# CLEAN COAL TECHNOLOGIES: OPTIONS AND RESEARCH ACTIVITIES

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**ABSTRACT.** According to the World Energy Council (WEC), at the beginning of the next century three main energy sources — coal, nuclear power and oil will have equal share in the world's total energy supply. This forecast is also valid for the USSR which possesses more than 40% of the world's coal resources and continuously increases its coal production (more than 700 mln tons of coal are processed annually in the USSR).
The stringent environmental regulations, coupled with the tendency to increase the use of coal are the reasons for developing different concepts for clean coal utilization. In this paper, the potential efficiency and environmental performance of different clean coal production cycles are considered, including technologies for coal clean-up at the pre-combustion stage, advanced clean combustion methods and flue gas cleaning systems. Integrated systems, such as the combined gas-steam cycle and the pressurized fluidized bed boiler combined cycle, are also discussed. The Soviet National R&D program is studying new methods for coal utilization with high environmental performance. In this context, some basic research activities in the field of clean coal technology in the USSR are considered. Development of an efficient vortex combustor, a pressurized fluidized bed gasifier, advanced gas cleaning methods based on E-beam irradiation and plasma discharge, as well as a new catalytic system, are presented. In addition, implementation of technological innovations for retrofiting and repowering of existing power plants is discussed.

## THE AVAILABILITY AND ABUNDANCE OF COAL

As is well known, coal is the most abundant and available fossil fuel with estimated resources of about 10 trillion tons (7.7 trillion tons of coal equivalent, TCE). This amounts to about 87% of all available fossil fuel resources.

Distribution of coal resources and reserves in selected countries is given in Table 1. USSR, USA and China each have more than 1 trillion tons of coal resources; Australia has about 800 billion tons. These countries account for about 90% of the total world coal resources. In spite of that, coal deposits are regionally distributed over the world, even more than oil. Coal is a very important energy source for many countries, such as Germany, South Africa, Poland etc., with resources of over a hundred billion tons of coal each. Such coal resources are certainly more than enough for their energy supply in the coming years.

As is illustrated in Table 1, USA shares are 29% of the world's coal reserves, USSR — 17% and China — 15%.

WEC assessments of coal resource-reserve categories are the following: resources — 9700 bln ton (7700 bln TCE), proven reserves — 1520 bln ton (1200 bln TCE), proven recoverable reserves — 946 bln ton (690 bln TCE). The Statistical Review of World Energy estimates the quantity of the world proven recoverable reserves as 757 bln TCE. This value differs somewhat from WEC data but has the

Table 1. *Coal resources, proven recoverable reserves and production in the main coal producing countries (WEC, 1986)*

| Country | Resources (trillion tons) | | Reserves (billion tons) | | Recoverable Reserves (billion tons) | | Production (million tons) | |
|---|---|---|---|---|---|---|---|---|
| | T | TCE | T | TCE | T | TCE | T | TCE |
| USA | 1.57 | 1.00 | 429 | 348 | 257.2 | 204 | 746 | 637 |
| USSR | 4.40 | 1.34 | 288 | 203 | 239.4 | 167 | 718 | 565 |
| China | 1.93 | 1.42 | 200 | 182 | 99.0 | 90 | 593 | 540 |
| S. Africa | 0.13 | 0.12 | 112 | 102 | 51.8 | 47 | 130 | 118 |
| Germany | 0.29 | 0.23 | 99 | 61 | 65.1 | 41 | 214 | 132 |
| Australia | 0.79 | 0.64 | 91 | 62 | 65.7 | 41 | 125 | 96 |
| Poland | 0.18 | 0.15 | 76 | 61 | 37.0 | 29 | 204 | 164 |
| World | 9.7 | 7.7 | 1520 | 1200 | 946.0 | 690 | 3822 | 2900 |

same order of magnitude, which again hints to the role of coal in future energy supply.

According to the statistics, proven recoverable resources of oil and gas are about 135.7 and 131.4 bln TCE, respectively. The reserves of gas condensate, oil shales and peat amount together about 40 bln TCE. Hence, there is a total of more than 1060 bln TCE recoverable reserves of fossil fuels from which coal amounts for 757 bln TCE, or about 70% (Table 2). To stress the quantity of coal reserves, note that the total cumulative coal consumption from 1860 till 1985 amounted to 155 bln TCE. Analysis of coal production history shows that there is a steady trend in growth of coal demand, which currently accounts for about 3 bln TCE; of this, more than 700 mln tons are processed annually in the USSR.

Table 2. *Assessment of world fossil fuel reserves (bln TCE) (Statistical Review of World Energy, 1986.)*

| Region | Oil | Gas | Coal |
|---|---|---|---|
| North America | 6.650 | 10.080 | 201.400 |
| Latin America | 18.321 | 6.920 | 4.542 |
| West Europe | 4.340 | 6.678 | 74.200 |
| East Europe | 15.607 | 50.393 | 352.829 |
| Africa | 10.721 | 7.407 | 56.785 |
| Middle East | 76.270 | 32.421 | — |
| Asia/Oceania | 3.800 | 7.523 | 67.385 |
| Total | 135.709 | 131.427 | 757.141 |

Table 3. *Projection of the world primary energy production sources*

| Energy Source | 1980 bln.TCE | 1980 % | 2000 bln.TCE | 2000 % | 2020 bln.TCE | 2020 % | 2040 bln.TCE | 2040 % |
|---|---|---|---|---|---|---|---|---|
| Solid fuels | 2.9 | 26.6 | 4.1 | 25.8 | 6.6 | 30.5 | 8.3 | 32.2 |
| Oil | 4.3 | 40.0 | 4.9 | 30.8 | 4.4 | 20.5 | 4.0 | 15.6 |
| Natural gas | 1.9 | 17.3 | 2.7 | 17.0 | 3.7 | 17.2 | 4.4 | 17.2 |
| Nuclear energy | 0.2 | 2.3 | 1.3 | 8.1 | 2.4 | 11.3 | 3.3 | 12.8 |
| Renewable sources | 0.0 | 0.0 | 0.3 | 1.9 | 1.3 | 6.0 | 2.3 | 8.9 |
| Noncommercial resources | 0.9 | 8.0 | 1.6 | 10.1 | 1.7 | 7.9 | 1.4 | 4.5 |
| Total | 10.8 | 100 | 15.9 | 100 | 21.5 | 100 | 29.5 | 100 |

Table 4. *Forecast of energy sources in the USSR.*

| Source | 1990 | 1995 | 2000 | 2005 |
|---|---|---|---|---|
| Oil and gas condensate (mln t) | 617 | 600-610 | 590-610 | 580-610 |
| Natural gas (bln m$^3$) | 845 | 1000-1050 | 1070-1170 | 1150-1250 |
| Coal, (mln t) | 771 | 810-830 | 860-920 | 920-1050 |
| Oil shale, (mln t) | 28 | 28.3 | 30-35 | 30-35 |
| Fuel peat, (mln t) | 22.6 | 20 | 20 | 15 |
| Fuel wood (mln t) | 11 | 11 | 10 | 10 |
| Renewables (mln TCE) | 2 | 7 | 20-25 | 35-40 |

The world total annual energy production in the late 80's was more than 10 bln TCE. The distribution of energy resources is shown in Table 3. As illustrated, a large share of the current world energy demand (about 38%) is still supplied by oil. On the other hand, the recoverable oil reserves are less than 13% of total fossil fuel reserves. At the current rate of consumption, oil could be exhausted in the next 35 years.

The only practical way to change this trend is a shift from oil to coal utilization. USSR energy policy recognizes this need. In the 50's coal accounted for about 60% of the country's total primary energy sources; by 1990 coal's share dropped to less than 20%. But at present there are plans to overturn this trend. In the next 15 years coal production growth of 26-35% is expected (Table 4).

This increased coal processing is closely related to a growth in its consumption for power generation. Currently, electricity is supplied by coal (32%), heavy oil (22%) and natural gas (43%); in the year 2000 the expected figures will be 42%, 8% and 47% for coal, heavy oil and natural gas, respectively. In 2010, 45% of the power generated in the country will be supplied by coal..

## ENVIRONMENTAL IMPACT

Until recently specialists of many countries have been predicting a sharp increase in coal consumption, mainly for electric power generation and production of different multi-purpose liquid and gas synthetic fuels. Recently, however, the attitude toward coal combustion has become less favorable due to a stringency of environmental regulations.

Ecologically, coal is one of the most polluting fuels: it contains various impurities, mineral matter, sulfur, nitrogen and heavy metals which restrict its usefulness as a fuel. Coal combustion generates a large amount of sulfur and nitrogen oxides, as well as particulates (fly ash and dust). It produces the highest amount of $CO_2$ per unit of generated power, compared with other types of fossil fuels. For example, during combustion of coal the rate of $CO_2$ emission is 90 kg $CO_2$ per kj; oil combustion produces 73 kg $CO_2$ and natural gas combustion generates only 55 kg. Ecological problems caused by coal have been experienced for a long time. Besides some domestic problems, such as penetration of disposed soot and ash particles into apartments, the presence of solid pollutants in the air has provoked various respiratory illnesses. Combustion of coal also leads to the formation of extremely harmful polyaromatic hydrocarbons, which have very strong carcinological and mutative effects.

On a global scale, coal consumption growth would increase sulfur and nitrogen oxides emission into the atmosphere. Emitted oxides are transformed into higher oxides, which interact with water vapor to form fine drops of sulfuric ($H_2SO_4$) and nitric ($HNO_3$) acids. These drops become the nucleuses of acid rain, which causes tremendous damage to trees, animals, constructions and cultural monuments; it also presents a severe health hazard to human beings.

Nitrogen oxides (mainly NO and $NO_2$, but also some $N_2O$) are major contributors to photo-chemical smog. $N_2O$, which is relatively unreactive in the troposphere, becomes an effective catalyst in the destruction of ozone at the stratosphere.

As was mentioned above, combustion of coal and other fossil fuels leads to an emission of a great amount of carbon into the atmosphere — approximately 7 bln tons of $CO_2$ per year. Many specialists believe that the growth of $CO_2$ concentration in the atmosphere could lead to global warming. Most scientists predict a significant global warming over the next 50 years unless emissions of carbon dioxide and other greenhouse gases are substantially reduced. To counter this trend, the World Commission on Environment and Development recommended a reduction of 20% in $CO_2$ emission level by the year 2005, based on the 1988 level. It was assumed that about half of this reduction would be obtained by increased energy production efficiency and improved conservation measures; the other half would be achieved by modification of energy sources, among others, by an increased use of renewables and nuclear power.

To illustrate the negative influence of coal combustion on the atmosphere, we can use the data of the American ecologist J. Holdren (Table 5). The annual emission of pollutants to the atmosphere associated with coal combustion is accordingly: sulfur oxides — $90 \cdot 10^6$ tons, nitrogen oxides — $30 \cdot 10^6$ tons and particulate matter — $30 \cdot 10^6$ tons; these constitute, 80, 32 and 54% respectively of the total fossil fuel combustion emissions, respectively. Table 6 provides the emission components of different fuels, including the most important air pollutants.

Concerning the situation in the USSR, emissions from the heat and power industry constitute 24% of the total industry emission; the part of the main pollutants is very high — 35.5% of the total particulates emission, 44% of the $SO_2$ and 57% of the $NO_x$ emissions (Table 7).

As shown in Tables 5 and 6, the combustion of coal leads to considerably higher emissions of harmful substances than an equivalent amount of any other fossil fuel. Besides particulates, nitrogen and sulfur oxides, the combustion of coal emits into the atmosphere about 60,000 tons of lead; 50,000 tons of nickel; 30,000 tons of arsenic; 300 tons of mercury

Table 5. *Emissions to the atmosphere originated by human activities (Holdren, 1985)*

| Form of Activity | Global Material Flow (Mt/y) | Emission (mln tons per year) Particulates | HC | $NO_x$ | $SO_2$ |
|---|---|---|---|---|---|
| **Energy supply** | | 55.5 | 38.8 | 92.5 | 113.5 |
| Coal | 3000 | 30.0 | 1.0 | 30.0 | 90.0 |
| Oil, oil refining | 3000 | 3.0 | 3.0 | 0.6 | 3.0 |
| Motor fuel | 1500 | 6.0 | 30.0 | 45.0 | 5.0 |
| The rest of combustion processes | 1500 | 1.5 | 0.8 | 15.0 | 1.5 |
| Biomass | 1500 | 15.0 | 4.0 | 1.9 | 0.7 |
| **Non-energy industrial activities** | | | | | |
| Copper smelting | 10 | 3.0 | — | — | 25.0 |
| Iron and steel making | 700 | 4.0 | — | — | — |
| Cement production | 900 | 30.0 | — | — | — |
| Lime production | 150 | 5.0 | — | — | — |
| **Other human activites** | 5300 | 50.0 | 50.0 | 4.8 | 1.9 |
| Wildfires (partly anthropogenic) | 2300 | 23.0 | 23.0 | 2.3 | 0.9 |
| TOTAL | | 170.5 | 112.0 | 110.0 | 141.5 |

Table 6. *Components of fossil fuel derived pollutants*

| | Particulates | | Hydrocarbons | | $NO_x$ | | $SO_2$ | |
|---|---|---|---|---|---|---|---|---|
| | kg/tc | multiple range | kg/tc | multiple range | kg/tc | multiple range | kg/tc | multiple range |
| Coal combustion | 100 | (10) | 0.4 | (3) | 10.0 | (2) | 30.0 | (3) |
| Natural gas combustion | 0.1 | (3) | 10.0 | (2) | 0.0 | (2) | 0.01 | (2) |
| Oil refining | 1.0 | (3) | 1.0 | (30) | 0.2 | (2) | 1.0 | (3) |
| Oil as a motor fuel | 4.0 | (2) | 20.0 | (2) | 30.0 | (2) | 3.0 | (2) |
| Other oil combustion | 1.0 | (2) | 0.5 | (2) | 10.0 | (2) | 10.0 | (3) |
| Biomass combustion | 10.0 | (4) | 5.0 | (5) | 2.0 | (3) | 0.4 | (3) |

Note: All figures in parentheses indicate multiple ranges of given values, e.g., (2) means that the range extends from 2 times smaller to 2 times larger than the indicated value.

Table 7. *Emissions from heat and power industries in the USSR (mln tons/year)*

| Emission | 1980 | 1985 | 1988 |
|---|---|---|---|
| Total | 19.3 | 17.9 | 15.35 |
| Fly ash | 6.4 | 6.36 | 4.94 |
| Sulfur dioxide | 10.6 | 9.66 | 7.55 |
| Nitrogen oxides | 2.3 | 2.41 | 2.67 |
| Average ash removal efficiency (% ) | 93.3 | 93.3 | 94.2 |

Table 8. *Nitrogen oxides emissions in flue gases of boilers (mg/m$^3$)**

| Fuel | Boilers (capacity or type) | Emissions as designed | Actual emissions | Controlled combustion |
|---|---|---|---|---|
| Oil | 230-670 t/h | 413 | 500-700 | 350 |
| | 300-1200 MW units | 447 | 700-1200 | 400 |
| Brown coals | Dry-bottom | 445-576 | 500-600 | 350 |
| | Slagging | 524-576 | 600-800 | 500 |
| Bituminous coals | Dry-bottom | 639-778 | 600-1100 | 550 |
| | Slagging | — | 1200-2200 | 650 |

* for oil — dry gas sample with 3% $O_2$ and a = 1.167
for coals — with 6% $O_2$ and a = 1.4

and 60 tons of cadmium annually (which are concentrated in the fly-ash particles). All these substances are harmful, specifically to the kidneys and cerebrum; their large concentrations can cause poisoning and other health damage.

The above-mentioned emission is given under the assumption that no emissions control methods are used and all the pollutants formed are emitted into the atmosphere.

In practice, however, it is possible to reduce the disposal of harmful substances into the atmosphere by available methods. A wide variety of clean and efficient coal utilization techniques also is under development, awaiting commercialization. The main options of environmentally clean coal utilization are presented below.

## OPTIONS TO REMOVE POLLUTANTS

Figure 1 illustrates available options for coal pollutant removal. These options include:

- mineral matter and sulfur removal by physical and chemical cleaning at the coal preparation stage (before combustion or processing);
- retention of pollutants (mainly sulfur oxides) during the combustion stage by injection of absorbent;
- particulates and sulfur removal by integrated fuel processing (gasification pyrolysis and/or hydrogenation);
- particulates, sulfur and nitrogen oxides removal by advanced flue gas clean-up.

The most efficient sulfur removal is achieved with limestone or dolomite injected into a fluidized bed boiler (FBB), working under atmospheric or elevated pressures. In addition, due to low combustion temperature, a low amount of $NO_x$ is generated.

In the last few years worldwide efforts have been directed toward developing new, promising modifications of the fluidized bed concept. Among them is the circulating fluidized bed boiler (CFBB), which employs high velocities (5-25 m/sec) and actually promotes solids elutriation. The CFBB has higher heat intensity per surface area (up to 8 MW/m$^2$) and higher steam productivity of each unit (up to 100 tons of steam per hour) than the FBB. Moreover, a CFBB allows burning of various solid fuels and a better sulfur retention is achievable. The dense bed is maintained at a reducing atmosphere, resulting in essential suppression of $NO_x$ formation by multi-stage air feeding. In FB reactors heat exchange surfaces are usually located within the bed itself, while in CFB reactors the combustion and heat exchange regions are separated; a separate design diminishes the erosion rate of heat exchange surfaces.

Four main CFBB designs have been developed and commercialized: Lurgi, Batelle, Ahlstrom and

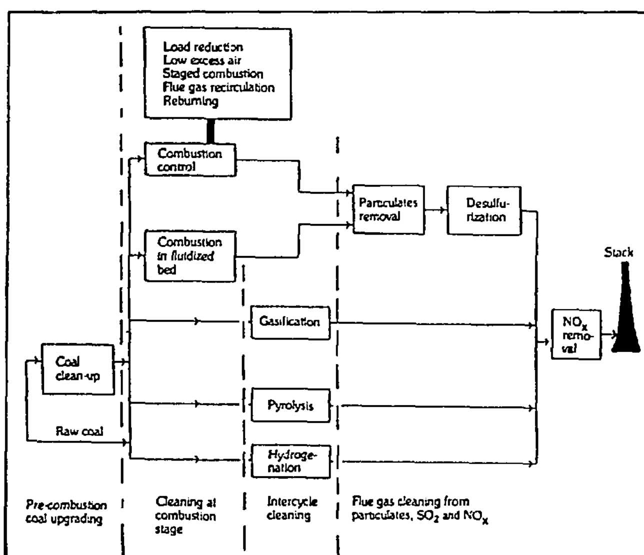


Fig. 1. *Different emission control options*

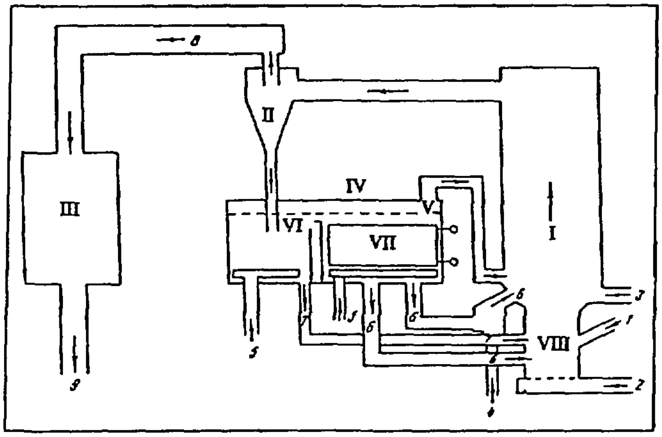


Fig. 2. *Scheme of Batelle CFBB*
I — combustor; II — high efficiency cyclone; III — convective heat transfer surface; IV — external heat surface; V — "cold" compartment; VI — hot compartment; VII — heat transfer surface; VIII— dense bed
1 — coal; 2 — primary air; 3 — secondary air; 4 — lift air; 5 — fluidizing air; 6 — cold recycle; 7 — hot recycle; 8 — hot flue gas; 9 — flue gas to clean-up equipment and chimney.

Stone-Webster. A scheme of the CFBB designed by Batelle is shown in Figure 2. In 1989 the Lurgi company started the commercialization of CFBB with a capacity of 900 MW (thermal), supplied by hot cyclones and external ash heat exchangers.

R&D on CFBB is also being conducted in the USSR at the Krzhizhanovsky Power Engineering Institute (ENIN) and at the All Union Thermal Engineering Institute (VTI). The ENIN combustor is shown in Figure 3. This design is suitable for combustion of fuels with high ash content and incorporates a reactor-pyrolyzer for a preliminary coal thermal processing. The products of coal pyrolysis feed the steam boiler or gas turbine combustor; the char residue from the reactor is burned in the CFB pre-combustor. Flue gases are cleaned from particulates in the hot cyclones and then flow into the steam boiler. ENIN's technology provides high environmental performance: exhausted flue gases contain no more than 200 mg/m$^3$ of sulfur oxides, 159 mg/m$^3$ of nitrogen oxides and 100 mg/m$^3$ of dust [Volkov, Gavrilov, 1991].

A semi-industrial module, incorporating reactor-pyrolyzer and CFB pre-combustor designed to supply 120 tons of steam per hour, has been erected at the Dobrotvorskaya plant and fed by high-ash Lvov-Volynsky coal.

VTI design uses a conventional CFBB concept. The first module will be erected in 1994 in the Petrovskaya cogeneration power plant, generating 1200 MW of electricity, by Kuznetzky coal. The plant will be equipped with 6 CFBB, generating 620 tons steam per hour. The construction of the plant will be completed in 1999.

Pressurized fluidized bed combustion (PFBC) can be incorporated with a combined cycle, resulting in a remarkable increase in plant efficiency, and hence, in electricity output.

The following attributes of PFBC may be distinguished:

- hot gases require particulate cleanup before entering the gas turbine;
- no flue gas cleanup is required;
- high pressure and intense turbulent mixing produce higher combustion rate and reduce the size of the unit;
- plants can be composed of standard modules. This leads to easier installation and a relatively low cost without the usual economy of scale penalties;

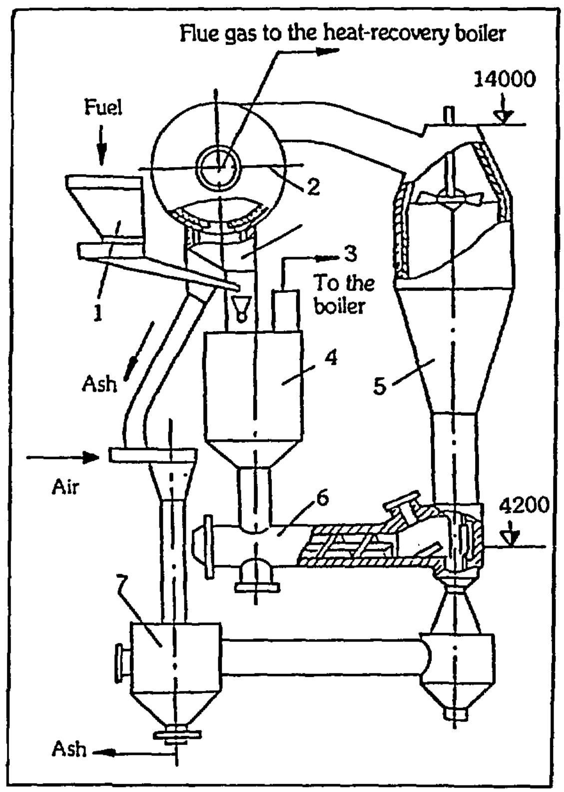


Fig. 3. *Layout of the ENIN combustor module*
1 — crushed fuel hopper; 2 — separator; 3 — ash/gas flow divider; 4 — reactor-pyrolyzer; 5 — air spray combustor; 6 — screw conveyer; 7 — ash heat exchanger.

- modularity provides stage construction, which permits smaller increments of capacity, thereby shortening construction time and lowering costs;
- the waste generated is a dry, benign solid that can be disposed of easily or usefully employed.

Unfortunately, R&D on PFBC is currently only in its laboratory scale in the USSR.

Now we return to combustion control techniques and options to remove or suppress the formation of pollutants. The following means of combustion control greatly reduce the formation of nitrogen oxides:

- load reduction
- low excess air combustion
- staged combustion
- flue gas recirculation
- reburning
- selective non-catalytic reduction

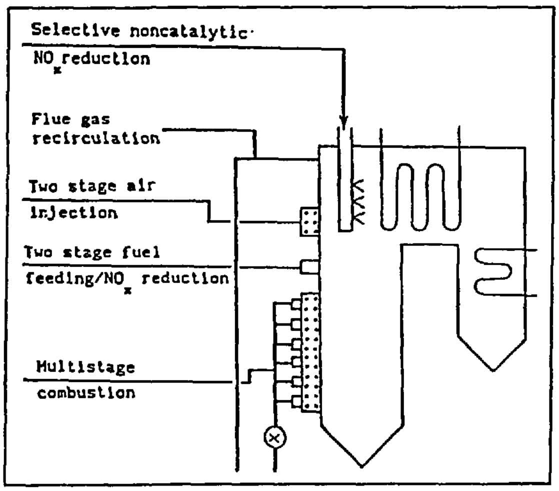


Fig. 4. *Methods for $NO_x$ control at the combustion stage*

The main principles of combustion control are presented in Figure 4. Such control techniques are broadly implemented in the USSR at existing oil and coal-fired boilers; as shown in Table 8, they effectively reduce $NO_x$ emission.

Removal of mineral matter and fuel molecules can also be achieved by inter-cyclic fuel processing, i.e., by integrated gasification, pyrolysis and maybe hydrogenation. The integrated gasification can be incorporated into combined steam-gas turbines cycle, providing highly efficient power generation.

The following attributes of integrated gasification combined cycle (IGCC) may be distinguished:

- it is relatively non-sensitive to coal feedstock;
- gases require only particulate and sulfur clean-up before the gas turbine;
- in addition to increased energy production efficiency, the units can be composed of standard modules, applicable to large and small utilities. This leads, as mentioned, to easier installation, less construction time, and relatively low cost without the usual economy of scale penalties;
- sulfur removal of over 99% is achievable;
- nitrogen oxides removal of 40% is possible;

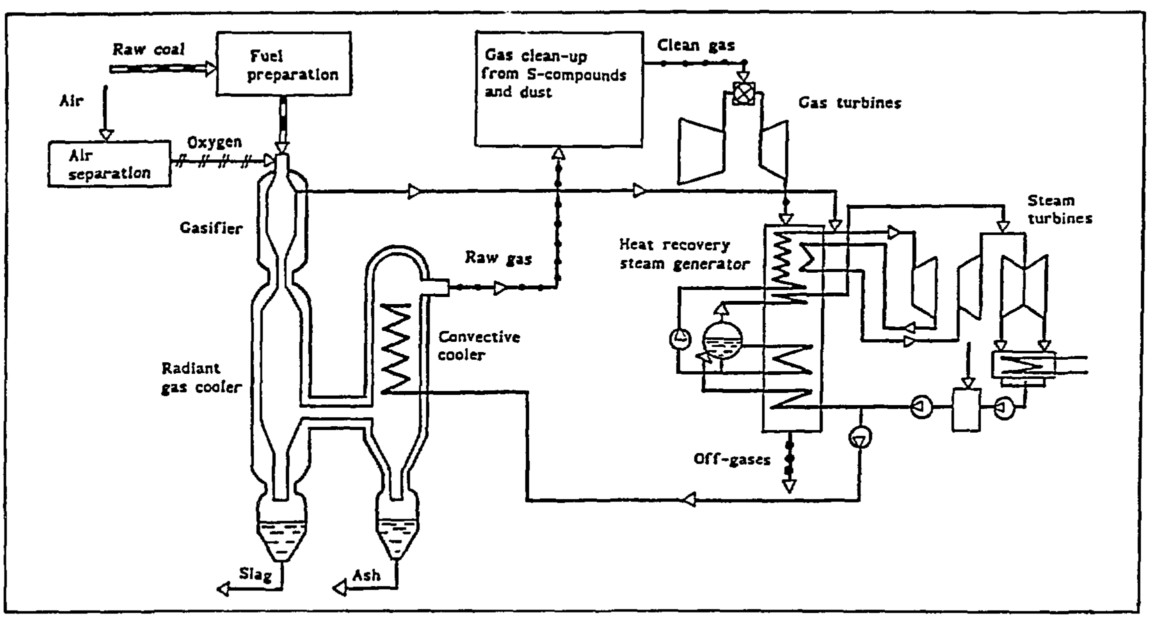


Fig. 5. *Principal scheme of the 625 MW IGCC unit (Berezovsky Plant-2)*

R&D conducted at the All Union Thermal Engineering Institute within the frame of the national "Environmentally Clean Power Generation" program, is aimed at developing 625 MW integrated gasification-combined cycle units. Each unit consists of two modular entrained bed slagging gasifiers with 100-120 t/h coal throughout, two 200 MW gas turbines designed for gas inlet temperatures of 1250 °C, two recuperators downstream from the gas turbines and one 225 MW steam turbine (Figure 5).

Such an IGCC unit will have a thermal efficiency of 44-45% and very low pollutants emission: particulates — 1.5 mg/m$^3$; $SO_2$ — 7 mg/m$^3$ and $NO_x$ — 80 mg/m$^3$. A demonstration facility will be built in 1992-1994. The first commercial plant with a 5000 MW output (8 IGCC units; 625 MW each) will be put into operation in 1999 in the Krasnoyarsk region using brown coal from the Berozovskoe basin.

Another IGCC technology was developed by the Central Boiler and Turbine Institute (CKTI). CKTI's 300 MW concept consists of steam-air gasifier (100 t/h coal under 2 MPa), gas cleaning system, pressurized gas-fired boiler, 114 MW gas turbine (with a gas inlet temperature of 1100°C) and 180 MW steam turbine (Figure 6).

The technology has the following environmental performance: emission of particulates — 9 mg/m$^3$, $SO_2$ — 34-70 mg/m$^3$, $NO_x$ — 80 mg/m$^3$. Compared to the conventional coal-fired plant, it saves 10-12% of the fuel consumption per kWh of generated electricity. Two such modules are planned to be constructed in 1998-2000 at the Petrovskaya plant near Kemerovo.

Removal particulates, sulfur and nitrogen oxides from the flue gases can be obtained also by conventional and advanced methods of gas clean-up. These include precipitators, bag filters or wet scrubbers. The efficiency of gas cleaning from particulates in power plants of the leading industrial countries is as high as 99.9%. In the USSR, the average efficiency of particulates removal in 1988 was still only up to 94.2% ( Table 7).

All environmentally clean combustion technologies propose gas clean-up from particulates (dust, fly ash, soot) by introducing electrostatic forces.

Such development was carried out also in the USSR to improve the efficiency of dust and particulates removal. These studies emphasized the use of pulse and alternating-sign power supply to the electrostatic filters. Units with a relatively large distance between the electrodes were also recommended. These efforts are aimed both at assuring dust removal and improving the economic characteristic of the equipment.

It should be stressed that the alternating-sign power supply to electric filters is a promising idea currently in use only in the USSR. This concept is based on the fact that an inverse corona is formed on a high resistant dust layer sometime after the voltage (which is required to accumulate the layer) has been applied. At this moment, if the polarity of the voltage is alternated, the inverse corona formation could be eliminated over the time necessary for the layer to be recharged. Thus, by periodic alternation of the voltage polarity, we can completely eliminate or significantly reduce the formation of the inverse corona. In this case, the drop in the rate of dust precipitation cannot be allowed. This is achieved by choosing an optimum time interval for each voltage polarity.

The second advantage of the alternating-sign power supply, which expands its application range beyond high resistant dust, is the ability of precipitation electrodes for self-shaking. At the moment the polarity is inverted under the effect of the alternating voltage, the force

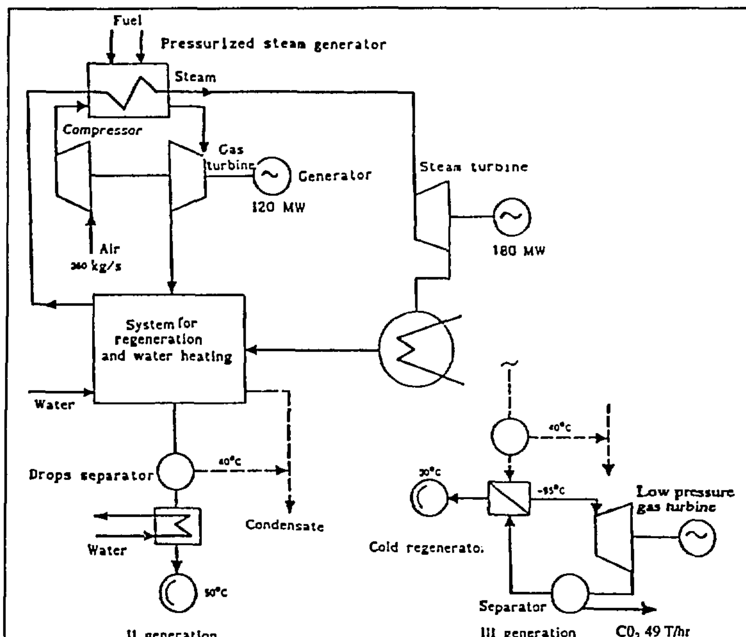


*Fig. 6. Principal scheme of IGCC concept, developed by CKTI*

which keeps the charged layer close to the electrode transforms into a breaking one. This contributes to self-purification and allows either to suspend or to simplify significantly the system of electrode shaking.

An optimized alternating-sign power supply, which was applied in an industrial bipolar electric filter, reduced ash emissions by a factor of 1.5 compared to the unipolar supply mode. Activities in this direction are also carried out in a number of other coal-fired power plants which use coal adverse electro-physical properties. A prototype of a complete supply source, in which elements of a commutator and a high-voltage source are combined in a single container filled with oil, is being currently tested.

In many cases combustion of coal with a high sulfur content requires flue gas cleaning to meet existing environmental regulations on sulfur oxide emissions. The wet scrubbing of gas with limestone injection seems the most efficient technology for $SO_2$ removal, which presently has a commercial application. On the other hand, it is rather difficult to ensure maximum permissible $NO_x$ emission values (MPEV) by simple combustion control. Therefore, all ecologically clean technologies are currently equipped with a system for flue gas cleaning from nitrogen oxides. Such $NO_x$ removal system is shown on the right side of Figure 1.

The selective catalyst reduction (SCR) of $NO_x$ to $N_2$ is commercially acceptable and gains in the presence of ammonia and a vanadium catalyst. A main disadvantage of this SCR method is the short life of the $V_2O_5$ catalyst and the disposal of the spent catalyst. Hence much efforts has been made in IVTAN, ENIN and other research centers to develop new, more efficient and cheap ways. Novel methods for $SO_2/NO_x$ oxidation by radicals (such as $OH^•$ $O^•$ $HO_2^•$ and $O_3^•$) which are formed in flue gas under an irradiation or electric discharge, are currently under study. The main advantages of this technology are the absence of catalyst, high degree of gas cleaning, extraction of pollutants in the form of valuable fertilizers and a relatively low energy consumption.

An interesting possibility to remove simultaneously $SO_2$ and $NO_x$ is provided by ozone treatment. In this case the ozone oxidizes $SO_2$ and $NO_x$; then the products ($SO_3$ and $NO_x$) are neutralized and converted into sulfate and nitrate of ammonia. Based on this idea, an ozone-ammonia gas cleaning method was developed by ENIN. The process is carried out in one absorption chamber, in which ozone is injected into the flue gases via spray nozzles installed in the Venturi tube orifice. This increases pollutants removal efficiency by 10-12%. A combination of oxidation and neutralization stages (only in one unit) produces a practially neutral mixture and significantly decreases corrosion.

The consumption of ozone amounts to 1.1-1.2 kg per kg of $NO_x$. The method allows removal of 75-80% of the $NO_x$ and 90% of the $SO_2$ from flue gases and consumes approximatly 5% of the power generated by the unit. About 90% of this power is consumed for ozone production. The method is implemented now in its demonstration stage in a coal-fired plant. Ammonia fertilizers utilization, as process by-products, ensures the economic feasibility of the technology.

In many cases the fulfillment of the required environmental regulations could be achieved only by a combination of several cleaning methods. For example, it is possible to apply simultaneously preliminary coal washing, wet scrubbing of flue gas (to remove particulates and sulfur compounds) and selective catalytic reduction to reduce the amount of nitrogen oxides.

Implementation of different cleaning options shown in Figure 1 would ensure the environmental acceptance of the process. Realization of these options is not simple, but quite a realistic task which has been implemented in many coal-fired power plants (in the U.S., Japan, and the former West Germany).

Utilization of complex clean-up systems leads to a considerable rise in the cost of coal technologies. Thus, in the U.S. the cost of new coal power plants equipped with flue gas desulfurization and SCR is up to $2,000 per kW of installed capacity; at least 25% of the capital cost is related to sulfur and nitrogen oxides clean-up systems.

Figure 7 depicts an evaluation of cost and efficiency of various emission control measures. Industrial processes, such as physical clean-up by upgrading of ash, pyrite sulfur removal, combustion in an atmospheric fluidized bed with limestone injection, wet scrubbing of flue gas and combustion control to suppress $NO_x$ formation, are shown double shaded. Technologies which are at their demonstration stage are shown simply shaded. Dots mark off prospective technologies.

## OPTIONS TO MODIFY EXISTING COAL-FIRED PLANTS

Reasonable, cost-effective options to improve significantly conventional coal power plant environmental performance do exist. The innovative clean coal technologies considered here could be grouped into two major categories.

**Retrofit Technologies**

This system can be installed in existing plants to reduce emissions. They are used at the "front end" or the "back end" of the fuel chain and at the

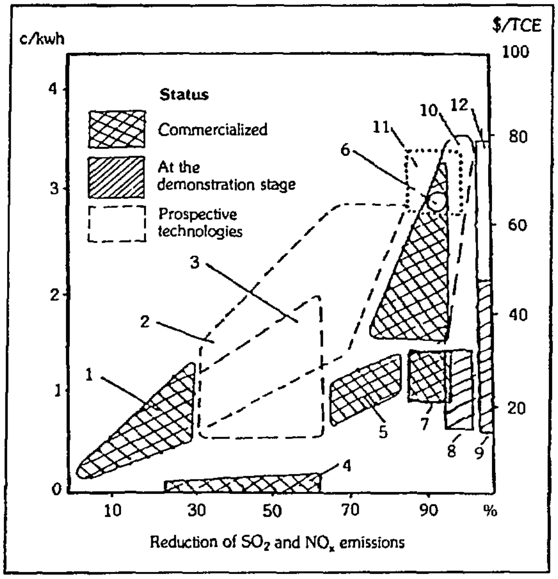


Fig. 7. *A comparison between costs and efficiencies of various emission control measures [EPRI assessment with author's additions]*
1 — physical cleaning; 2 — advanced physical and chemical cleaning; 3 — dry absorbent injections; 4 — suppression of $NO_x$ formation by controlling combustion regimes; 5 — $NO_x$ selective catalytic reduction (SCR);6 — wet flue gas desulfurization (FGD); 7 — atmospheric fluidized bed combustion (AFBC); 8 — pressurized fluidized bed combustion (PFBC); 9 — combined steam/gas cycle with coal gasification; 10 — electron beam gas cleaning; 11 — FGD + SCR; 12 — natural gas-fired combined steam-gas cycle

combustion stage. Technologies which could be used for retrofiting at the fuel side include conventional coal cleaning (coal washing) and innovative methods such as advanced physical, chemical and microbial cleaning.

Retrofit technologies generally cause some losses of efficiency (3 to 10%) and power output, because power is also required to implement them. Post-combustion clean-up technologies, namely conventional and advanced flue gas scrubbing, have similar economic performance penalties. Flue gas scrubbing generally costs more than combustion modification processes, such as stage burner, reburning, slagging combustors and sorbent injections. Pre-combustion clean-up, i.e., coal cleaning and coal slurry preparation, can result in a better efficiency due to less ash handling, however, fuel cost is increased. In general, the advanced retrofit control devices expand the range of coal types that can be cost-effectively used; they also are not space or site limited as is flue gas scrubbing.

**Reconstruction Technologies.**

This option is aimed at replacing a significant portion of the original plant to reduce emissions and often to increase capacity.

Reconstruction options include:

- Integration of coal gasification with combined cycle;
- Fluidized bed combustion at atmospheric pressure (AFBC);
- Pressurized fluidized bed combustion integrated with combined cycle;

These technologies (except AFBC) are currently at a demonstration stage and their wide commercialization is expected by 1995.

Reconstruction technologies usually increase efficiency and boost power output. To reconstruct an existing coal-fired power plant, the boiler has to be replaced by a new coal gasifier or fluidized bed combustor. If PFBC is used, integrated with a gas turbine, gas clean-up and heat recovery systems are required. The remaining equipment (coal handling, steam turbine and power generation equipment) would likely need to be renovated. Although reconstruction requires significant capital investment, the increased power output offsets most of the capital cost.

According to available estimates, reconstruction of an existing coal-fired power plant with IGCC (a gasifier-turbine configuration) would require an investment of $1100 to $1300 per kW installed (the 1988 US price). But since electric power will be generated more efficiently when the plant is renovated, the electricity price would increase to no more than 0.2 cents/kWh. $SO_2$ emissions from the reconstructed plant would be reduced by up to 99% and $NO_x$ emissions would be significantly lower than in the original plant.

Reconstruction using IGCC can increase the efficiency from a nominal 35% to more than 40% and boost its power output as much as 50% to 150%. Reconstruction using PFBC increases plant efficiency to 42-44% [Krishna, K.Pillai, 1989] and increases power output by 50-70%. Capital cost is somewhat lower ($800-$1,000 per kW installed), but the increase in power output is less than that of IGCC; thus the cost of electricity is greater by about 0.4 - 0.6 cents per kWh.

AFBC reconstruction would not change significantly power plant efficiency. It would result only in a 10% to 15% increase in power output. The initial investment is low ($700 to $900 per kW installed), but the relatively small increase in power output results in a cost-of-electricity rise of 0.6-0.8 cents per kWh. Table 9 provides the estimated performance of the various mode-of-operation options.

Table 9. *Technical and economic performance of innovative clean coal technologies in comparison to a conventional coal-fired power plant**

| Technology | Efficiency | $SO_2$ & $NO_x$ reduction (%) | Power output | Plant life | Capital cost ($/kW) | Cost of electricity (c/kWh) |
|---|---|---|---|---|---|---|
| **Conventional** | | | | | | |
| Coal cleaning | small increase | >30, no change | no change | slight extension | additional fuel cost only | 0.2-0.3 |
| Flue gas scrubber (FGD) | decrease | 90-95 no change | moderate decrease | no change | 180-200 | 0.9-1.1 |
| **Retrofit** | | | | | | |
| Advanced flue-gas clean-up | decrease | >90 high | small decrease | no change | 175-190 | 1.0-1.2 |
| Limestone injection multi-stage burner | decrease | 50-60 moderate | small decrease | no change | 80-110 | 0.5-0.8 |
| CFB pre-combustor | small decrease | 50-90 moderate | small decrease | slight extension | 50-60 | 0.1-0.2 |
| Gas-reburning | no change | moderate | no change | slight extension | 10-20 | depends on gas price |
| In-duct sorbent injection | small decrease | 55-75 | small decrease | no change | 40-90 | 0.2-0.4 |
| Advanced coal cleaning | small increase | 30-90 no change | no change | slight extension | additional fuel cost only | 0.6-2.1 |
| Coal slurry | small decrease | 10-60 no change | small decrease | no change | 20-50 | 1.1-2.3 |
| **Reconstruction** | | | | | | |
| IGCC | moderate increase | 95-99 moderate | 50-150% increase | moderate extension | 1100-1300 | 0.1-0.2 |
| PFBC | moderate increase | 90-95 moderate | 50-70% increase | moderate extension | 800-1000 | 0.2-0.4 |
| AFBC | no change | | 10-15% increase | moderate extension | 700-900 | 0.6-0.8 |

* Assumes a conventional coal-fired power plant with only particulate matter removal. For reconstruction technologies, capital costs are relatively high because the capacity of the plant is increased. The incremental costs of electricity are costs associated with reducing emissions from the original plant.

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