to several of the gasifiers described earlier, with appropriate fuel gas coolers where necessary. It offers the possibility of improved sulphur retention performance for the Topping Cycle beyond the 90% level in Table 2.

Turbine Combustors

Particular extensions from current practice are needed for topping and direct coal firing combustors. Both would feature proven rich and lean burn staged combustion techniques to modulate NO_x formation. Combustor (computer) modelling is now well established and calibrated for clean gas turbine fuels, so that fine tuning for minimisation of NO_x and unburnt hydrocarbons, and hardware development are the next tasks.

Topping combustor

In addition to cleaning the gas, fuel control, distribution and combustion systems are required for the turbine. There is a need for a gas turbine manufacturer to provide the gas quality specification for the gas turbine to set the standards for development of these areas. Control technologies for the gas turbine and Topping Cycle plant as a whole, to meet power system requirements, are also required and all are under investigation. For example, a 1MWth low-emission gas turbine combustor has been built under contract. This is being used to develop a design suitable for scale up for the gas turbine appropriate to a demonstration plant. Particular features are the use of hot fuel gas and combustion staging to reduce conversion of fuel-bound nitrogen to NO_x. The durability of the gas turbine itself will be investigated during a turbine test at Grimethorpe.

Direct combustion

Initial research shows credible prospects for 'beneficiated' coal. References (Cowell 1989) (Staub 1988) (Horner 1988) and (Wenglarz 1989) give a brief overview of current status, covering combustion, deposition, NO_x, SO_x absorption by additives etc. These all involved a coal water mix (CWM), a slurry of near 50% 'beneficiated' coal, The coal is ground typically to 6 micron mean and 15 micron top cut, which typically when washed has a residual ash circa 1%. (The cost of coal preparation will have a significant but as yet unquantified impact on process economics.)

Long term reliability of the new generation of special purpose pumps, flow proportioners, metering nozzles, and fuel lines are considered a wear/reliability problem until longer term experience is accumulated. (Bearing in mind that the comparable components on conventional PF boilers are the continuing main source of faults and maintenance on conventional coal generation plant.)

Turbine

Hot gas path durability

The gas turbine and allied supply industries have developed specific alloys suitable for blading, combustor and ducting, capable of accepting the steady and cyclic stresses for base load operation at firing temperatures up to 1260°C. Air cooling is employed to limit metal temperature within the range 800-900°C as appropriate to the components. These alloys already have substantial corrosion resistance, which is needed for the 'clean' conventional fuels, natural gas and petroleum distillates. A range of more highly resistant coatings has been developed, particularly for marine operation.

The most aggressive corrosion species are the sodium, potassium and calcium, chloride and SO_x which are common to both the coal based and distillate fuels. However, the mass loadings and vapour pressures tend to be higher for coal based fuels. The platinum aluminide diffusion coatings are particularly effective provided particulate erosion is minimal. We are helped here by notable progress in porous ceramic filters which virtually eliminate multi micron particulates from the gas flow. The remaining sub micron sizes are transported in close correspondence to the gas streamlines and thus have minimal impact on the turbine blading. The planned topping turbine test on the Grimethorpe PFBC will be a major step forward in demonstrating the durability of components for this duty. A wide range of blade alloys and coatings will be tested.

Raising firing temperature

The commercial objective for advanced coal based systems is 1260°C. Initially an 'Introductory' rating of 1100°C, below the ash fusion of many coals and giving more generous margin for gas path integrity, may be advisable to amass experience before uprating in steps to the 'Mature' rating of 1260°C.

Longer term, higher temperatures, with improved cooling techniques offer further reduction in fuel consumption. The bulk of the technology will again be derived from the industry leaders, the aero engine makers. IGCC and topping cycles have the capability for 1400 to 1500°C. More advanced air 'cooling' will be viable towards 1400°C. Water cooling has been exhaustively researched, but has been abandoned due to pulling too much heat from the combustion gases, thereby losing performance. Ceramics are demonstrating great progress in quality and manufacturing. (Complete small turbine wheels are now running successfully.) Ceramic thermal barrier coatings are increasingly used on flight engines. The general prospects for ceramic components, casing and coatings on the industrial gas turbine are firm, and will enable further temperature uprating.

CONCLUSIONS

Fossil fuelled power generation relied for many years upon large PF fired plants using a conventional steam cycle. Increasing pressures for the environment have already promoted the use of low NO_x and SO_x removal at the combustion stage using fluid bed technology (CFBC and PFBC). Changes in the UK will promote the use of smaller plants which are ideal to exploit this new technology because of lower costs of generation when environmental protection is included.

Further worries about the environment are more recently centred on greenhouse gas emissions. It is accepted that fossil fuel burning will continue if we are to maintain, if not improve, the present standard of living. The most promising way of achieving this in the future is to couple high temperature gas turbines with coal fired generation. One of the ways of achieving this is to develop the Topping Cycle concept which shows the promise of low SO_x and NO_x emissions together with a saving of about 20% in the CO_2 emitted per unit of power produced.

British Coal commenced the development of the Topping Cycle in 1989, having previously established many years of experience of development of fluidised bed combustion and gasification. Technical support for the development is being provided by PowerGen plc and GEC Alsthom. Substantial financial contributions are being made by the UK Department of Energy, PowerGen plc, the European Community, the European Coal and Steel Community, the Electric Power Research Institute and GEC Alsthom.

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TABLE 1

PLANT SIZE, EFFICIENCY AND CAPITAL COST SUMMARY

TECHNOLOGY	NOMINAL SIZE (MWe)	NET EFFICIENCY LHV	SPECIFIC CAPITAL COST (£/kWe)
PF-FGD	200	38.8	1140
CFBC	200	39.6	955
Natural Gas CC	240	52.0	375
PFBC	200	41.4	935
IGCC	250	43.0	975
BCC Topping Cycle	330	46.9	870

TABLE 2

ENVIRONMENTAL IMPACT DATA

TECHNOLOGY	NOMINAL SIZE (MWe)	CO_2 (kg/kWh)	SO_x RETENTION (%)	NO_x (mg/m³ @ 6%O_2)	PARTICULATES (mg/m³ @ 6% O_2)
PF + FGD	200	0.87	90	500-650	50 *
CFBC	200	0.86	90	100-300	~30 **
Natural Gas CC	240	0.42	Neglig-ible emission	100-200	Negligible emission
PFBC	200	0.82	90	150-300	~10 ***
IGCC	250	0.78	99	120-300	Negligible emission
GT/PF +FGD	150	0.66	90	-	-
BCC Topping Cycle	330	0.72	90	200-300	~30 **

* Predicted performance
** Filter bag house
*** Ceramic filter

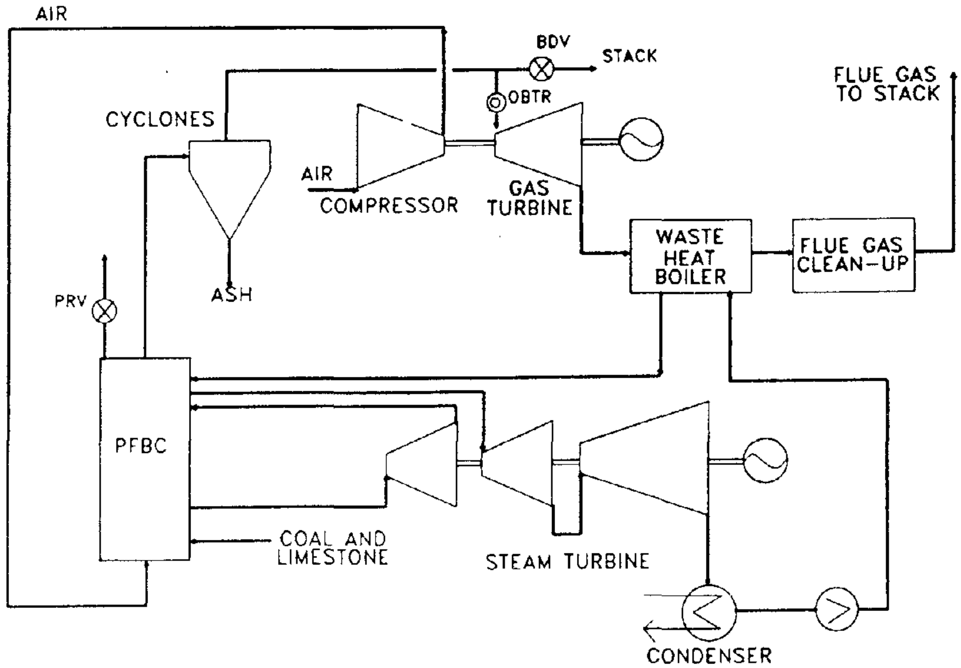


Figure 1   Simplified schematic of PFBC combined cycle plant (single shaft gas turbine)

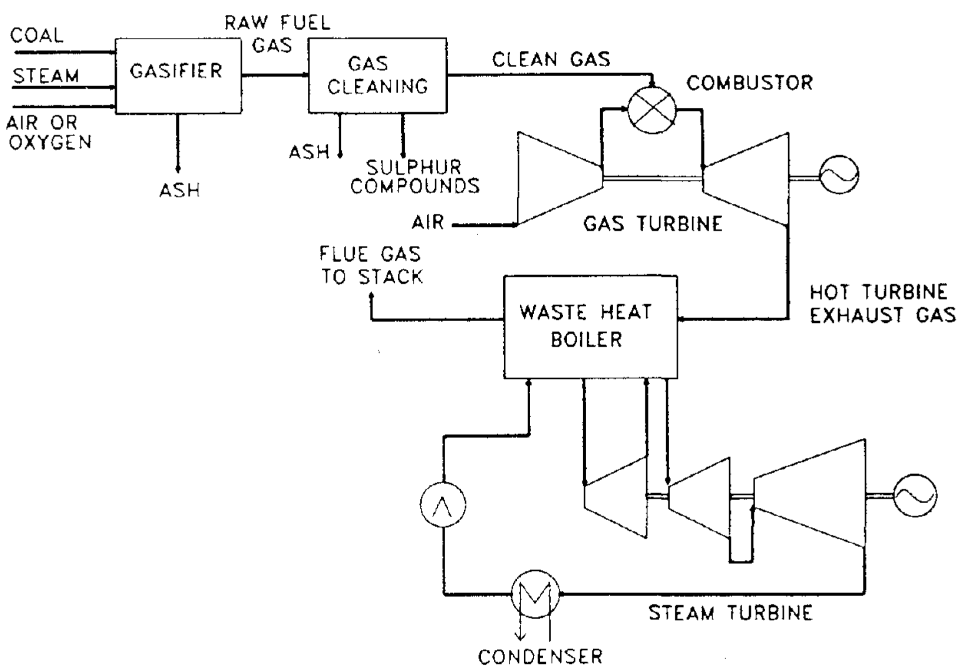


Figure 2   Basic features of IGCC Cycle

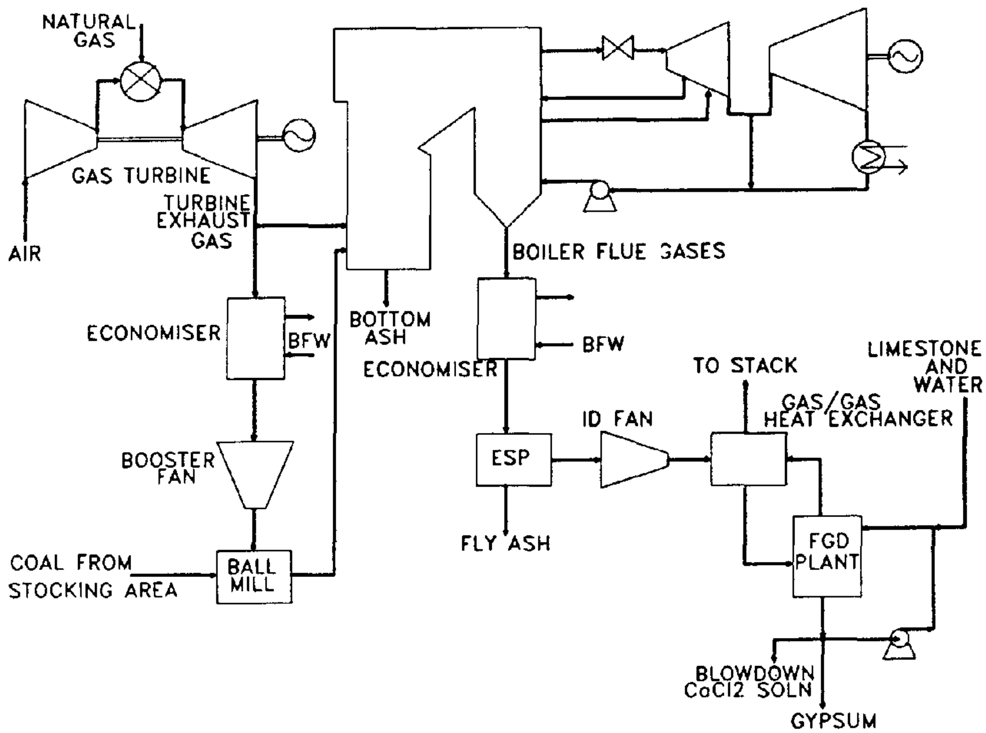


Figure 3 Schematic of GT/PF-FGD plant

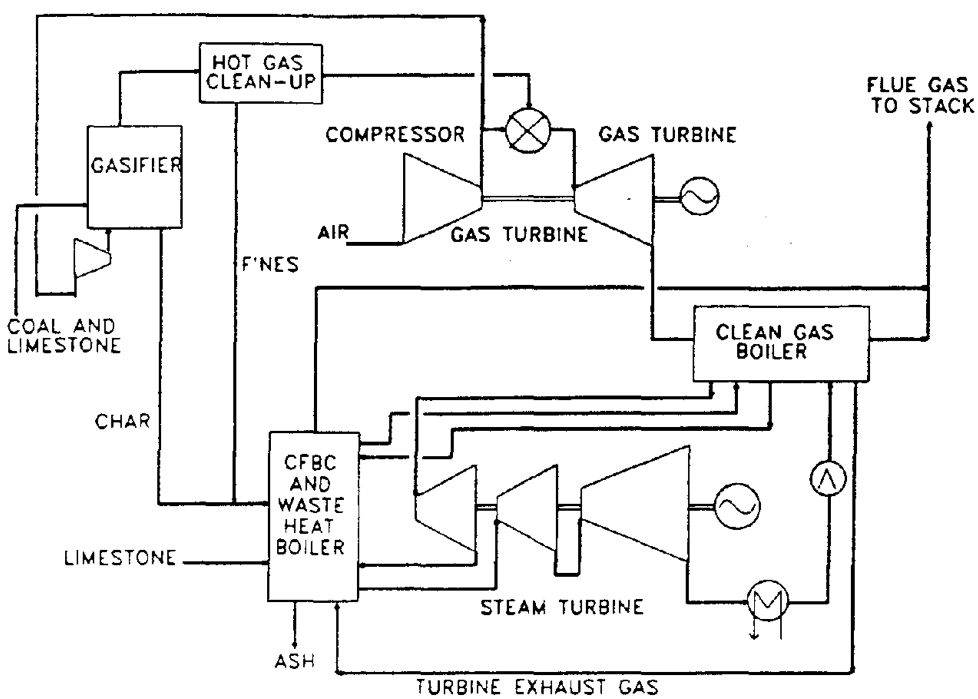
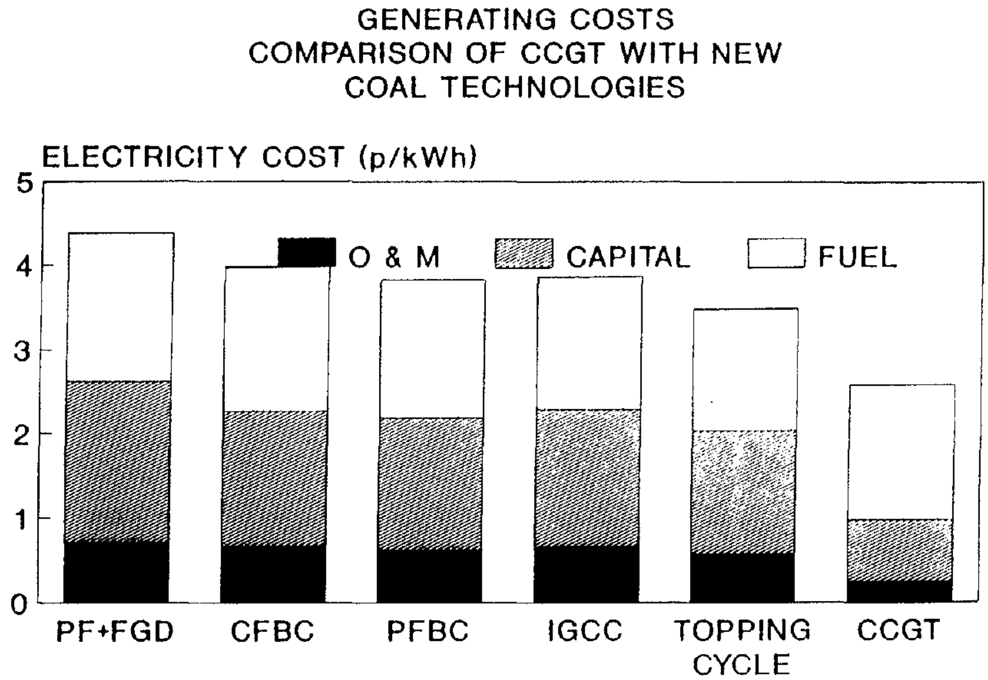


Figure 4 Schematic of British Coal Topping Cycle



Coal @ 190 p/nGJ, gas @ 22.1 p/therm
Repayment period gas 15 yrs, coal 25 yrs
DCF 10 %, load factor 85 %

Figure 5

HYDROTHERMAL DEWATERING OF BROWN COAL SLURRIES : FUNDAMENTAL STUDIES

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ABSTRACT

This study is part of a program of research into high efficiency power generation plant designed to reduce capital costs and CO_2 emissions. Hydrothermal dewatering of brown coal slurries followed by combustion of the product in conventional boilers or coal-fired gas turbines are two of the options. The effects of the dewatering process parameters on the physico-chemical structure of the dewatered product, and rheological properties of the slurries have been investigated. Batch autoclave and continuous pilot-plant dewatering tests have shown that, by optimising process conditions, low-ash slurry fuels can be prepared with a net wet specific energy of up to 14 MJ kg^{-1}.

INTRODUCTION AND BACKGROUND

The State Electricity Commission of Victoria (SECV) generates most of its electricity from brown coal located in the Latrobe Valley in Victoria, Australia. This coal is characterised by a very high moisture content (60-70% wet basis) and low ash content (1-2% dry basis (db)).

Owing to the high moisture content of brown coal, the SECV boilers are very large and they have a low thermal efficiency and high CO_2 emissions. Faced with the problem of maintaining competitiveness of brown coal power generation, the SECV commenced a program of research into new technologies for brown coal based electricity generation. Four technologies were selected as having the best prospects. They were -

(a) hydrothermal dewatering (HD);
(b) steam fluidised bed drying;
(c) direct coal-fired gas turbine with combined cycle; and
(d) integrated gasification combined cycle.

All four technologies have specific advantages for Latrobe Valley coal and offer increased conversion efficiency either through energy-efficient drying or through the use of a gas turbine/combined cycle.

One option is HD of brown coal - water slurries followed by combustion in conventional boilers or coal burning gas turbines. The continuous HD slurry process is shown in Figure 1. Raw brown coal is crushed and then milled with added water to form a slurry; additives may be added at this stage. The slurry is pumped under high pressure through heat exchangers and the temperature is raised to 300°C for a period of a few minutes. The pressure is maintained above saturated steam pressure to prevent evaporation. During heat treatment the coal is

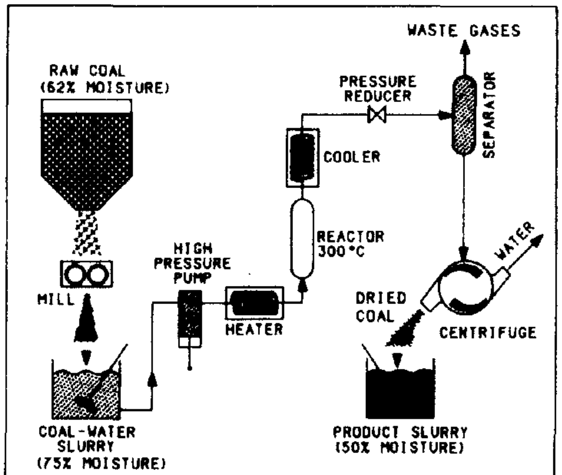


FIG.1 HYDROTHERMAL DRYING PROCESS

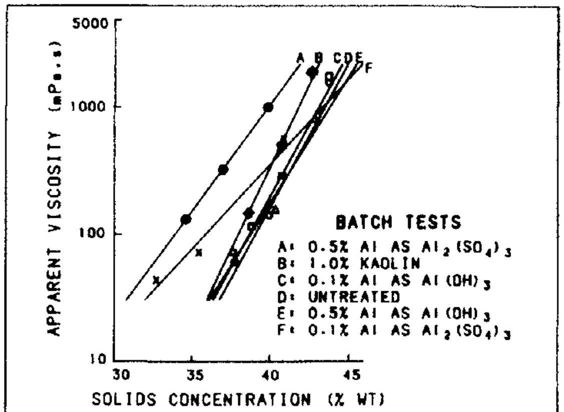


FIG.4 APPARENT VISCOSITY OF HD LOY YANG COAL SLURRIES WITH VARIOUS ALUMINIUM ADDITIVES REACTION CONDITIONS: 300°C, 5 MIN

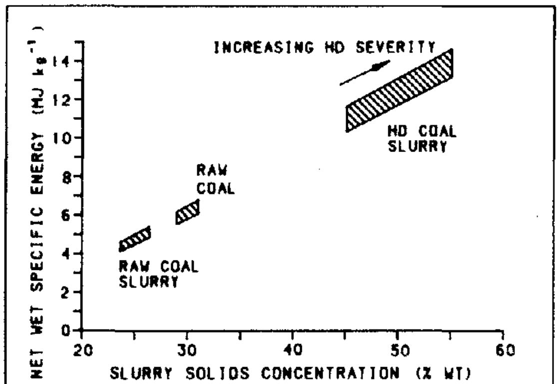


FIG.2 LIMITS OF NWSE WITH INCREASING SOLIDS CONCENTRATION

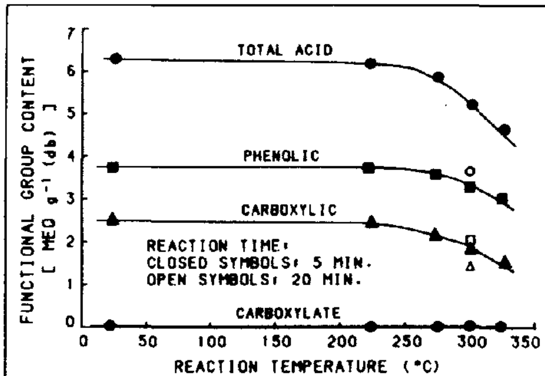


FIG.5 EFFECT OF PDU HD REACTION TEMPERATURE ON FUNCTIONAL GROUP CONTENT OF COAL

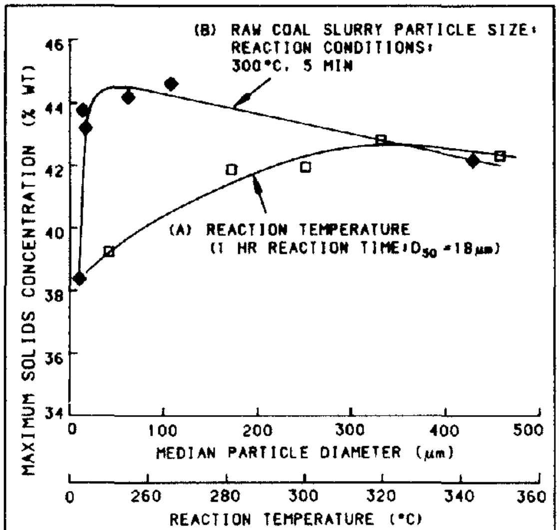
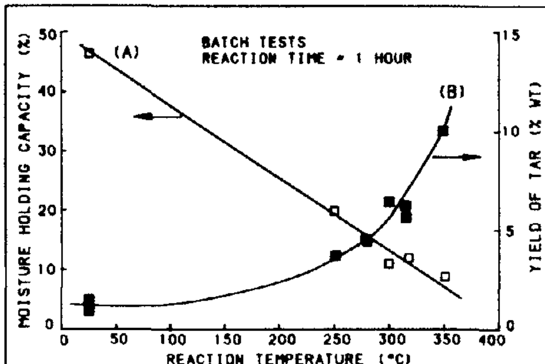


FIG.3 MAXIMUM SOLIDS CONCENTRATION OF HD LOY YANG COAL SLURRY AS A FUNCTION OF (A) AND (B)



(A)
MOISTURE HOLDING CAPACITY OF HD LOY YANG COAL AS A FUNCTION OF REACTION TEMPERATURE

(B)
YIELD OF EXTRACTABLE TAR AS A FUNCTION OF REACTION TEMPERATURE

FIG.6

dewatered and chemically upgraded.

After reaction, the slurry is cooled, depressurised and the excess moisture and product gases are removed. The concentrated, dewatered coal slurry can then be used for power generation. The estimated cost of power generation by HD followed by combustion in coal burning gas turbines, is about 75-80% of that for conventional plant (Simpson et al, 1990).

The Evans-Siemon (1970, 1979) HD process removes water from brown coal by non-evaporative means, hence the energy consumption is about 20% that of evaporative drying. Further, HD permits the removal of sodium and other ash-forming constituents as water soluble ions, thus reducing the fouling and slagging tendency of the fuel. The upgraded coal product is one of the more suitable fuels for use in a coal-fired turbine.

The mechanism of HD proposed by Murray and Evans (1972) involves moisture removal by -

(a) thermal expansion of water;
(b) shrinkage of the coal structure;
(c) expulsion - due to CO_2 generated in the pores by decarboxylation reactions; and
(d) alteration of the surface characteristics from hydrophylic to hydrophobic.

Alkali and alkaline earth metal ions, chlorine and sulphur are removed from the coal during the process but iron, aluminium and silicon are not.

The limiting factor in achieving high solids concentration slurries is the high intra-particle porosity of brown coal. Boger et al (1987) showed that the inherent pore volume of brown coal particles could be reduced by mechanical or chemical densification. Thermal treatment of the densified coals resulted in removal of some of the functional groups and changed the surface characteristics from hydrophylic to hydrophobic. The products were of low porosity and did not re-absorb water when slurried. The solids loading achieved with an unspecified thermal treatment of coal was 50% and with thermally treated, densified coal was 63%. This result provides an upper bound value for a milled slurry without particle size blending.

The theoretical limits of net wet specific energy (NWSE) are shown as a function of slurry solids concentration and HD severity in Figure 2. The objective is to produce a pumpable slurry fuel with as high a NWSE as possible. To achieve this, the solids concentration and extent of decarboxylation must be maximised. The extent to which slurry solids concentration can be maximised is dependent on the severity of HD reactions and provides the impetus for optimising the HD reaction. By the use of appropriate additives, the fouling properties of the fuel can be reduced and the rheological properties optimised. This paper reports on the results of the chemical, physical and rheological properties of HD coal slurry.

METHOD

Batch Autoclave Tests

The fundamentals of the HD process have been studied at laboratory scale in batch autoclaves ($500\ cm^3$). The autoclaves were filled with coal slurry (270 g) and any additives, and heated to the reaction temperature in a fluidised sand bath. Most of the batch autoclave experiments used a homogeneous, non-settling Loy Yang coal slurry (D_{50} = 18 µm). Tests were also performed on a range of coal seams and types. Once the reactor had reached 90°C, and water vapour had displaced air in the reactor, it was sealed. Typically, the reactor heat-up rate was 6°C min^{-1}. After reaction, the autoclave was quenched in cold water and the contents subsequently removed for analysis.

Pilot Plant Tests

Following successful testing at the laboratory scale, preliminary pilot-scale tests were carried out in a HD Process Demonstration Unit (PDU) at the Energy and Environmental Research Centre (EERC) in Grand Folks, North Dakota, USA. The purpose was to evaluate the technical feasibility of using the HD process to produce high energy slurry fuels of low-fouling propensity and to provide design data for the construction of an advanced pilot-scale test facility.

The PDU operates at a feed rate of 91 kg h^{-1}, a maximum temperature of 340°C and a maximum pressure of 27.6 MPa. Reactor vessels were available for residence times of 5 and 20 minutes. A residence time of 1 minute was obtained by by-passing the reactor vessels. Loy Yang slurry with a particle size (D_{50}) of 16 µm was studied. Smooth continuous operation was achieved at temperatures of up to 300°C. At 325°C coking resulted in reactor blockages.

Chemical, Physical and Rheological Characterisation

Chemical analysis techniques developed in Australia specifically for lower rank coals were employed.

The true density was measured by helium displacement whilst the surface area was measured by carbon dioxide absorption (Dubinnin Method) on the granular product. The pore volume distribution was measured by mercury intrusion porosimetry (Quantachrome Autoscan 60) on the dried product over the pressure range 0.1 to 414 MPa for PDU tests and 0.01 to 414 MPa for batch tests. Zeta potentials were measured using a Malvern Zetasizer. The yield of extractable tar was measured by exhaustive extraction with dichloromethane.

The rheological properties of the slurries were measured using a narrow gap Haake concentric cylinder rheometer (nominal shear rates 0-1000 s^{-1}). Prior to testing, each of the batch test products was milled in a domestic blender to a median particle diameter of 12 µm. As the severity of dewatering increased, the effort required to mill the slurries increased. Rheograms of shear rate vs shear stress were constructed for each slurry sample at three solids concentrations and its apparent viscosity determined at 100 s^{-1}. Maximum solids concentration ($\emptyset_{max}$) was taken at an apparent viscosity of 1000 mPa.s.

RESULTS AND DISCUSSION

Chemical Properties

The results of one-hour batch autoclave tests show that increasing the reaction temperature from 250 to 350°C had the effect of: increasing the carbon content of the product from 71.4 to 79.0% (db); reducing the volatile matter yield of the product from 48.1 to 37.2% (db); and increasing the net wet specific energy from 9.1 to 11.6 MJ kg^{-1} (Table 1).

For reactions carried out at 300°C, increasing the residence time had a small but significant effect on the extent of HD, consistent with the high reaction rates reported by Stanmore and Boyd (1977/8). The raw coal slurry particle size had little effect on the chemical properties of the product, however, the NWSE showed an optimum at a raw coal slurry particle size of about 50 to 100 µm (Figure 3).

For HD reactions carried out in the PDU at a residence time of 5 minutes, increasing the HD

TABLE 1 : CHEMICAL ANALYSIS OF HD COAL PRODUCTS FROM BATCH AUTOCLAVE TESTS

SAMPLE	ASH	VM	C	H	GDSE	NWSE
Raw Coal	1.0	49.9	68.3	4.8	26.8	5.9
Temperature Series (°C)	Reaction Time = 1 Hour					
250	0.7	48.1	71.4	2.8	27.9	9.1
280	0.6	46.2	73.0	4.8	28.6	10.2
300	0.8	41.5	76.4	4.7	30.0	10.9
320	0.8	40.8	76.0	4.9	30.4	11.2
350	1.0	37.2	79.0	4.9	31.5	11.6
Time Series (min)	Reaction Temperature = 300°C					
0	0.8	46.2	72.8	4.8	28.6	11.3
5	0.7	46.1	73.2	4.8	28.8	10.9
10	0.8	45.8	73.1	4.8	28.6	10.8
30	0.7	43.2	74.3	4.8	29.0	11.1
Particle Size Series (μm)	Reaction Temperature = 300°C; Time = 5 min					
9.3	0.8	45.2	73.7	4.8	28.9	9.4
68	1.0	45.4	72.6	4.9	28.6	11.0
101	0.8	45.0	73.2	4.7	28.6	11.1
413	0.8	44.7	72.8	4.8	28.7	10.4
Coal Types Series	Reaction Temperature = 300°C; Time = 5 min					
Morwell ROM	2.6	43.4	72.0	4.6	28.4	10.7
Morwell Dark	0.4	41.4	72.3	4.5	28.4	9.2
Morwell Wood	2.2	41.6	72.4	4.6	28.5	10.1
Maryvale	2.3	44.2	71.0	4.6	27.8	7.7
Loy Yang Salty	1.4	43.8	71.5	4.5	27.8	10.3

ASH = Ash Yield (%db); VM = Volatile Matter (%db); C = Carbon (%db); H = Hydrogen (%db); GDSE = Gross Dry Specific Energy (MJ kg^{-1}); NWSE = Net Wet Specific Energy of Slurry at $\emptyset_{max}$ (MJ kg^{-1})

temperature from 225°C to 325°C had the effect of: increasing the carbon content of the product from 68.6 to 72.1% (db); reducing the oxygen content of the product from 25.4 to 21.8% (db); reducing the volatile matter yield of the product from 49.0 to 46.1% (db); and increasing the NWSE of the product from 5.9 to 15.4 MJ kg^{-1}. The best results (56% dry solids) were achieved in a run carried out at 300°C and 20 minutes residence time. However, repeat experiments failed to duplicate this result; some of the differences between the characteristics of this product and the other PDU tests is a higher mean particle diameter (17 μm cf 8 μm) and a higher level of silica and alumina (possible clay).

Interestingly, it was found that upon ageing over a period of several months, the maximum solids concentration achieved increased by about 6%. It is postulated that this effect is due to the gradual degassing of the slurries; i.e. entrained bubbles cause a reduction in coal solids concentration (Woskoboenko, 1985). Work is progressing in this area.

The Loy Yang coals studied contain low levels of minerals and inorganics (0.7% db) mainly present as cations of iron, calcium, magnesium and sodium, and also quartz. Dewatering did not reduce the levels of calcium and magnesium in the coal (0.05 and 0.08% (db) respectively), as the temperature was raised to 325°C. However, the level of sodium decreased from 0.13% to 0.02% (db). The reduction in sodium would reduce the fouling propensity of the fuel (Anderson et al, 1988). SEM examination of laboratory ashes prepared from the PDU HD products showed that addition of aluminium to the coal slurry results in the production of a lower bulk density combustion ash compared with that of the untreated slurry. Such ash is known to cause less severe boiler fouling, however, the addition of aluminium to the slurry reduces $\emptyset_{max}$ and, hence, the NWSE of the slurry fuel (Figure 4).

As the HD temperature was increased from 225°C to 325°C, the level of carboxylic acid and phenolic functional groups in the product decreased from 2.40 to 1.58 meq g^{-1} and 3.74 to 3.03 meq/g respectively (Figure 5). For tests carried out at 300°C, increasing the reaction time from 5 minutes to 20 minutes reduced the level of carboxylic and phenolic functional groups from 1.84 to 1.54 meq g^{-1} and 3.34 to 2.04 meq g^{-1} respectively. The carboxylic acid groups began to show decomposition at temperatures above 225°C, whereas the phenolic groups were stable until about 275°C. The carboxylates (~0.05 meq g^{-1}) were stable at these temperatures.

The yield of extractable tar increases with HD reaction temperature from about 3.5% at 250°C to 10.0% at 350°C (Figure 6). During thermal treatment, coal tars are mobilised and the original coal structure is transformed. Some pores are filled and/or blocked by tar, coal macerals coalesce and surfaces are coated with tar. These transformations have been confirmed by microscopy, porosimetry and physical analysis.

Physical Properties

As the severity of HD increases (i.e. temperature and time), the pore structure of the coal collapses and the entrances to some pores are blocked with tar (Figure 7). Hence, as the HD temperature increases from 225°C to 325°C there is an apparent decrease in the true density and surface area of the dry product from about 1.54 to 1.36 g cm^{-3} and 248 to 121 m^2 g^{-1} respectively (Table 2). It should be noted that, owing to the functional group destruction during dewatering, the shrinkage-swelling characteristics are significantly changed (Woskoboenko, 1985; Boger et al, 1987). The swelling factors for oven-dried HD coal and oven-dried raw coal are 1.09 and 1.32 respectively (Woskoboenko, 1985). Accordingly, it is not valid to compare the physical properties (e.g. porosity) of oven-dried HD coal and oven-dried coal.

As the dewatering temperature increases, the moisture holding capacity of brown coal is reduced from 48 to 9% (Figure 6). This is attributed to the loss of oxygen functional groups and reductions in surface area and porosity. The porosity of the coal is also reduced by the processes described above. Figure 7 shows that the intruded pore volume (V_I) of the HD products decreases with treatment temperature as pores smaller than 1.0 µm are destroyed. The increase in porosity above 1.0 µm is inter-particle voidage created by particle coalescence. The pore destruction increases $\emptyset_{max}$ by a reduction in the volume of occluded attributed to an increase in

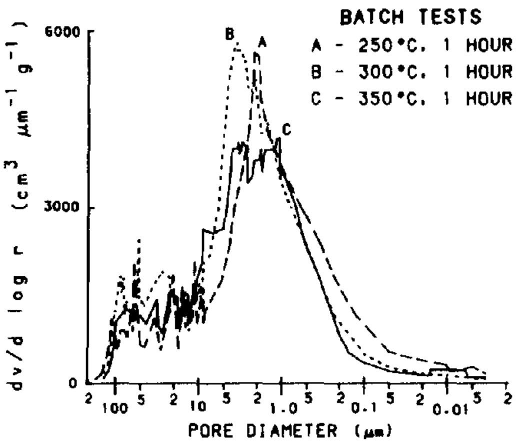


FIG.7(a)

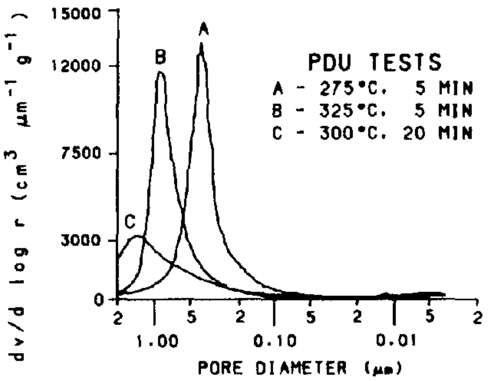


FIG.7(b) PORE VOLUME DISTRIBUTION OF HD COAL PRODUCTS

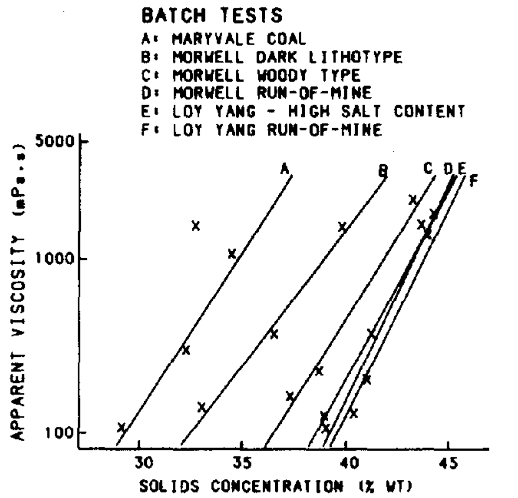


FIG.9 APPARENT VISCOSITY OF HD COAL TYPES

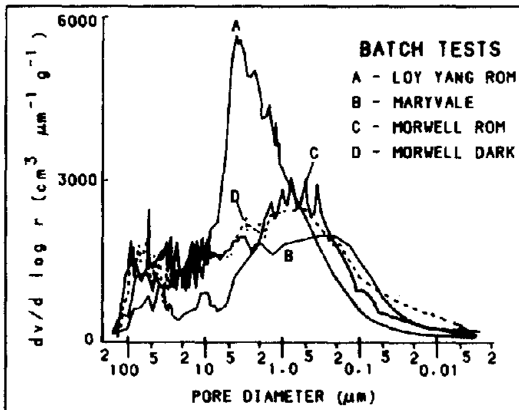
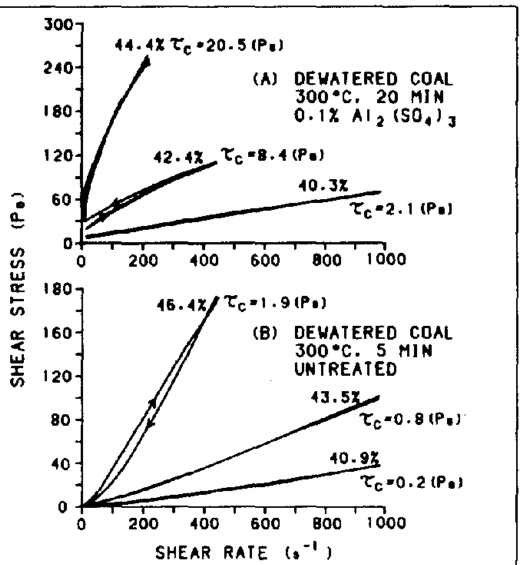
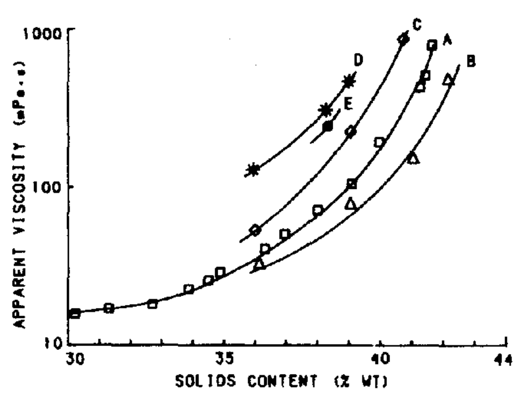


FIG.10 PORE VOLUME DISTRIBUTION OF VARIOUS HD COAL TYPES



RHEOGRAMS OF PDU HD COAL SLURRIES
(A) TREATED WITH $Al_2(SO_4)_3$
FIG.8 (B) UNTREATED



A HD SLURRY (300°C)
B A + ANIONIC ADDITIVE (0.4%)
C A + NON-IONIC ADDITIVE (0.05%)
D A + $Al_2(SO_4)_3$
E A + $Al_2(SO_4)_3$ + ANIONIC ADDITIVE (0.05%)

FIG.11 EFFECT OF SURFACTANTS ON SLURRY VISCOSITY

TABLE 2 : PHYSICAL AND RHEOLOGICAL PROPERTIES OF PDU HD COAL SLURRIES

SAMPLE	ρ_{He}	ρ_{Hg}	P	SA	$P_{0.5}$	V_I	$\emptyset_{max}$	D_{50}
Raw Coal	1.55	0.79	49.0	259	0.52	0.58	22	10.9
PDU TESTS								
Temperature (Time)								
225 (5)[a]	1.54	0.69	55.2	248	0.36	0.59[d]	42	9.4
250 (5)[a]	1.52	0.67	55.9	209	0.30	0.66[d]	42	11.6
275 (5)[a]	1.48	0.63	57.4	286	0.40	0.76[d]	45	7.0
300 (5)[a]	1.42	0.72	49.3	194	0.80	0.57[d]	49	6.1
325 (5)[a]	1.36	0.68	50.0	121	0.88	0.72[d]	46	7.5
300 (1)[a]	1.43	0.71	50.3	227	0.55	0.64[d]	46	5.3
325 (1)[a]	1.44	0.74	48.6	221	0.58	0.50[d]	51	10.4
300 (20)[a]	1.38	0.89	35.5	126	1.00	0.43[d]	54	16.8
250 (20)[a]	1.41	0.66	53.2	309	0.38	0.72[d]	43	5.2
275 (20)[a]	1.49	0.65	56.4	204	0.56	0.71[d]	46	7.0
300 (20)[b]	1.48	0.67	54.7	307	0.62	0.67[d]	48	6.1
300 (20)[c]	1.50	0.66	56.0	192	0.75	0.70[d]	44	11.6
BATCH TESTS								
Temperature Series (°C)		**Reaction Time = 1 Hour**						
250	1.47			176	1.50	1.43[e]	45	
280	1.40			169	2.50	1.64[e]	42	
300	1.38			140	0.80	1.50[e]	42	
320	1.43			162	–	–	43	
350	1.44				1.80	1.29[e]	42	
Time Series (min)		**Reaction Temperature = 300°C**						
0	1.40			189	2.40	1.51[e]	46	
5	1.44			175	0.60	1.28[e]	44	
10	1.41			170	2.20	1.43[e]	44	
30	1.40			130	2.50	1.44[e]	44	
Particle Size Series (µm)		**Reaction Temperature = 300°C; Time = 5 min**						
9.3	1.42			166	0.80	1.67[e]	39	
68	1.49			–	–	–	44	
101	1.42			177	0.70	1.35[e]	45	
413	–			–	–	–	42	
Coal Types Series		**Reaction Temperature = 300°C; Time = 5 min**						
Morwell ROM	–			–	0.50	0.90[e]	44	
Morwell Dark	–			–	1.30	1.20[e]	39	
Maryvale	–			–	1.50	1.11[e]	34	

a = 11.0 MPa Pressure; b = 13.8 MPa Pressure; c = 11.0 MPa + Al; d = 0.1 to 414 MPa; e = 0.01 to 414 MPa; ρ_{He} = True Density (g cm^{-3}); ρ_{Hg} = Apparent Density (g cm^{-3}); P = Porosity (% vol); SA = Surface Area (m^2 g^{-1}); $P_{0.5}$ = Volume-Median Pore Diameter (µm); V_I = Intruded Pore Volume (cm^3 g^{-1}); $\emptyset_{max}$ = Maximum Solids Concentration (% Wt); D_{50} = Mass-Median Diameter (µm) water. However, $\emptyset_{max}$ is reduced by particle coalescence and the formation of macropores. It has been found that $\emptyset_{max}$ of the dewatered products can be increased by up to 5% by re-milling the product and destroying some of the newly formed macropores.

SLURRY RHEOLOGY

Slurries prepared from Loy Yang coal are mildly thixotropic (viscosity decreases with shear time) and due to their semi-flocculated state they are plastic (i.e. they have a true yield stress). Casson yield stress values (τ_c) are shown in Figure 8.

Upon thermal dewatering the colloidal gel structure of brown coal is destroyed, much of the pore structure is collapsed and water is expelled from the coal particles. Accordingly, for the same volumetric solids concentration, the maximum weight concentration for dewatered coal (~50% Wt) is much higher than that for raw coal (~22% Wt).

The dewatered coal slurries displayed time-independent, mildly rheopectic rheological behaviour (Figure 8). Owing to their high zeta potential (~-50 mV) and relatively large particle size (D_{50} ~10 μm) the dewatered slurries were unstable and readily formed hard packed sediments.

Coal Types

For given processing conditions, $\emptyset_{max}$ is dependent not only on coal rank, as Khan and Potas (1991) have shown, but also on coal type (Figure 9). In general, Loy Yang coal is low in carboxylates (which are thermally stable at these temperatures (Murray and Evans, 1972)) and, thus, undergoes extensive dewatering at 300°C. However, Morwell and Maryvale coals contain appreciable quantities of carboxylates and are less reactive. Accordingly, Morwell and Maryvale coals undergo less pore destruction than Loy Yang coal (Figure 10). Thus, HD Morwell and Maryvale coals have lower $\emptyset_{max}$ than Loy Yang coal. Further, the relatively high non-pyritic iron content of Maryvale coal will increase the degree of slurry flocculation and, hence, decrease $\emptyset_{max}$.

Aluminium Addition

The slurries treated with $Al_2(SO_4)_3$ were partially flocculated and, hence, displayed pseudoplastic flow properties; consequently, they settled more slowly and were readily re-dispersed. However, $Al_2(SO_4)_3$ flocculation reduced $\emptyset_{max}$ by ~5% (Figure 4).

In contrast, the addition of $Al(OH)_3$ and kaolin have little effect on $\emptyset_{max}$. The reduction in $\emptyset_{max}$ with $Al_2(SO_4)_3$ addition can be minimised by the addition of a suitable surfactant to deflocculate the slurry (Figure 11).

Surfactant Addition

Surfactants may be used to alter the degree of flocculation of the HD coal slurries and, hence, their rheological properties. In general, anionic surfactants deflocculate HD coal slurries, decrease viscosity and reduce their stability. At low additive concentrations (<1%), the non-ionic surfactants increase the degree of flocculation, increase viscosity and, hence, increase slurry stability. At higher additive concentrations the slurries are sterically stabilised and viscosity decreases (Tudor et al, 1991). It was found that the viscosity of the HD suspensions treated with $Al_2(SO_4)_3$ could be reduced by deflocculating with anionic surfactants (Figure 11).

Maximum Solids Concentration

Viscosity increases logarithmically with solids content and, as the maximum particle packing efficiency is approached, the viscosity asymptotically approaches infinity (Figure 11). For deflocculated slurries such as these, the weight fraction solids can be increased by increasing the process severity or by particle size blending to improve particle packing efficiency. The relationship between $\emptyset_{max}$ and V_I is shown in Figure 12. These results show that as the inter and intra-particle pore volume is reduced, by pore collapse, filling with pyrolysis tars and particle coalescence, $\emptyset_{max}$ approaches about 63%. It is worth noting that this is precisely the maximum solids loading achieved with a low-porosity (~4%) densified brown coal (Boger et al, 1987).

As with previous studies (e.g. Khan and Potas, 1991), this study showed that, in general terms, $\emptyset_{max}$ increases as dewatering temperature and residence time increases. However, an important new finding of this study is that there is an optimum degree of pyrolysis and coalescence, and that beyond this optimum $\emptyset_{max}$ diminishes. Excessive pyrolysis can result in coalescence of coal particles and the development of new pores which immobilise water and reduce $\emptyset_{max}$. This effect was observed in two series of batch autoclave tests. In a series of experiments conducted between 250-350°C it was found that $\emptyset_{max}$ increases to 320°C (Figure 3(a)). At 350°C severe coalescence of particles occurred resulting in a solid cake product.

An important finding of this study is that $\emptyset_{max}$ of the product slurry is dependent on the particle size of the feed slurry (Figure 3). The batch tests showed that, for HD slurry with a product particle size (D_{50}) of 12 µm, the optimum feed slurry particle size is 50-100 mm.

The pore size data shows that $\emptyset_{max}$ is governed by the pore size distribution of the product. For very coarse particles, insufficient tar migration has occurred and, hence, pore destruction is below optimum. In contrast, for very fine particles, excessive pyrolysis results in severe particle coalescence and the creation of new macropores.

Clearly, it is critical to optimise the degree of pyrolysis and/or post dewatering milling in order to maximise $\emptyset_{max}$.

SECV HD PILOT PLANT

The SECV has constructed a HD pilot plant and coal-fired turbine simulator (Anderson and Johnson, 1991). The test facility (Figure 13) has a design slurry capacity of 1 tonne hr^{-1} and a maximum temperature of 325°C. The design incorporates full-scale simulation of slurry heating and efficient post-reaction heat recovery. The plant features state-of-the-art computer control technology and extensive data logging capabilities.

The combustion characteristics of the slurry are studied in a gas turbine simulator. The simulator has a slurry feed rate of 200 kg hr^{-1} and operates at a pressure of 1.0 MPa.

SUMMARY

The results of this study demonstrate that HD of brown coal slurries can be used to increase the NWSE of brown coal slurry fuels from 4.5 to about 14 MJ/kg. The primary mechanism for the increase in $\emptyset_{max}$ is the reduction in water occluded in intra-particle pores.

Laboratory batch tests have shown that, for coals of the same rank, those with the lowest carboxylate content produce the least porous products and the highest NWSE slurry fuels. The particle size of the feed slurry is critical in determining post treatment porosity and solids loading, the optimum particle size was determined to be in the range 50-100 µm. In terms

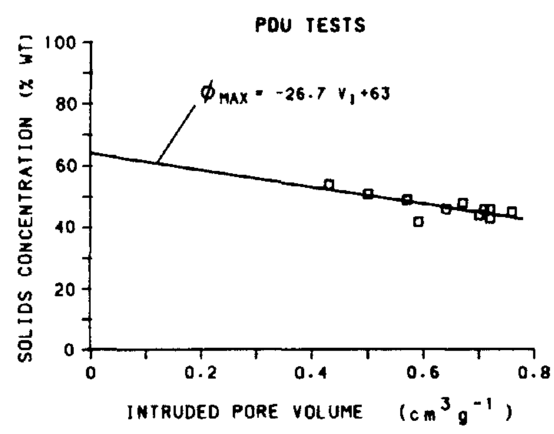


FIG.12 MAXIMUM SOLIDS CONCENTRATION VS INTRUDED PORE VOLUME

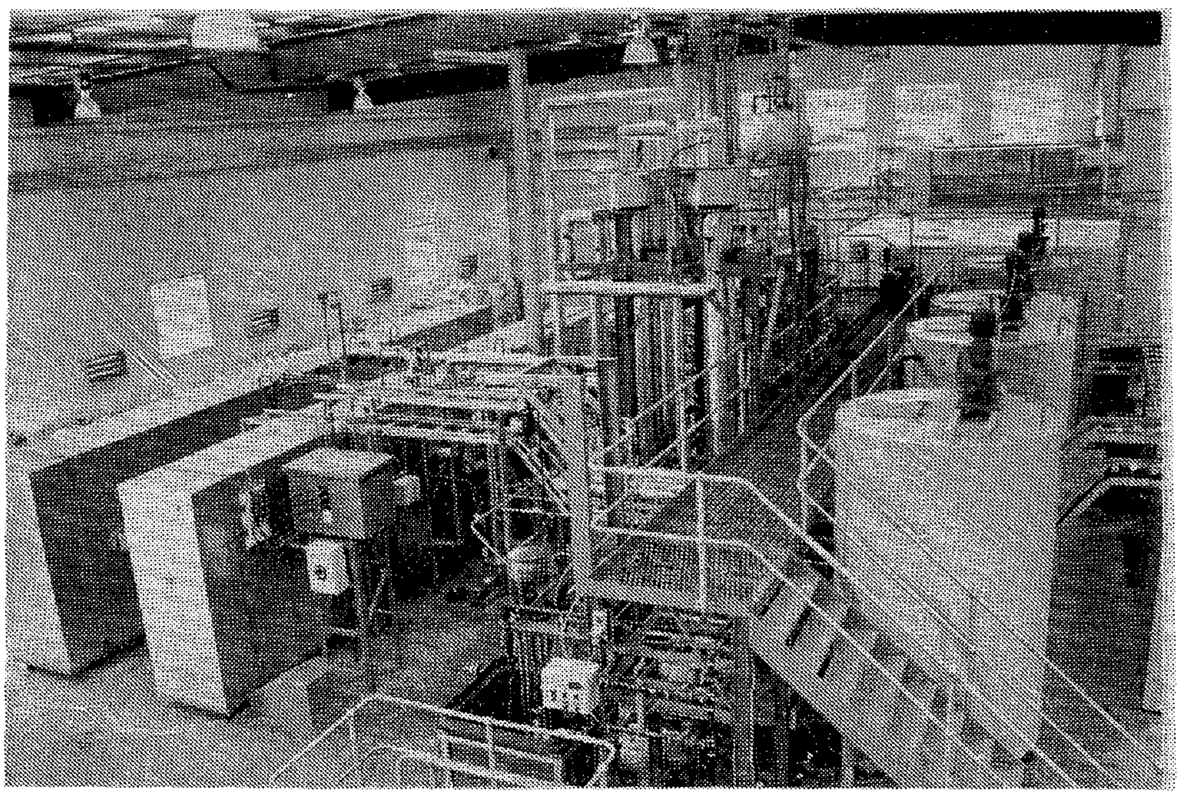


FIG.13 SECV HD PILOT PLANT (1 TONNE HR^{-1}), MULGRAVE, AUSTRALIA

of slurry solids concentration, the optimum dewatering temperature was about 320°C.

Pilot plant scoping tests in the EERC PDU have confirmed that the HD process is technically viable. The SECV HD pilot plant (1 tonne/hr) has been commissioned and an extensive research program undertaken to: (a) verify the findings of laboratory-scale work; (b) to provide data required to evaluate the technical and economic viability of HD; and (c) to provide a slurry fuel for the development of a coal-fired gas turbine.

ACKNOWLEDGEMENTS

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Gas-/Steam Turbine Power Stations for Electricity Generation from Hard and Brown Coal

by

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ABSTRACT

In many parts of the world, hard and brown coal are the leading energy sources for power generation. Many years ago, the demands for pollution control led to the development of new technologies for power generation from coal. In the current development efforts for new techniques for power generation from coal, the discussion of the greenhouse-effect has put the aspect of efficiency into the focus of interest. The CO_2 emission can only be reduced to the same extent by means of a significantly increased plant efficiency. Most of the techniques are based on the combined gas/steam turbine process, which is characterized by a high upper process temperature and as a result of this by a high efficiency. The gas generated by coal gasification serves as a fuel for the gas turbine. The process of gas generation and gas cleaning is coupled with the combined gas/steam turbine process. This heat-economical close coupling is the fundamental condition of a high efficiency level. A lot of test and demonstration plants are in operation or under construction.

AIMS - REQUIREMENTS

Modern conventional designed coal-fired power stations have reached a high stage of development from the point of view of technology, availability, economics and environmental protection. According to the opinion of many experts the level of efficiency of traditional steam turbine power stations cannot be increased significantly due to fundamental thermodynamic aspects and the available materials. In the past the design of power stations was deeply imprinted with considerations such as availability, economy and pollution control, especially in respect of the emission of dust, sulphur dioxide and nitrogen oxide. Both, the conservation of resources and the drastic reduction of the carbon dioxide emission are demanded in consideration with the world-wide concern over the effect of carbon dioxide in the earth climate (greenhouse-effect). This goal can only be achieved by a considerable increase in efficiency of the power stations.

As a new technology is being developed world-wide, the combined cycle process becomes a possibility. This type of power plant can utilize the thermodynamical benefit of developing gas turbines to extremely high inlet temperatures. In contrast to the conventional steam turbine process the upper process temperature is essentially increased, which is the main reason for the high efficiency. The development of this technology alone does not provide the whole answer. Demonstration plants must be realized as quickly as possible in order to make this technology available for the construction of new power stations.

METHODS OF COAL GASIFICATION

For coal gasification there are three techniques available, which are principally different:

- the fixed bed
- the fluidized bed and
- the entrained reactors.

Furthermore, coal gasification processes were developed, which provide the gasification reaction in a molten metal or molten salt. But this development work was not successful. With the basic types of gasifiers there are a number of different features to be noted concerned with each method. The principle shows an overview of the basic types of coal gasifiers (Fig. 1). Dependent on the coal quality and the utilization of the generated gas, the different types of coal gasifiers offer special characteristics, which must be seen in respect to the requirements for the integration of coal gasification with the combined gas turbine/steam turbine process.

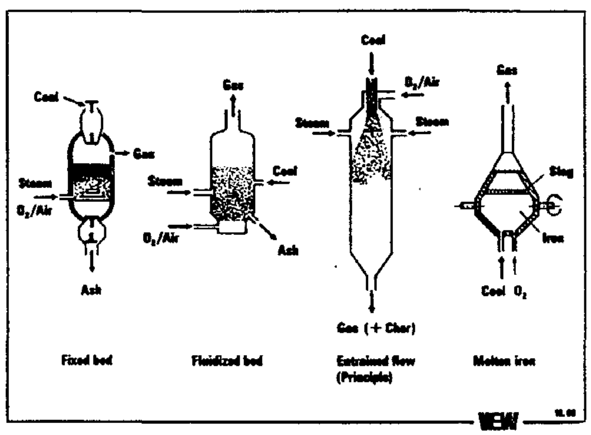

Fig. 1
Gasifiers, different types

Fixed Bed Gasifier

Coarse grains of coal (between 3 and 30 mm), which are fed into the pressurized gasifier by lock hoppers, move from the top to the bottom of the reactor against the stream of the oxidizing agent and steam. During this way through the gasifier the coal is first dried and degasified before it is finally gasified. The gasification temperature lies between 800 and around 1000 °C, if the ash is drawn off in a solid and not in a liquid form.

The gasification in a fixed bed reactor leads to a high level of carbon conversion and a high level of cold gas efficiency, too. That means, the produced gas has a high amount of chemical energy. On the other hand, due to the low temperatures in the gasifier, especially in the upper level, where the coal is degasified, tars and oils are formed, which prevent the utilization of the sensible heat in the whole temperature range.

Fluidized Bed Gasifier

The fluidized bed gasifier is operated with coal pieces between 1 and 6 mm. The operation temperature lies between 800 °C and 1100 °C and, thus, is below the ash softening point. The gasification process can be operated air- or oxygen-blown. The fluidized bed gasifier operates relatively uneffected by sudden alterations in the ash content. The residence time in the fluidized bed gasifier is sufficient for high coal conversion and cold gas efficiency by operation with reactive coal qualities as well as for an oxygen- or air-blown reactor. Even for low reactive coal it is possible to reach a partial gasification with a high conversion rate in an air-blown gasifier. The residues of the gasification process in form of char can be fired in the boiler of the process or in a special combustor, which is integrated in the whole process.

Entrained Gasification

The entrained gasifier is operated with fine coal dust (particle size less 0.1 mm) at temperatures between 1400 °C and 1900 °C, that means above the ash melting point. Because of the short residence time in the gasifier very fine coal particles and a high operation temperature is necessary. In an oxygen-blown gasifier a complete coal conversion is possible in contrast to the application of air as oxydizing agent, which leads to a partial gasification only. The remaining residue in form of powdry char is burnt in the boiler, which is integrated in the whole process.

Because of the high operation temperature of the gasifier and in consequence of this the high outlet temperature, the generated gas contains a high amount of sensible heat. To realize a high efficiency of the total process a high-valued heat recovery system at the gasifier's outlet is necessary, which is integrated with the combined cycle process. The opportunity for operation with almost any coal quality is a special advantage of this type of gasifier. In contrast to this fixed bed and fluidized bed gasifiers demand certain coal qualities. The high amount of sensible heat at the outlet of the gasifier must be seen as a disadvantage of this technology. For coals with a high ash content heating up of the coal to the operation temperature of the gasifier must be considered in the total energy balance. For a complete gasification according to the entrained principle the energy balance over the gasifier is influenced by melting the ash.

Dependent on the special characteristics of each gasification method and on the coal quality it must be analysed, which type of gasifier is suitable in a particular instance with regard to the associated technical, thermodynamic and econimic conditions. An overview of the advanced gasification technologies in the operated test and demonstration plants is given in table 1.

process	owner	location	coal throughput	product
fixed bed				
BGL	British Gas	Westfield, Schottland	550	fuel gas
fluidized bed				
HTW	Rheinbraun AG	Wesseling, BRD	156 1)	fuel gas
HTW	Kemira Oy	Oulo, Finnland	650 2)	chemical feedstock
HTW	Rheinbraun AG	Berrenrath, BRD	720 1)	chemical feedstock
KRW	KRW Energiesystems	Waltz Mill, USA	30	fuel gas
U-Gas	Institute of Gas Technology	Chicago, USA	30	fuel gas
entrained flow				
DOW	DOW Chemical	Plaquemine, USA	2.200	fuel gas
GSP	Gaskombinat Schwarze Pumpe	BRD	720 1)	town gas
PRENFLO	Krupp Koppers	Fürstenhausen, BRD	48	fuel gas
SHELL	Shell Oil Company	Deer Park, USA	250	fuel gas
TEXACO	Tennessee Eastman	Kingsport, USA	820	chemical feedstock
TEXACO	Ruhrchemie/ Ruhrkohle Oel- und Gas GmbH	Oberhausen, BRD	720	chemical feedstock
TEXACO	Ube Industries	Ube City, Japan	1.500	chemical feedstock
TEXACO	Cool Water Project	Daggett, USA	910	fuel gas
VEW	Vereinigte Elektrizitätswerke Westfalen	Gersteinwerk	240	fuel gas

Tab. 1: advanced gasification processes examples of operating plants

1) dried brown coal
2) peat

COMBINED CYCLE PROCESS WITH INTEGRATED COAL GASIFICATION

The common application of a gas and a steam turbine in a combined cycle with integrated coal gasification means an essential increase of the upper process temperature in contrast to the conventional steam turbine plant. This effect, which leads to an essentially improved efficiency of the power plant will be further increased by the development of the gas turbines to higher inlet temperatures. In this way, the goal of a reduced carbon dioxide emission can be achieved. Besides of this, the described technology enables the reduction of all emissions in such a degree that the application of a flue gas treatment is not necessary.

As it has already been mentioned in the presentation of the different types of coal gasifiers, the coal can be converted completely or partially into gas. The diagram shows the principle of the process with an integrated complete gasification according to the principle of oxygen-blown entrained gasification (Fig. 2).

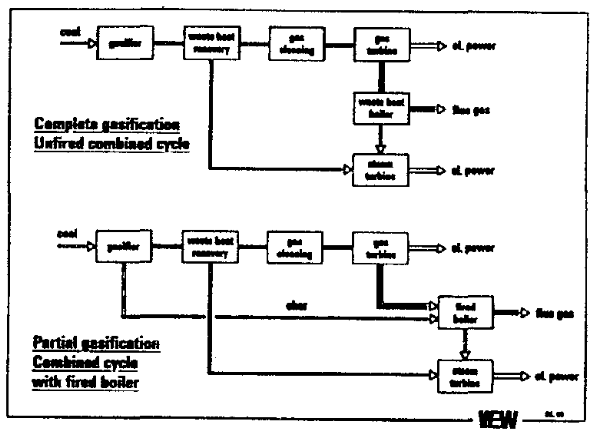

Fig. 2 Typs of combined cycle with integrated coal gasification

The waste heat recovery system and the various steps of gas cleaning follow the gasifier. The generated gas is used as fuel for the gas turbine, the waste heat is recoverd for steam production. The design of the steam turbine cycle is characterized by the outlet temperature of the gas turbine. In consequence of this, the steam pressure and steam temperature are on a lower level as it is known from conventional steam turbine plants. For a complete waste heat recovery it may be necessary to install a second or even a third pressure stage in the steam cycle. This steam is introduced at an appropriate point into the steam turbine.

The application of a partial gasification, that means gasification without complete coal conversion into gas, leads to a modified process design (Fig.2). Dependent on the conversion rate of coal into gas only a certain amount of the input energy is available in form of gas as a fuel for the gas turbine. The remaining residue in form of powdry char from the gasification process is fired in a boiler. The lower output share of the gas turbine compared with the process gasifying the coal completely does not mean, however, a disadvantage compared to the previously described process. Because of the better steam quality for the steam turbine process in contrast to the process with an unfired boiler an essential positive influence for the efficiency of the total process arises.

The two processes, which have been described are in principle appropriate for both brown and hard coal. Assuming for gas generation from brown coal the application of the advantageous fluidized bed technology, in principle a partial gasification will result, however, with a high level of coal conversion. The remaining relatively small residue of char can be burned in a supplementary fired boiler. Alternatively it is also possible to choose a process design as in the first example and to fire the remaining char in a separate boiler. The necessitiy of a high-valued waste heat recovery system for high temperature gasification processes (entrained gasifier) for achieving high efficiencies has already been pointed out. Gasification processes with low outlet temperatures like fixed bed or fluidized bed gasifiers in this regard offer an advantage for the thermodynamic of the process and for plant equipment.

For entrained gasification with high outlet temperatures in order to realize lower costs and to avoid material problems in the waste heat recovery system a so-called quench cooler is often suggested. This means to recycle cold gas and to mix it with the generated hot gas to reduce the inlet temperature of the heat exchangers. This measure results, however, in a reduction in the level of efficiency of up to 2 % points. Furthermore, a high valued waste heat recovery system means a design for generating steam with high pressure and high temperature.

Beside the waste heat recovery system of the gasifier the gas cleaning system means a process step with a not insignificant loss of energy. As the gas cooling must be restricted to a temperature of approximately 200 °C because of the formation of salts, this results in a proportional loss of heat. Furthermore, the consumption of energy in the gas cleaning process in form of steam and electric energy is also to be noted as a decident influence on the energy balance of the total process.

GAS CLEANING SYSTEM

The gas cleaning system follows after cooling the gas in the waste heat recovery section to a temperature of about 200 °C

(Fig. 3). According to the available technology the first step of the gas cleaning system consists of a scrubbing system for the removal of dust, chlorine, fluorine and some other substances contained in small quantities. By application of a high-valued gas dedusting system for example by candle filters or bag filters the input of solid particles into the scrubbing liquor can be reduced in such a way that a removal of solids from the generated waste water is not necessary.

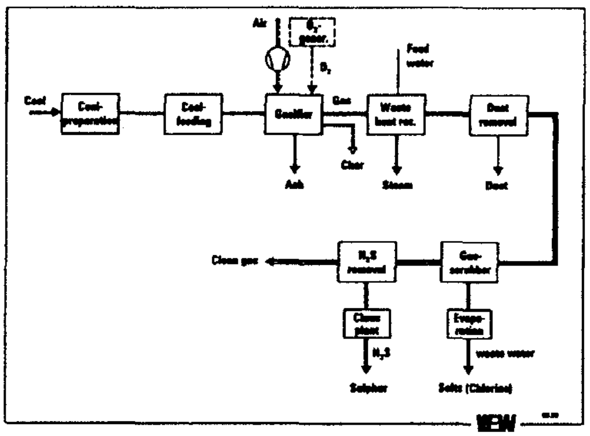

Fig. 3
Principle Coal Gasification

A certain amount of water must be continously be drawn off from the scrubber in order to retain allowable concentrations of individual substances, in particular the chloride content. Some gaseous substances, which are dissolved in the waste water must be removed. By stripping the waste water with steam not only ammonia, but also cyanides, sulphide and other organic compounds are removed. After stripping the make up of the waste water is possible by well known technologies.

All substances removed by stripping, especially acid gas components like H_2S, HCN and CO_2, can be given to the plants for desulphurization or sulphur recovery. The removed ammonia can be treated by special combustion steps or a catalytic cracking.

In the second step of the gas cleaning sulphur is removed and converted in a Claus Plant into elemental sulphur, which can be utilized in the chemical industry.

For separation of sulphur compounds from the coal gas principally the application of cold chemical or physical scrubbing processes as well as catalytic and dry adsorbtion processes can be considered. Although the before mentioned process offers the possibility to operate the gas cleaning process on a high temperature level for realizing further increase of efficiency of the power plant, the present state of development does not allow the application of such a technology. So, it is necessary to provide conventional well proven scrubbing processes.

A basic requirement for processes to remove sulphur from the gas is the selectivity to avoid the simultaneous separation of other gas components, which would mean a reduction of the mass flow in the gas turbine and consequently a reduction of the electric output. The removed sulphur compounds, mainly H_2S and COS, must be converted as far as possible into elemental sulphur.

The mentioned requirements are fulfilled by a lot of processes which are applied in large scale operation. The choice of the process depends on the sulphur concentration as well as on the exact gas composition. Generally it is true that physical scrubbing processes offer advantages for the purification of sulphur rich gas, whereas for cleaning gas with low sulphur concentration as it is generated from low sulphur coal or in air-blown gasifiers, cleaning processes based on amin like MDEA, Flexsorb, are advantages due to the consideration of the total costs.

Although the technology of desulphurization is well known and applied in many plants, processes must be tested under the conditions of combined power stations, that means the operation with rapid load changing in pilot and demonstration plants.

STATE OF DEVELOPMENT

For developing and testing the technology of coal gasification in a design, which is directed to the application in power plants, world-wide a lot of test and prototype plants were constructed. The main activities for developing and testing this technology are taken place in Europe, mainly in Germany, and in the United States. Also in Japan great efforts have been made to develop this technology. A demonstration plant with a combined cycle and an integrated coal gasification in the United States finished its operation in the meantime. For all processes the concern about the significant increase of efficiency to reduce the carbon dioxide emissions (greenhouse-effect) has reached a high importance after the emphasis in earlier years of the possibility to reduce the sulphur dioxide emission in a high degree.

By the operation of test and demonstration plants a good progress has been made in the recent years for the development of coal gasification and gas cleaning. Many plants showed a reliable operation of the gasifier with an acceptable availability and sufficient life time of the used materials. With all processes operating with high temperatures and in consequence of this with high outlet temperatures of the gasifier like it is given for entrained gasification, the recovery of waste heat is of particular interest. An energy efficient recovery of the waste heat is the basic requirement for realizing a high efficiency of the total process. As already mentioned in connection with the basic design of the combined cycle processes with integrated coal gasification solutions were proposed to simplify the recovery of waste heat (Fig. 4).

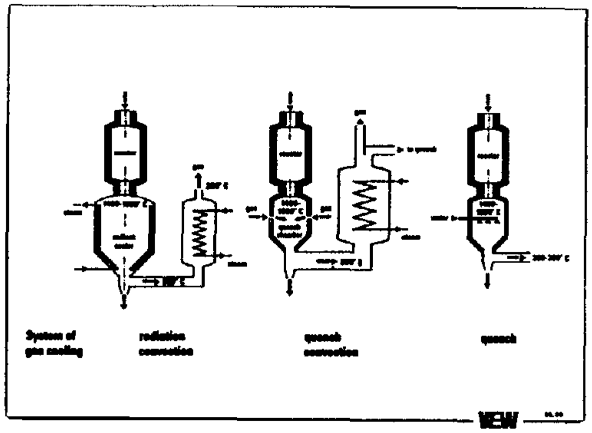

Fig. 4 Entrained Gasifier Waste Heat Recovery

These suggestions, which basically relate to the application of a quench cooler in order to avoid a radiant cooler, have a significant influence on the efficiency of the total process. In order to avoid a radiant cooler water can be injected instead of the so-called gas quench, which happens by recycling of cold gas. Because of the loss of vaporization heat an extremely high reduction of the efficiency of the process is effected by such a measure. The application of a quench cooler for reducing the gas temperature from approximately 1400 or 1600 °C to approximately 800 °C enables to avoid a radiant cooler and to provide only a convective cooler. By these means the problems associated with corrosion and fouling of heat exchangers at high temperatures can be avoided. The compact proportions of the convective heat exchangers lead to a reduction of the plant costs. Only in a single prototype plant operating according to the principle of an entrained air-blown partial gasification of bitumious coal (VEW process) has so far been a success in producing high super-heated steam with high pressure in a waste heat recovery system which was equipped with a radiant cooler.

The coal feeding and metering system is one system of the total plant, which has special importance for the function of the gasification process. This is especially true for entrained gasifiers, whose exact function is dependent on the exact coal feeding and metering system. An exact metering is necessary in order to always maintain the wanted ratio between coal and oxygen. This is on the other hand the prerequisit for a steadily continous coal conversion on the wanted high level. In both, the overall system and the valves to be used improvements have been made in course of the years. The availability of valves with a sufficient life time is a prime requisit for gasifiers according to the principle of fixed or fluidized bed.

In many places hot gas cleaning systems are developed. By avoiding gas scrubbing and heat losses on the lower temperature level an increase of the efficiency is achieved. However, the hot gas cleaning is a relatively complicated process. Because the coal gas contains various escort subtances, which must be removed, the hot gas cleaning system consists of several stages. The regeneration of the absorbent is necessary in all stages assuming that a deposit of the reacted material is impossible. In view of the characteristics of the individual substances a separation will take place on different temperature levels. This means to heat up or to cool down the gas between the various stages of the cleaning process. Further development work in this field of hot gas cleaning is awaited with some interest.

EXAMPLES OF COMBINED CYCLE PROCESSES WITH INTEGRATED COAL GASIFICATION

Combined Cycle Process with Brown Coal

As the fluidized bed gasification using the high temperature "Winkler" gasifier plays a dominant role and as at this present time there is a definite plan to build a 300 MW demonstration plant with the name of KoBra (Kombikraftwerk Braunkohle = combined cycle power station based on brown coal). We shall use this as a basis for the following example of the overall process. It is planned to put the plant into commission in autumn 1995. The layout of the plant is shown in illustration no. 5.

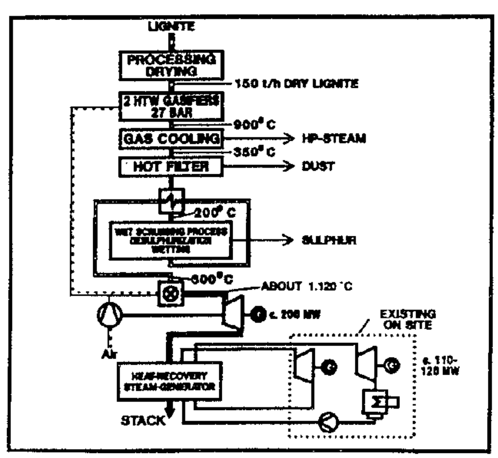

Fig. 5 KoBra Demonstration Plant (RWE)

The brown coal has a water content of approximately 55 % and after grinding to particle size of less than 6 mm, it is dried to approximately 12 % remaining moisture using the fluidized bed drying process with integrated waste heat recovery system (Wirbelschichttrocknungsverfahren mit integrierter Abhitzenutzung - WTA) developed by Rheinbraun, which is thermodynamically very favourable. This new drying process is mainly responsible for the high level of efficiency of the whole plant.

The gasifier with the subsequent process steps is constructed with a two-line design with 75 t/h throughput each in the demonstration plant. In order to enable the scaling up of the gasifier to a throughput of 150 t/h as it is necessary in combination with a gas turbine of 200 MW without a risk in two steps. The experience for design and construction of the gasifier was gained in a test plant with a capacity of 30 t/h.

In the before mentioned example the fluidized bed gasifier is air-blown. The gasifier is followed by the waste heat recovery system for cooling the gas from 900 °C to 350 °C with the production of high pressure steam (120 bar, 30 K superheated). The dust removal is achieved with ceramic candle filters at a temperature level of 350 °C. The cleaned cold gas is heated to a temperature of approximately 300 °C before entering the gas turbine by recovering the waste heat of the raw gas. The raw gas enters the gas scrubbing system with a temperature of 200 °C for removal of all substances, which can be solved in water.

After reheating the gas to a temperature of 175 °C with a catalytic conversion of the sulphur component COS into hydrogen sulphide H_2S the final cooling to 40 °C and the desulphurization of the gas follows together with the conversion of H_2S in elemental sulphur by a Claus Plant. The following saturation of the cleaned gas with water reduces the nitrogen oxide emission of the gas turbine and at the same represents the first step of reheating the gas.

All the gas produced is fired in the gas turbine. For an air-blown operation of the gasifier the compressor of the gas turbine delivers the oxidizing agent by means of an additional compressor. For an oxygen-blown operation of the gasifier the compressed air coming from the gas turbine's compressor is directly fed into the air separation plant for generating oxygen. The nitrogen produced in the air separation plant is mixed with the coal gas before entering the burners of the gas turbine to reduce the nitrogen oxide formation. The exhaut gas from the gas turbine with a temperature of about 550 °C is recovered for steam production. The high pressure steam recovered from the gas cooling system is fed into the waste heat recovery system of the gas turbine for further superheating.

The total output of the demonstration plant is about 320 MW. By the combustion of the residues of the gasifier in a fluidized bed boiler additionally 26 MW electric output are generated. The demand for auxiliary energy of the total plant is about 50 MW for an air-blown operation of the gasifier and about 60 MW for an oxygen-blown operation. In the total balance the following net efficiencies of the plant are reached:

for an air-blown operation of

the gasifier approx. 45,5 %;

for an oxygen-blown operation of the gasifier (additional injection of steam) approx. 45 %.

Combined Cycle Process with Hard Coal

For the description of the combined cycle with hard coal the entrained gasification, which plays an important role in the current development, was chosen for the shown example (Fig. 6).

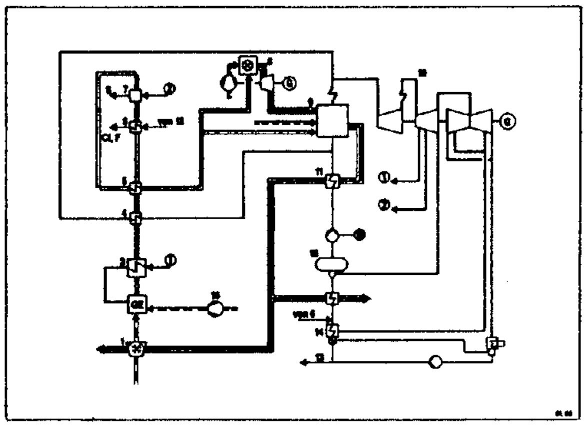

Fig. 6 Combined cycle with complete gasification (O_2)

In case of a complete gasfication of coal the gasifier is blown with oxygen generated in an air separation plant, which is directly coupled to the combined cycle process. The various steps of gas cooling and gas cleaning follow the gasification process. The recovered waste heat steam from gas cooling is directly fed into the steam turbine of the combined cycle process. For cooling the gas in the lower temperature range a heat exchange between raw and clean gas is provided. Condensate and feed-water are completely preheated with the waste heat recovered from the gas turbine's exhaust. So, the regenerative preheating, which is a characterstic part of a normal steam power plant can be avoided. The performance ratio between the gas turbine and the steam turbine has a value of about 1,5. The output share of the gas turbine is lower compared with natural gas-fired combined cycle plants because a certain amount of the input energy is converted into steam and finally the demand for auxiliary energy and all losses in the process are on a higher level than in a natural gas-fired combined cycle plant.

The combined cycle process with integrated partial gasification of coal according to the principle of an entrained air-blown gasifier is presented as an alternative (Fig. 7).

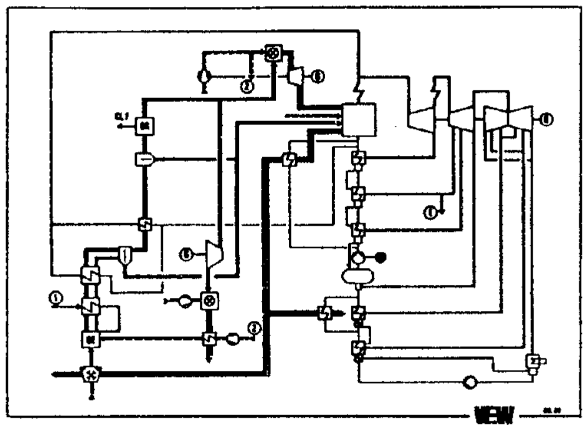

Fig. 7 Combined cycle with partial gasification (air)

The coal conversion rate lies between 60 and 80 %. The unconverted residue from the partial gasification process in the range of 20 to 40 % in form of powdry char serves as fuel in a supplementary fired boiler by utilizing the remaining oxygen content in the exhaust gas of the gas turbine. In this concept the design figures of the steam turbine process are not determined by the outlet temperature and the waste heat characteristic of the gas turbine. High-valued steam data can be realized. For the combustion of the remaining char from partial gasification a fluidized bed furnace can be applied, which enables by addition of limestome to remove the sulphur contained in the char. The gas cleaning system can be simplified by renouncing the sulphur removal system and introducing the exhaust gas of gas turbine containing sulphur dioxide in the furnace of the fluidized bed boiler. The sulphur content is absorbed there by addition of lime. The separation of some other escort substances in the coal gas like NH_3 and HCN, which contribute to the formation of nitrogen oxide in the combustion chamber of the gas turbine is not necessary, as the chemical equilibrium in the fluidized bed combustion depending on the temperature in the furnace leads to a low formation of nitrogen oxide. The wanted low emissions can be reached without flue gas treatment. The output share of the gas turbine in this process is on a lower level in contrast to the previously mentioned process with a complete gasification.

For developing a combined cycle with integrated partial gasification of coal, a plant according to the principle of the VEW technology has been operated in Germany for many years. This plant with a coal throughput of 10 t/h was equipped with a complete gas cleaning system. According to the design of the plant for the first time world-wide in a plant for coal gasification super-heated steam with high pressure was produced from the waste heat of the gasifier (180 bar/530 °C). This steam was immediately fed into the turbine of the connected power plant. The process technology is thus available for scaling-up and demonstration.

The efficiency of the total process is about 45 % for application of gas turbines with an inlet temperature of 1100 °C. The design of the steam cycle with conventional steam data was provided. Furthermore, a re-cooling mode of operation was assumed as it is usual at sites in Germany. Gas turbines as they can be expected in future with inlet temperatures of 1250 °C would raise the process efficiency to 47 %. Together with high-valued steam data, an efficiency of more than 48 % can be reached.

EFFICIENCY AND ENVIRONMENTAL ASPECTS

The efficiencies of each process greatly depend on the individual design, for example the type of waste heat recovery and the system of gas cleaning. The several steps of the process are determined by the special operation conditions of the gasifier, the gas composition and the escort substances in the generated gas. A further important factor, which has a decisive influence on the level of efficiency of the whole process, is the inlet temperature of the gas turbine.

For the combined cycle process with integrated gasification of brown coal as it was described above an increased gas turbine inlet temperature of 1120 °C to 1170 °C arises the mentioned efficiency to 47 %. According to the literature there are differing values attributed to the wide range of combined cycles for hard coal. This depends not only on the factors mentioned above but also on the special process design and the type of combined cycle process. The illustration shows a relatively wide spread for the achievable level of efficiency (Fig. 8). The wide range is the result of the fact that the level of efficiency for both, the state of development already achieved and the development target being worked towards are cited for the individual methods. At present, it cannot be foreseen to what extent the development targets will be achieved in each case.

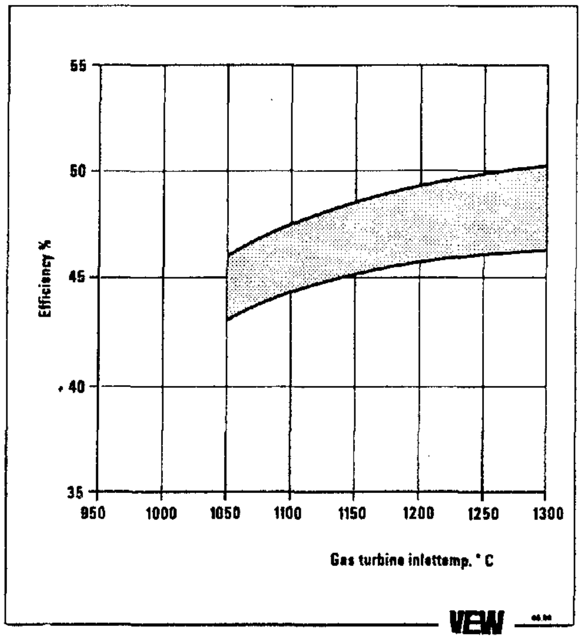

Fig. 8 IGCC; Efficiency

In contrast to conventional hard coal-fired plants the mentioned efficiencies mean a reduction of the fuel consumption of about 20 %. The efficiency of the brown coal-fired combined cycle means a reduction of the fuel consumption of about 30 % in contrast to existing plants. The same reduction is reached for the carbon dioxide emission.

The technology of combined cycle with integrated coal gasification provides in an advantageous way the means to remove all pollutants. The removal of all substances is achieved during the process of converting coal into gas through the technology and the equipment, which is necessary for this process. In contrast to the flue gas treatment, almost elemental sulphur is generated, which can be utilized in the chemical industry. Besides the often mentioned advantage for removing sulphur in a high degree we must also take into account the necessity of removing other substances as well as the make-up of waste water. Apart from the reduction of carbon dioxide emission as a result of the increased efficiencies of the plant the absolute reduction of some emissions is also to be valued.

For some year, a reduction of plant cost by means of the new technology has been calculated, but the experiences gained by the current development work and demonstration projects showed that this cannot be expected. The exact costs of this new technology can basically better be calculated when large scale demonstration plants are in operation.

Regardless of the state of development and the attractiveness of this technology a realistic assessment must be made of the time schedule for scaling up this technology. At present, demonstration plants are planned or even under construction, which will allow testing of some process steps and typical equipment under large scale conditions. It will only be possible to construct bigger plants after positive experiences have been gained by these demonstration plants. A greater number of power plants built according to the principle of combined cycle with integrated coal gasification can only be realized after the year 2000. Thus, an estimation can be made for the possibility of using this new power plant technique for the reduction of carbon dioxide emission. Besides the availability of an attractive technology the demand of capital for realizing the application of this new plant type in a large extent should be considered.

EXPERT SYSTEM FOR THE EARLY DETECTION OF FAULTS IN THE FUNCTIONING OF THERMAL POWER STATIONS

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ABSTRACT

The operation of industrial boilers is already quite automated, assuring high efficiency and continuous service. The technology of expert systems can help operating staff by providing them helpful and detailed information as soon as an anomaly appears.

This paper describes an expert system developed by the Research Center of the French National Coal Company (Cerchar), with application to coal and pulverized coal boilers. It presents the structure, the functionalities and the first results.

This expert system operates like a human expert. It makes a continuous overview on the boiler operation, at the moment in the areas of combustion, water/steam circuits and coal pulverizers.

The end goal of the system developed by Cerchar is to obtain better quality in operation, and thereby cost savings, mainly in industrial boilers and power plants pulverized coal units.

INTRODUCTION

This paper describes an expert system developed by the Research Center of the French National Coal Board (Cerchar), with application to coal and pulverized coal boilers. The development of the system began in 1987 and led to the implementation in 1989 of an industrial prototype at the Cerchar coal research laboratories located in Mazingarbe (north of France), on a spreader stoker boiler rated at 15 tph (33,000 lb/hr).

A prototype for pulverized-coal operation was installed on the unit 6 (600 MWe) of Emile Huchet power plant in Lorraine (East of France), in september 1990.

The computer application is an on-line, real-time monitoring system which, once the normal operating regime of the unit has been observed, diagnoses anomalies as they occur and gives explanations to the operator. With this information, it becomes possible for him to optimize boiler operation and the maintenance programme.

EXPERT SYSTEM DEVELOPMENT

The system imitates the deductive reasoning of the expert. The reasoning is initiated when some facts, called symptoms, are detected. A symptom may be a difference from normal values, a drift, or a sudden variation which can be very short.

Dysfunction hypothesis are automatically generated when a symptom appears, and are confirmed, modified or retracted, depending on the facts present in or entering the data base. The system is able to explain its reasoning in case of diagnosis (see Fig 1 below).

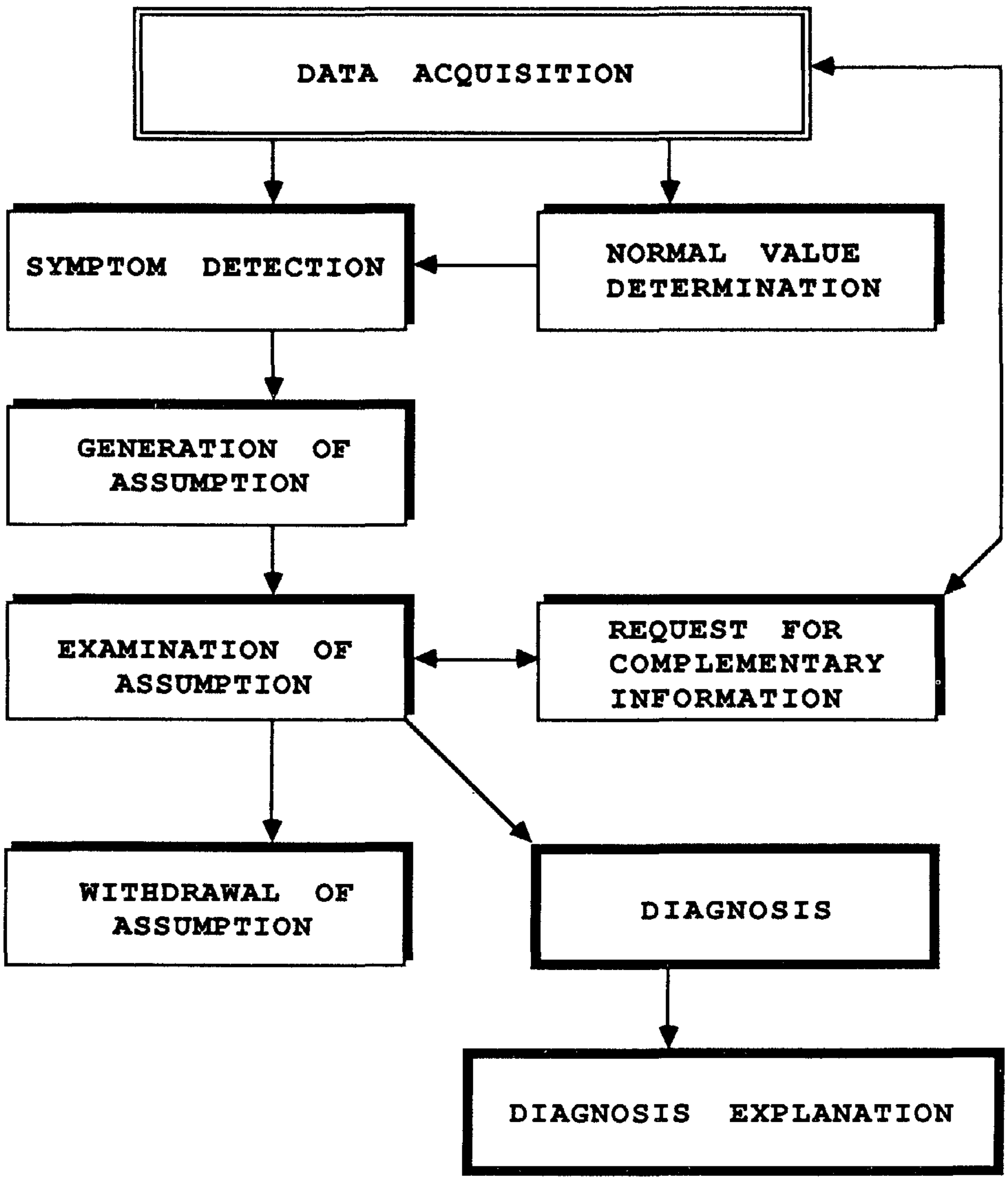

Fig.1. Working principle of the system

The system has been developed with the ART expert system shell, a high-performance tool developed by Inference Corporation (California, USA) and distributed in France by SYSECA (Thomson Group). The ART generator is based on a first order logic, is written in the Common-Lisp language, operates in a UNIX environment and is implemented on a SUN workstation.

The knowledge base organization uses the ART "schema" concept, which provides for the objects description, with common properties and the relationships between these objects.

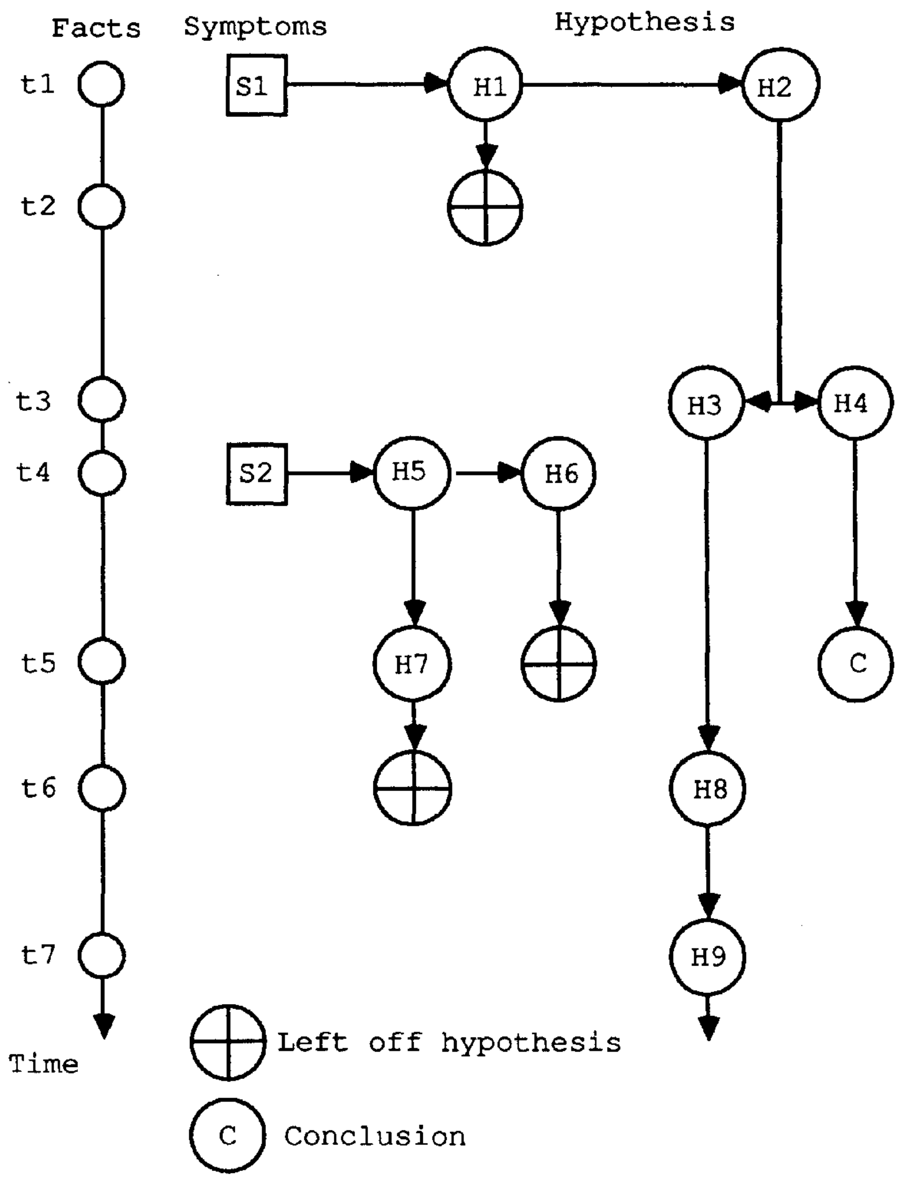

Fig.2. Continuous diagnosis principle

Furthermore, thanks to the ART "viewpoint" mechanism, it is possible to structure the base and to have several lines of reasoning developed in parallel, in independent contexts (see Fig. 2). A viewpoint is created to formulate an hypothesis.

Each context is composed of a set of facts, the validity of which is limited to a subset of the knowledge base. This mechanism makes it possible to carry on reasoning in different directions and eventually to profit from the progress made in one or more of these directions.

Any new fact may be present in one or more of the contexts developed, to ensure that the relevant events be taken into account in all the reasonings. This is why the system is real-time.

The development team included experts (specialists and very well-trained operators), who have analysed their experience in terms of appliable knowledge to non-predicted situations. The organisation of the knowledge base gives an open expert system, easily extendable to a wider knowledge area, and adaptable for an increasingly accurate supervision of the process.

The knowledge base is made of two main parts, the first one devoted to the plant description (arranged to be easily adapted to any plant configuration) and the second one to diagnosis rules.

The main structural aspects are the following ones:

- the system explains its diagnosis and is able to justify it at the request of the operator,
- there is no operating limit on the number or the simultaneity of the symptoms indicating a malfunction,
- it is easily adaptable to any plant configuration,
- the system operates in an open-loop mode, without any action on the plant control system. Its sole function is to provide information to the operator, who may be questioned. His answer makes the diagnosis easier or faster, but if he does not reply, this does not interrupt system reasoning.

APPLICATION CHARACTERISTICS

An essential characteristic of the system is the automatic and continuous monitoring of the available process data. It works on-line, without direct action of the operators in the control room. They may be questioned. Their answer makes the diagnosis easier or faster, but if they do not reply, this does not interrrupt system reasoning.

On a power plant boiler, the data are very numerous, in the hundreds or thousands. They are not given equal consideration. Only some of them (about 250 for instance) are monitored.

For processes with a relatively high inertia, the time period for data collection may not to be very short. Data collection occurs every ten seconds for this application. These data are treated and may give symptoms, the other being used for additional information to the expert system or for explanation to the operators.

Some particular values (especially with vibratory characteristics) need special treatment. The interesting characteristic to follow is then a variation in the amplitude or in the frequency, or a change in the spectrum. The richness of such information, combined with the current development of the analysis methods will lead to use them later for the monitoring of the process.

Until now, no additional sensor has been installed on the units. The data are collected from the control system computer, or directly at the source. The data acquisition system classifies and eventually stores them. They are sent by serial link to the real-time system VX WORKS on VME rack, and then treated and transformed into symbolic data. These symbolic data are sent by an ETHERNET network to the SUN station on which the expert system is implemented.

Among the different kinds of data treatment, the difference between operating and normal values is automatically monitored in a so-called "reference module". This module imitates the expert reasoning when he compares the data to what they should be under normal operating conditions. This module is able to work during both steady-state periods and load variations.

SCOPE OF DIAGNOSES

It is possible to distinguish two kinds of diagnoses : "short" and "long" term. The former concerns events such as air inleakages, water or steam leaks, because they have to be detected before the effects of the control system action are felt. The latter concerns tube fouling or small drifts for instance, because their detection is made over longer periods of time.

On the Mazingarbe spreader stoker boiler, the system looks at any perturbation an the air, flue gas and water/steam circuits. The main dysfunctions which may be detected are : air inleakages, formation of uncompleted combustion products, tube fouling and steam or water leaks. The knowledge base allows early detection of leaks, and may be extended to the detection of risky situations and to the location of the leaks.

On the Lorraine industrial prototype, it also detects incidents on the coal pulverizers (overcharging, changes in the feedstock, wear...).

Other work is being carried out at Cerchar for improving the diagnoses in terms of better use of the existing information from the process data. The use of signal processing techniques, and particularly harmonical analysis of boiler noise, could lead to a complementary diagnosis method.

FIRST RESULTS

The first on-line tests have been carried out on the Mazingarbe spreader stoker boiler, which was modified in order to allow the simulation of water/steam leaks. These tests have been successful. The system gives a proper diagnosis and determines the approximate location of the problem. When the problem is not severe, the system provides information on what seems to be wrong. The diagnosis may appear a few minutes later, when the system has gathered enough accurate information to do so. This response time is due to the process inertia.

On this type of industrial boiler, the system is able to see a 180 kg/h steam leak (1,2 % of the nominal output) and 500 Nm3/h air inleakage (estimation, which represents roughly 3 to 4 %).

A prototype was installed on a 600 MWe unit at Emile Huchet power plant (East of France) in September 1990. The results are very promising, despite of the difficulties encountered (continuous load variations combined with a coal feedstock of bad and changing quality). At the moment are implemented on-line and continuous estimations of the coal pulverizers behaviour and of the state of the water/steam circuit.

CONCLUSION

Such an expert system application using existing information from the process has been demonstrated to be possible. The first results obtained by Cerchar with the two prototypes on an industrial boiler and a power station unit of 600 MWe are very promising.

The on-line diagnosis system is an additional tool for power plant control rooms, in which it must be fully integrated. Then the conditions will be present for a new man/machine relationship.

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THE BROWN COAL INDUSTRY IN THE REUNIFIED GERMANY

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ABSTRACT

The brown coal industries in West Germany and in the former German Democratic Republic saw completely different developments resulting from the different economic systems.

In the energy supply of the old Federal Republic of Germany, the free market economy has produced a sound energy mix with brown coal as a primary energy source accounting for 8 %. In East Germany, on the other hand, brown coal - being the only domestic primary energy source of major importance - reached a disproportionate share of 70 % as a consequence of state planning measures within the scope of the controlled economy system.

To avoid expensive energy imports and cover the rising demand, the government of the former GDR strongly stepped up brown coal mining and use. Before reunification, the East German brown coal output amounting to 300 million annual tonnes was about three times as high as that of West Germany.

The latter has economically mineable brown coal reserves of approx. 35 billion tonnes (12 billion tce). Together with the 21 billion tonnes (7 billion tce) of the former GDR, the reunified Germany accounts for more than 50 % of the European and more than 10 % of the worldwide brown coal reserves.

In East Germany, brown coal mining and use for power and heat generation and in particular for chemical production have involved serious environmental problems due to a lack of appropriate countermeasures and capital expenditure.

The reunification on October 3, 1990, also saw the introduction of West German environmental legislation with transitional periods for its enforcement in East Germany. In the medium term, the free market economy is expected to adjust energy prices to the level of those in West Germany and the European Community.

The energy requirements will be met by a manifold supply of imported hard coal, oil, gas, nuclear energy and brown coal. Billions of DM will have to be invested to shape the energy sector, in particular the brown coal industry, to the Western structure and high environmental standard.

In the long run, brown coal as a competitive domestic energy source will reach a share of approx. 15 % in the primary energy consumption of the reunified Germany, thus providing a secure basis for the energy supply of the country.

BROWN COAL RESERVES IN THE FEDERAL REPUBLIC OF GERMANY

Thanks to the large economically mineable brown coal reserves of today's Federal Republic, brown coal being a competitive, politically secure raw material will make a major contribution to the country's energy supply even on a long-term basis.

Of the worldwide brown coal reserves amounting to approx. 523 billion tonnes (174 billion tce), which can be mined economically using state-of-the-art technology, the reunified Germany with 56 billion tonnes accounts for more than 10 % (Figure 1).

Approx. 35 billion tonnes occur in the Rhineland (old Federal States) and approx. 21 billion tonnes are distributed over the eastern mining districts (new Federal States), with the Halle/Leipzig area accounting for approx. 8 billion tonnes and Lusatia for approx. 13 billion tonnes (Figure 2).

SITUATION OF THE BROWN COAL INDUSTRY BEFORE REUNIFICATION

The brown coal industries in Germany's western and eastern mining districts saw completely diverging developments resulting from the different economic systems in West Germany and in the former German Democratic Republic. While in the former Federal Republic brown coal had to compete with other energy sources under free market conditions, brown coal extraction and its use in East Germany were strongly stepped up by the Government with the object of ensuring self-sufficiency and saving foreign currency. This planned economy in the field of energy did not consider economic efficiency at all, and environmental protection, an indispensable factor in Western countries, was completely ignored. So, several opencast mines and processing plants were operated uneconomically, and extremely long and cost-intensive haulage distances were tolerated. The cost burden, however, could not be passed on to the prices paid by the final consumer, the energy sector was subsidized, and due to the lack of appropriate incentives to save energy a constant increase in energy consumption was recorded. To cut the cost involved in power generation, the necessary investment, in particular in respect of environmental protection, was in most cases dispensed with. So, the necessary reclamation of the exhausted opencast mines was performed on an inadequate scale only, and power plants were not equipped with desulphurization systems. This is why major part of the eastern brown coal mining industry is marked by obsolete, technically worn-out conditions and completely inadequate environmental protection facilities.

THE IMPACT OF REUNIFICATION ON THE BROWN COAL MINING INDUSTRY

With Germany's reunification on October 3, 1990, the eastern brown coal districts have been subjected to strong competition within the world energy market. Due to the long distances, West Germany's brown coal market is not expected to exert major influences. But there is a direct competition between the East German brown coal districts of Halle/Leipzig and Lusatia. This competition is strongly determined by the different qualities of the coals occurring there (see Figure 3). While the Lusatian coal is characterized by a minor heating value, it has clear advantages in respect of its sulphur content.

The East German brown coal industry is presently undergoing far-reaching adaptation processes which were mainly triggered by the following factors (see Figure 4):

- Since reunification, West German environmental protection legislation with appropriate transitional arrangements has been valid in East Germany.
- Different cyclical and structural trends in the power and heat markets.
- Restructuring and adaptation with the object of returning to private ownership.

To assess the situation and make further forecasts for the eastern brown coal industry, it is in many cases possible to use the knowledge acquired in the Rhineland district during the last 40 years; similar developments and adaptation processes took place there under free market conditions, though at a slower pace.

IMPACT OF WEST GERMANY'S ENVIRONMENTAL PROTECTION LEGISLATION

The following environmental protection legislation or regulations which came into force on the day of reunification have a major impact on the eastern brown coal industry:

- As laid down in the 'Bundesimmissionsschutzgesetz (1. BimschV)' (First Federal Act on Air Pollution Control and Noise Abatement) small-scale furnaces are no longer allowed to burn fuels having a sulphur content of more than 1 % with effect from 1995.

As a result, with a lead time of approx. one year no briquettes are permitted to be produced for domestic heating purposes in the Halle/Leipzig district.

- The 'Großfeuerungsanlagenverordnung (GFAVO)' (Regulation Governing Industrial Furnaces) inter alia restricts the sulphur emissions of power plants depending on the plant's capacity and operating life. It is in particular industrial furnaces which will have to observe the limit values as specified in the 'Technische Anleitung Luft (TAL)' (Technical Directive Governing Air Pollution).

Since the East German power plants work without flue-gas desulphurization systems and even the electrostatic precipitators are often in a poor condition, the 'GFAVO', i. e. the Regulation Governing Industrial Furnaces, is expected to trigger an investment programme for those boilers continuing operation; this approach will be comparable to the programme dealing with the retrofitting of flue-gas desulphurization systems which was implemented in the Rhineland in the mid-80s and involved investment costs of DM 6 billion. While the West German brown coal processing plants have constantly been adjusted to comply with the 'TA-Luft' (Technical Directive Governing Air Pollution), substantial investment will be required in the eastern brown coal industry due to the lack of environmental protection guidelines. The adaptation to the current environmental protection standards will call for substantial investment in the eastern brown coal industry.

IMPACT OF MARKET TRENDS ON POWER AND HEAT

The major field of brown coal application in the Federal Republic is the public power generation sector and the heat market for industry and private households.

In 1989, a total of 440 TWh was generated in the old Federal States. Of this, the Rhineland accounted for about 78.6 TWh, i. e. 17.9 %, which were produced from 87.4 million annual tonnes of brown coal in power plants having a total capacity of approx. 10,000 MW. This share, brown coal has in West German power generation, is assumed to remain more or less constant on a long-term basis (see Figure 5).

The contribution, brown coal makes to the long-term power supply in the East German States, is somewhat different. In 1989, East Germany produced 119 TWh of electricity, 98 TWh of which were generated in public power plants; 81.5 % of the public power supply (78.4 TWh) is based on brown coal. This corresponds to approx. 98 million annual tonnes of brown coal used. According to estimates an additional amount of 10 to 20 million annual tonnes of brown coal was employed for power generation in industrial power plants; this means that a total of 110 to 120 million annual tonnes of brown coal was consumed by the power sector.

Due to the stagnant industry, power requirements are expected to decrease until 1995 and then to reach the present level only after the year 2000.

According to present assumptions the capacity of brown coal-based power plants supplying the public sector which now amounts to 16,000 MW will be reduced to approx. 8,000 MW in the long run. But about 50 % of these plants would still have to be built while the existing ones accounting for 4,000 to 5,000 MW would have to be retrofitted with flue-gas desulphurization systems. There is a vehement discussion underway dealing with the question of whether it is politically feasible to meet part of the new power plant requirements by nuclear energy. On the assumption, however, that this demand will be covered by the addition of brown coal-based power plants, the coal needed for power generation in the new Federal States is estimated at 80 to 95 million annual tonnes.

Together with the West German share this results in approx. 150 to 180 million annual tonnes of brown coal required by the power-generating sector on a long-term basis.

The second major field of brown coal application is the heat market for private households and industry which is subject to keen competition under free market conditions. In the Rhineland, briquette sales to private households have sharply been declining since the 60s, and are now recording low, but relatively stable consumption figures amounting to 0.9 to 1.2 million annual tonnes. With new products launched into the industrial sector such as industrial briquettes (1.2 million annual tonnes), pulverized brown coal (approx. 2.5 million annual tonnes), brown coal coke (0.2 million annual tonnes) and fluidized-bed coal (0.3 million annual tonnes - being in the market for about two years) this severely shrinking market has succeeded in making good lost ground so that now a total of 15 million annual tonnes of run-of-mine coal equivalent can be sold. According to forecasts, more intensified consulting efforts in the field of application technology will help promote this industrial market.

In the former German Democratic Republic approx. 70 % of domestic heating was in 1989 still based on brown coal briquettes, and further 23 % was supplied by district heating systems which were likewise mainly fed by brown coal. Oil heating systems were practically unknown. Due to the cancellation of subsidies 1991 is already expected to experience a plunge in briquette sales from so far 17 million annual tonnes to 10.5 million annual tonnes; until the year 2000 this figure will have further decreased to 3.7 million annual tonnes. This means that restructuring of the domestic fuel market with a shift from coal to heating oil - similar to that West Germany went through in the last 30 years - will also occur in the new Federal States, though in a much shorter period.

After reunification, the industrial market for brown coal and its products will in the long run develop in approximately the same way as that in the West German States due to the energy mix offered. But the question arises how much time this adaptation process will require and in what way an application-specific customer consulting can succeed in maintaining shares in the declining market. According to forecasts the raw coal used in the industrial sector will fall from 43 million annual tonnes in 1989 to 8.5 million annual tonnes until 2000. Coke and gas production on the basis of industrial briquettes is expected to cease for environmental and cost reasons in the next few years. The industrial briquette market will also be confronted with sales dropping to approx. 2 million annual tonnes. The new products, pulverized coal and fluidized-bed coal, for which new plants will still have to be constructed, will offset part of the declining output.

On the whole, forecasts for brown coal consumption in the industrial and domestic heat markets see a drop from at present 150 million to 20 or 25 million annual tonnes in the year 2000.

Adding up the brown coal amounts forecast for the reunified Germany and assuming an approximately constant brown coal output of 120 million annual tonnes from the western mines and of 95 to 115 million annual tonnes from the eastern mines, we obtain a total of about 215 to 235 million annual tonnes in the long run. This corresponds to a primary energy share of 13 to 15 % (see Figure 6).

ADAPTATION MEASURES IN RESPECT OF OPENCAST MINES AND CONVERSION PLANTS

Opencast Mines

In the eastern brown coal mining districts, the individual opencast mine capacities have to be adapted to the declining brown coal consumption in the power generating industry, and in particular to that in the heat market; thus, the number of opencast mines will be reduced to a few large-scale operations. As a consequence of the varying coal qualities and existing power plants, the Halle/Leipzig and Lusatian districts will undergo different adaptation processes.

Since due to the sulphur-rich brown coals in the Halle/Leipzig district briquette production for the domestic fuel market will cease in the next two or three years and the larger brown coal-fired power plant units continuing operation will be supplied with coal from the Lusatian district, the Halle/Leipzig mining district is faced with the question to what extent it will be feasible to ensure brown coal sales to district heating systems and industrial power plants on a long-term basis. Assuming estimated sales of 30 to 40 million annual tonnes mining will concentrate on a few opencast mines. This year, 9 out of 19 opencast mines have already been shut down in the Halle/Leipzig district.

In the long run, the Lusatian district is expected to record brown coal sales of approx. 80 to 90 million annual tonnes used for power generation and 20 to 25 million annual tonnes for conversion. Thus, output will decrease by 50 %. Only 6 out of the present 18 opencast mines will continue operations, i. e. those mines which are even today operated efficiently and are equipped with up-to-date machinery.

A similar concentration process has taken place in the Rhenish brown coal industry in the last 30 years. While in 1959, 16 opencast mines produced a coal output of 80 million annual tonnes, it was only five mines which yielded 120 million annual tonnes in 1984. Today, mining operations have been concentrated on four mines, and in the long run it will be only three mines ensuring brown coal supplies from the Rhenish district.

Conversion Plants

So far, almost half of the conversion plants in the Halle/Leipzig district have been shut down. The low-temperature carbonization plants at Böhlen and Espenhain have already ceased operation for environmental and cost reasons. At present, efforts are made to find low-priced processes based on sulphur-rich brown coal, in particular in order to continue fulfilling the existing supply commitments in the field of district heating. Here, it will be advantageous to use the low-emission fluidized-bed combustion process yielding 100 to 400 tonnes of steam per hour; this technology has been successfully applied by the Rhenish mining industry for several years.

During the next 10 years, the conversion capacities in the Lusatian mining district will be cut back from a present dry coal capacity of 31.2 million annual tonnes to approx. 8 million annual tonnes in 2000, depending on how sales will develop in future (see Figure 7). The conversion activities will possibly be concentrated on one or two plant complexes which, however, will call for technical improvement measures involving considerable investment, above all in environmental protection.

The conversion plants in the Rhineland have experienced similar concentration developments. While after 1950, 20 briquetting plants produced 13 million annual tonnes of dry coal, Rheinbraun, i. e. the mine operator, at present has four plants with a dry coal capacity of approximately 7 million annual tonnes.

IMPACT OF RESTRUCTURING WITH A VIEW TO PRIVATIZATION OF ENTERPRISES

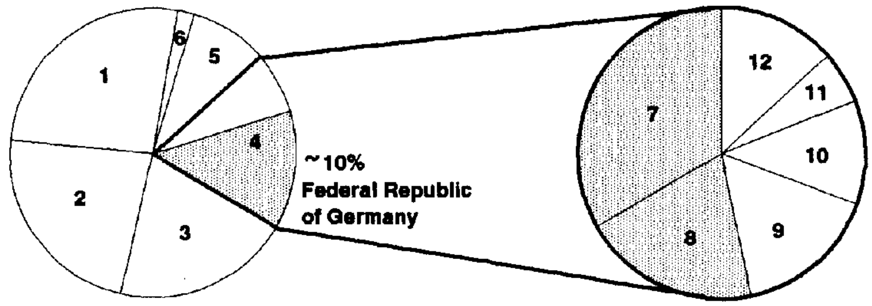
Before reunification, the eastern brown coal industry was divided into three large-scale collective combines (state-owned enterprises) which were directly responsible to the energy ministry. Today, the 'Treuhandanstalt' (institution in charge of privatization of state-owned enterprises) owns these enterprises which are now corporations on the way to privatization. Their organizational and operations structures are being reshaped with the object of meeting today's standards which can be compared with those prevailing in the West German brown coal industry.

Before reunification, approximately 150,000 people were employed by these three large-scale collective combines having a total brown coal mining output of 310 million annual tonnes. If we compare this figure to that of the West German brown coal mining industry where for an annual output of 100 to 120 million tonnes approximately 17,000 people were employed in 1990, and take the latter as a standard for a competitive energy production in the long run, it will be necessary to slim the workforce in the eastern mining districts to one third. In 1990, the employment level already decreased by approximately 25,000 to 107,000 in East Germany.

To initiate privatization, opening balance sheets in German Marks have been prepared since reunification, i. e. fixed and current assets have been revaluated. In privatization, the legacy of deficiencies left by the former mine operators has involved particular problems in the fields of ecology and economy.

As laid down in the Federal Mining Act, the mining operator undertakes to reclaim the areas used for exploitation. In the past, this commitment was fulfilled by the state-owned mining enterprises on a very limited scale only. In addition, a great number of industrial and domestic waste dumps are located in former mining areas, the removal of which along with the still outstanding reclamation work will involve several billions of German Marks. These costs cannot be borne by the brown coal mining companies of today which are orientated towards the free market system. So, financing of the cost burden, which the legacy of deficiencies left by the former mine operators has entailed, will be up to the government. As fas as working-off of this 'legacy' in practice is concerned, the brown coal industry, e. g. within the scope of a special-purpose association, will contribute its know-how, equipment and employees.

The question of whether privatization of the brown coal industry will succeed in East Germany will mainly depend on the approach to the problem of how to deal with the existing difficulties in the fields of ecology and economy.



World 523

1	USSR	137
2	China	120
3	North America	105
4	Europe	105
5	Australia	46
6	Others	10

Europe 105

7	Federal Republic of Germany (old)	35
8	Federal Republic of Germany (new)	21
9	Yugoslavia	17
10	Poland	12
11	Turkey	6
12	Others	14

(figures in bill. tonnes)

Fig. 1	**Brown coal resources world wide an in the reunified Germany**	*FE* *147-91*

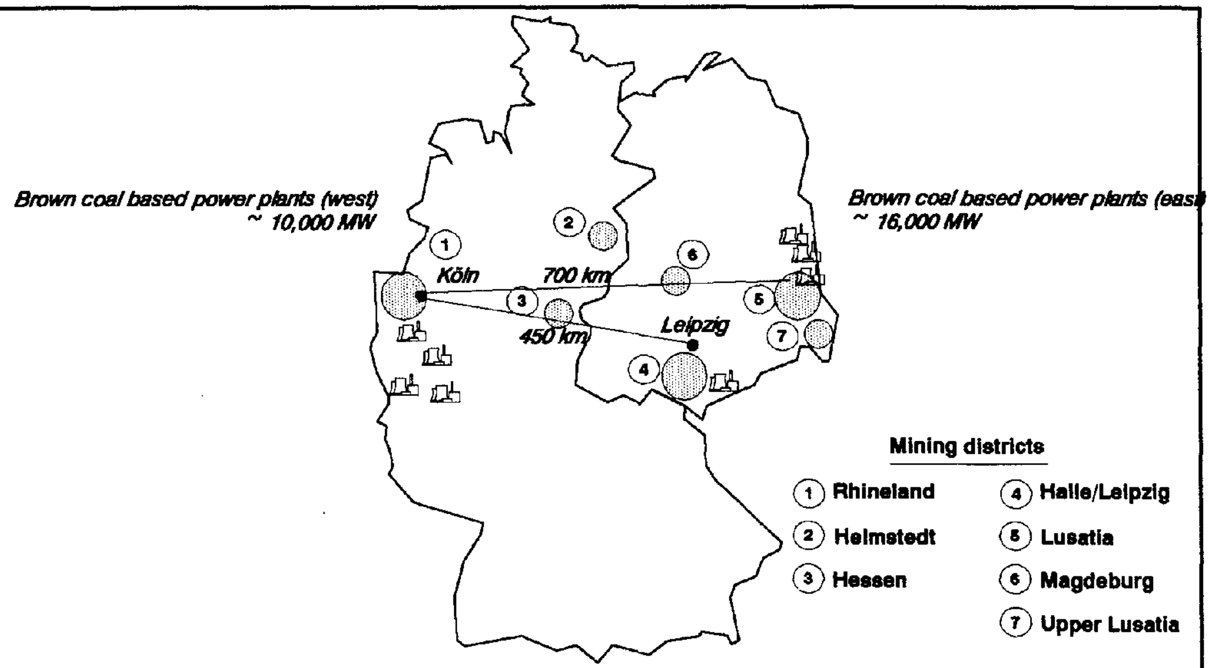


Fig. 2	**Plan showing the brown coal resources in the reunified Germany (western/eastern mining districts)**	*FE* *149-91*

Deposits	Quality parameters				Deposit parameter		
	Heat value Mj/kg	Ash %	Sulphur %	Water %	Overburden/ Coal	Seam thickness m	Depth m
Eastern							
Halle/Leipzig	9.0	6.5	3.4	54	4:1	10-15	70
Lusatia	8.7	6.5	0.9	54	6:1	10-15	90
Western							
Rhineland	8.5	6.3	0.5	56	5:1	30-40	190-200

Fig. 3 — **Comparsion of the quality parameters and other characteristic values of the eastern and western brown coal deposits** — *FE 148-91*

- Environmental protection legislation
- Markettrends for power and heat
- Privatization of enterprises

- Selective concentration and rationalisazion in respect of open cast mines, conversion plants, power plants and adaptation of work force to ensure the required economic efficiency
- High investment in environmental protection measures, elimination of economic and ecological burdens and attainment of western technical standards
- Restructuring of organization and operational sequences

Fig. 4 — **Impact of reunification on the brown coal industry** — *FE 150-91*

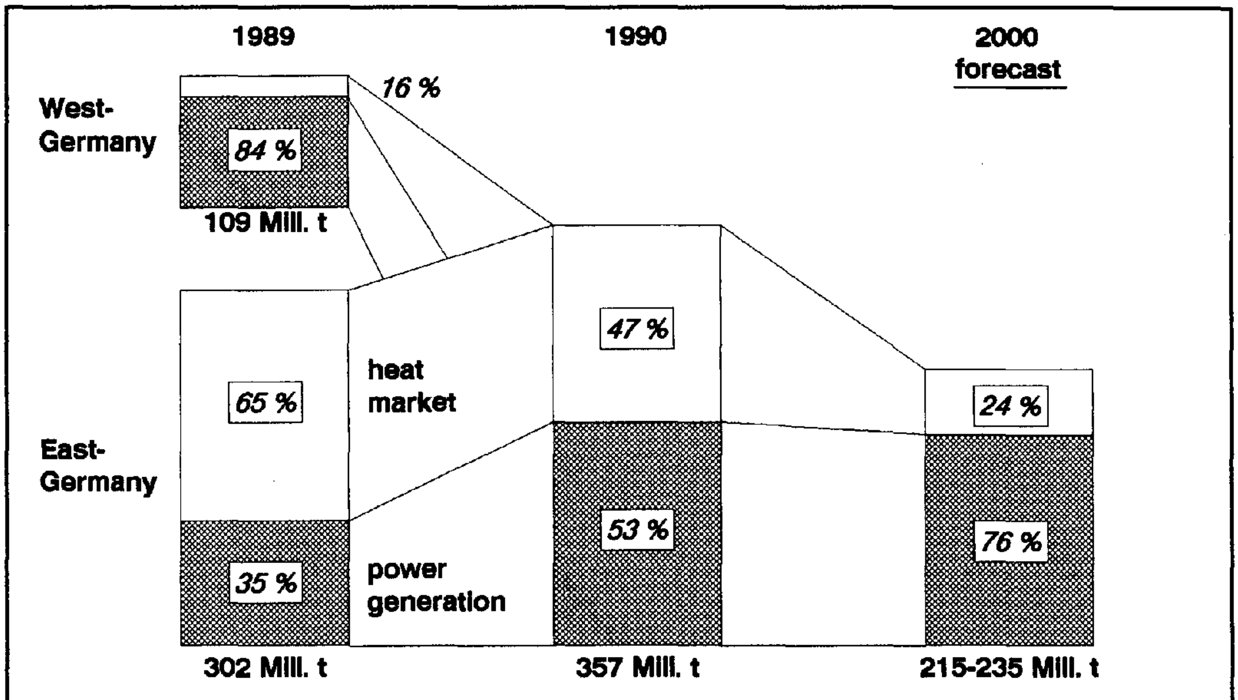


Fig. 5	Brown coal use in the Federal Republic of Germany before and after reunification	FE 151-91

	1989				1990		2000	
	Former Federal states		New Federal states		Federal Republic total		Forecast	
Energy source	Mill. t ce	%	Mill. t ce	%	Mill. t ce	%	Mill. t ce	%
Mineral Oil	153.2	40.0	17.4	13.6	178.0	36.1		
Hard coal	73.3	19.2	5.3	4.2	77.2	15.7		
Natural gas	65.5	17.1	11.9	9.3	78.1	15.8		
Nuclear energy	48.2	12.6	5.3	4.1	49.6	10.1		
Brown coal	32.5	8.5	87.7	68.4	104.4	21.1	60-83	~15
Others	10.0	2.6	0.6	0.4	5.7	1.2		
Total	382.8	100.0	128.2	100.0	493.0	100.0	406-553	100.0

Fig. 6	Primary energy consumption of the old and new Federal states in 1989/90 and forecast for 2000	FE 152-91

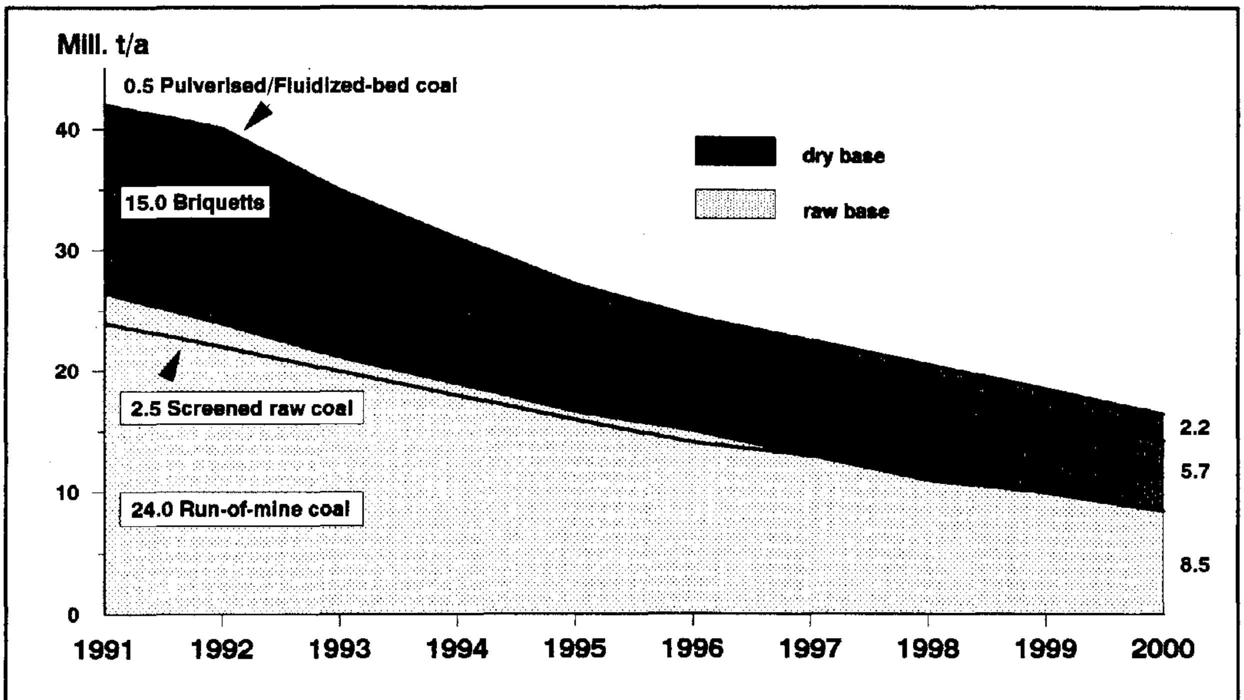


Fig. 7	Estimated sales for raw and converted brown coal products until 2000	*FE* *153-91*