Techniques to Improve the Economics of Limestone FGDS

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I. Abstract

Title IV of the Clean Air Act Amendments of 1990 established a unique "market based" approach to reduce SO_2 emissions from fossil fuel fired power plants. Many utilities have evaluated the cost of scrubbing versus fuel switching in various plans and scenarios to determine the most economical means for meeting the requirements of the new law. Presently, the future cost of removing a ton of SO_2 is based on fuel switching, and the market values are in the range of $150 - $250 per ton. The perceived cost of FGDS retrofits is $250 - $400 per ton for eastern medium to high sulfur coal.

ABB has studied the overall costs of FGDS and has developed a series of cost reducing improvements. and innovations. The improvements are manifested in ABB's new limestone FGDS technology known by the code phrase "Stealth FGDS". Stealth promises low capital and operating cost, high removal efficiencies for SO_2 and other pollutants, little or positive environmental and economic impact on the local community, salable or non-hazardous by-products, ease of retrofit, and exceptionally short installation schedules. Together with project efficiency enhancements, these improvements will offer a 20 to 30% overall cost reduction in traditional FGDS and promise to make FGDS competitive with fuel switching.

Stealth is based on sound technical development and the experience of a leader in the FGD industry, incorporating many innovations into what would appear to be the traditional, reliable open spray tower technology. These innovations have been tested to large extent in various pilot and full scale facilities, and patents have been filed for many aspects of the design. The concepts are being demonstrated in one system at the Niles Generating Station of Ohio Edison Company.

Bearing the name "LS-2 Advanced SO_2 Scrubbing", the Stealth scrubber at Niles is a 110 MWe turnkey, retrofit unit to be completed 20 months after the release of engineering. It will remove 20,000 or more tons per year of SO_2 from the flue gases generated by both Unit 1 and Unit 2 boilers, producing wallboard-grade gypsum. Earmarked to start up in August, 1995, the LS-2 scrubber will demonstrate cost saving and efficiency improvement features never before available in open spray tower scrubbers. Upon completion of a four month test program, the plant will be operated by Ohio Edison for a four to five year reliability demonstration period. At the end of

this period, OE may opt to continue operating the plant, provided the economics for doing so are compelling.

The performance and economic projections for LS-2 scrubbers show the technology to be quite attractive relative to projections for fuel switching when installed in a manner similar to the installation plan for Niles. The description and basis for these economic projections are described in this paper.

II. Description of Techniques to Improve Limestone FGD

A. Contemporary Practice with Limestone FGDS

While there are many different designs of FGD systems commercially available, all limestone FGD technology is based on the chemical reaction between sulfur dioxide (SO_2) and limestone or calcite ($CaCO_3$). Two different reaction products can be directly produced: gypsum and calcium sulfite hemihydrate. In the last decade or so, the gypsum producing version of this process has dominated, because gypsum is a byproduct useful for the building construction industry. In the gypsum process, the overall reaction is

$$SO_2 + CaCO_3 + 2H_2O + \frac{1}{2}O_2 \rightarrow CaSO_4 \cdot 2H_2O + CO_2\uparrow$$

Sulfur dioxide in the gas is transferred into a scrubbing liquid, then converted to solid calcium sulfate dihydrate, or gypsum. Oxygen is consumed and carbon dioxide released.

The methods for effecting the transfer of SO_2 from a gaseous pollutant to a gypsum byproduct vary quite a bit depending on the designer and supplier of the FGD technology. The major methods available today for large, utility-sized, fossil fuel fired power plants are

- Countercurrent open spray towers
- Countercurrent spray towers with one or more sieve trays
- Cocurrent/counter current absorbers with packing
- Bubbling-type stirred reactors

All of these commercial technologies offer SO_2 removal capabilities greater than 95%, and all are cost competitive. Generally speaking, the overall cost of FGDS runs about 170 - 210 USD per kWe for a 500 MWe retrofit plant, with operating costs (including capital recovery charges) of about 300 - 450 USD per ton of SO_2 removed for a 3.0 - 4.5% sulfur bituminous coal.

The features of each technology are listed below, in the form of advantages and disadvantages.

Countercurrent open spray towers

Advantages: low pressure drop, simple design and construction, open gas path, low probability for plugging, no pre-quench required, simple operation.. Disadvantages: perceived as less sophisticated technology, requires high liquid flow rates to achieve removal efficiencies greater than 95%, maximum tower velocities < 3 m/s due to vertical flow mist eliminator limitations.

Countercurrent spray towers with one or more sieve trays

Advantages: simple design and construction, lower liquid flow than tower without tray. Disadvantages: higher pressure drop than tower without tray, requires prequench, higher potential for plugging or blinding of tray, maximum tower velocities < 3 m/s due to vertical flow mist eliminator limitations.

Cocurrent/counter current absorbers with packing

Advantages: high gas velocity due to smaller cross section, low pressure slurry delivery (no spray nozzles), high solids content in recycle slurry simplifies dewatering, low gas pressure drop, readily adaptable for gas reheat. Disadvantages: more complex to construct, high gas inlet and low outlet not compatible with normal gas flow (fan to stack), sensitive to limestone reactivity and grind size, higher pluggage potential.

Bubbling-type stirred reactors

Advantages: low profile, less building height required for enclosure, no recycle pumps, nozzles, trays, or packing. Disadvantages: High gas pressure drop, no clear path to stack, potential for plugging, requires pre-quencher.

The advantages of a simple, open spray tower are compelling for most FGD installations, which is probably why this technology has been used predominantly throughout the world. The LS-2 project is expected to demonstrate the feasibility of higher tower gas velocity and slurry utilization combined with open spray tower technology which will bypass conventional FGD technologies and be competitive with projected costs for environmental fuel switching in the eastern United States, currently estimated to range between 150 - 250 USD per ton of SO_2 removed. It is essential that improvements be made in all types of FGD technologies if they are to be competitive with fuel switching in the United States. ABB's focus to date has been on improving open spray tower technology to enhance not only its competitiveness with other FGD technologies but, more importantly, to substantially improve the overall cost of FGDS relative to environmental fuel switching.

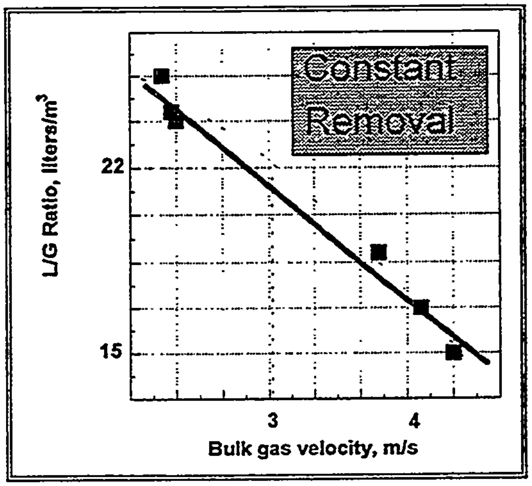
B. Improvements in Open Spray Tower Technology

Major cost reductions in open spray tower technology can be achieved if (1) the bulk gas velocity can be substantially increased, (2) the volume for gas/liquid contacting be significantly reduced, and (3) the amount of slurry in the reaction tank decreased.

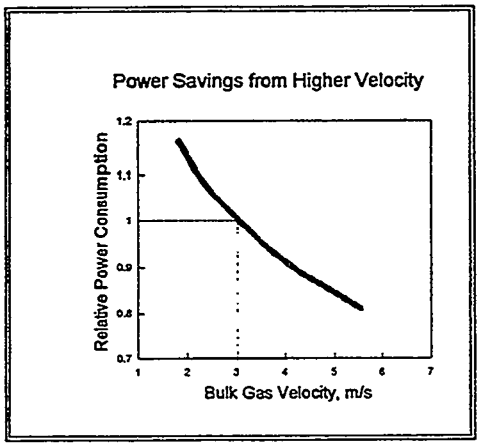
1. Increasing Gas Velocity

ABB has tested full scale state-of-art open spray towers over a wide range of velocities and L/G ratios. Testing confirms that the overall mass transfer coefficient for SO_2 increases dramatically with superficial gas velocity. By increasing the velocity from 2.3 to 4.3 m/s, representative full scale test data shows that the L/G can be decreased 32% while maintaining the same SO_2 removal. A 32% decrease in L/G corresponds roughly to a 50% increase in overall mass transfer rate.

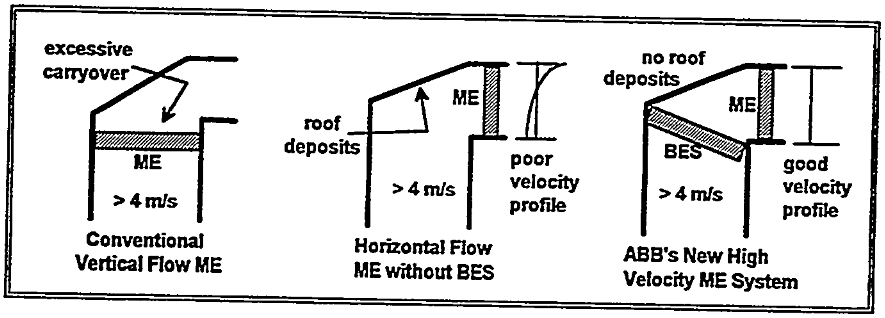
ABB's correlations suggest that open spray towers capable of bulk gas velocities in excess of 4.3 m/s will be operationally more efficient, that is, they will consume less power because the savings in L/G will more than offset the increase in pressure drop. The relative power consumption effect is shown below.



Increasing gas velocities demands close attention to the mist eliminator design in order prevent flooding and reentrainment. There is no known vertical flow, baffle-type mist eliminator that can be operated at velocities above 4 m/s without excessive mist carry-over. Consequently, ABB has developed a new mist eliminator design that is capable of gas velocities up to 6 m/s while providing excellent mist elimination. The new design has the following features:



- Inclined, well-drained, first stage bulk entrainment separator (BES)
- High efficiency, horizontal-flow, final stage mist eliminator (ME)
- Uniform gas velocity profile entering and leaving the final stage

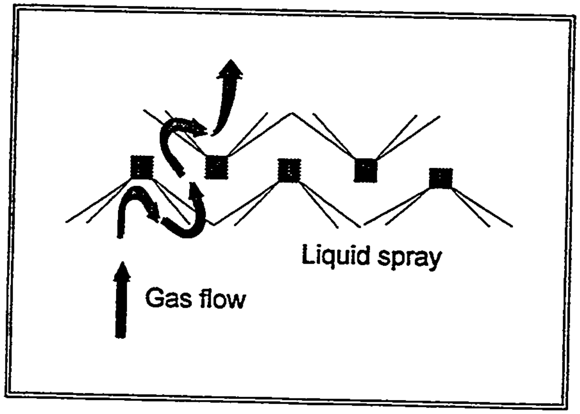


The uniform velocity profile afforded by ABB's new design is especially important. Without the unique BES, velocity profiles entering the final stage ME would be too high at the top and excessive carryover would result. Moreover, the velocity profile afforded by the BES provides a way for purging stagnant slurry from the roof of the absorber vessel, thereby preventing deposits from building up.

2. Reducing Spray Contacting Volume

Traditional mass transfer analysis in open spray towers often starts with the assumption of a uniform profile of droplets of a given volume-surface mean size, or in a more complex analysis, of a size ranging over a given droplet size distribution. These droplets are most often modeled as falling at terminal velocity through the counter-current contacting zone, while the gas passes upward through the falling spray.

ABB has conducted a number of detailed velocity measurements in a specially designed test facility to show that this traditional model for open spray tower gas liquid contacting is far from reality. Testing was performed on a 2 x 2 meter spray zone fitted with nozzles in a variety of configurations. In-situ gas velocity measurements were made using microfine dust and laser Doppler velocimetry (LDV).



What has been determined is that flue gas tends to flow around the nozzle spray pattern rather than through it. SO_2 mass transfer will occur most readily in zones with high rates of gas/liquid shear. Using the test facility, ABB has carefully studied velocity patterns from a large number of nozzle types and spray configurations and has determined that shear rates and SO_2 mass transfer can be maximized by careful placement of the nozzles in a staggered pattern. Liquid flux rates are increased dramatically, thereby decreasing the volume occupied by the spray zone and reducing the height of the absorber when compared to state-of-art designs. The net effect, when coupled with operation at much higher velocities (up to 6 m/s) is to dramatically reduce the size and power consumption of the absorber while maintaining very high removal efficiencies.

3. Decreasing Reaction Tank Volume

The reaction tank is a very important part of a limestone FGDS. The size of a forced-oxidized, limestone FGDS reaction tank is determined largely by the time it takes to substantially desaturate the liquid portion of the recycle slurry with respect to dissolved calcium sulfate. In addition, the size of the tank has an impact on the total amount of limestone utilized or the SO_2 removal in the absorber spray zone. Finally, the size (and shape) of the tank must be adequate to allow time for complete oxidation of the bisulfite to sulfate. Each of these factors must be understood and accounted for in sizing the tank to meet a specific gypsum specification and limestone utilization.

Optimum reaction tank sizing is further complicated by the performance of any primary dewatering device, which often not only separates most of the solids from the liquid but also fractionates the solids by size (and, as a result, by composition), recycling a different solids composition back in the overflow than what is discharged with the underflow. This solids fractionation by the primary dewatering device impacts the size and performance of the reaction tank.

ABB has studied these interacting effects extensively in both pilot scale and full scale facilities and has reached the following conclusions:

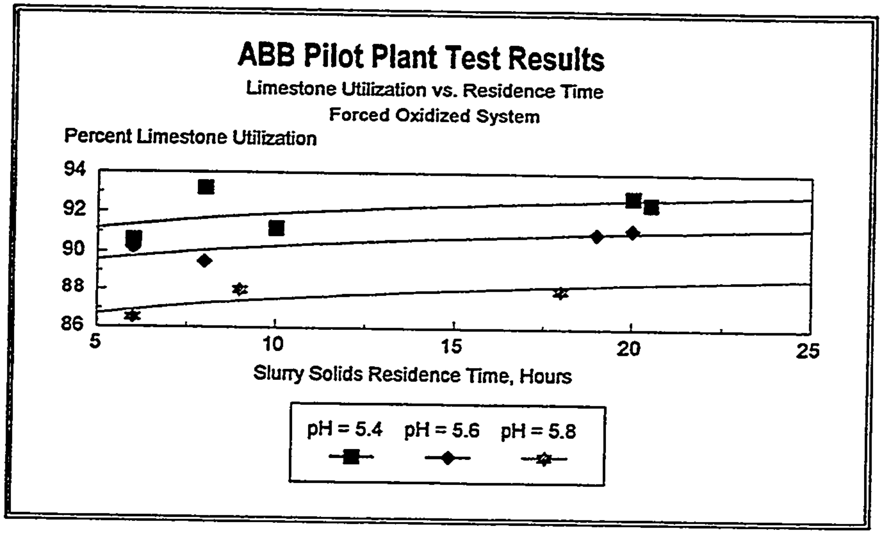
- Oxidation rate nearly independent of tank volume. At the pH and bisulfite/sulfite concentrations normally encountered in forced oxidation systems, the rate of oxidation is not very dependent on slurry residence time but more dependent on the rate of oxygen transfer from air to the liquid. Methods which enhance this mass transfer from the gas phase to the liquid phase have the most impact on the rate and degree of oxidation of bisulfite and sulfite to sulfate.

- Gypsum particle size not impacted by tank volume. Gypsum particle size seems to be more impacted by mechanical agitation than by solids residence time. Conventional gypsum-producing scrubbers have solids residence times of 15 hours or more. ABB has determined that reaction tanks with residence times as short as six hours may not produce a very significant reduction in gypsum particle size when compared to FGDS with much larger liquid residence times, because the intense mechanical agitation from pumping is the dominant size controlling mechanism, not the residence time.

- Gypsum desaturation can occur in less time than previously thought. Gypsum precipitation rates are fast enough with gypsum solids concentrations above 10% or more in the slurry to allow nearly complete gypsum desaturation with as little as two minutes of liquid residence time.

- <u>Limestone utilization impact from smaller reaction tank is small</u>. Limestone utilization will decrease with shrinking reaction tank volume, but the decrease will not be very significant for solids residence times over six hours. Conventional scrubbers have solids residence times of 15 hours or more, yet this time appears to be excessive for the benefit derived.

This last point would probably not be true if limestone were uniformly pulverized and graded (i.e., all particles of one discrete size). But pulverized limestone is a composite of many different sized particles, represented by a particle size distribution. The smaller particles quickly dissolve while the larger particles linger on, becoming smaller particles, and so forth. As a result, the impact of residence time on limestone utilization is less than expected, as shown below in data collected from pilot plant tests.



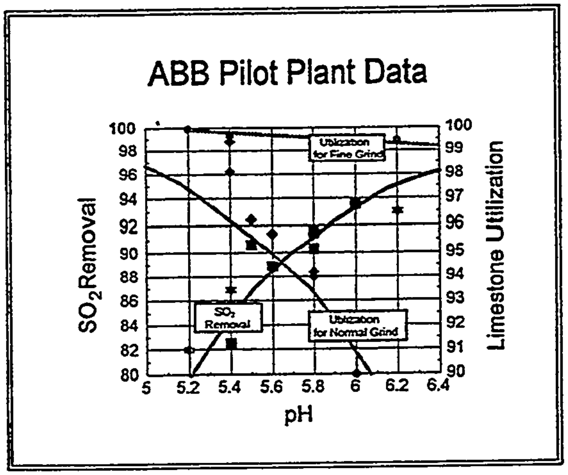
The pilot plant data shows a loss in limestone utilization of about 2% by decreasing the reaction tank residence time from 20 hours to 6 hours of solids holdup. This loss can be readily overcome by either decreasing the pH (<u>and</u> dissolved alkalinity) or by changing the grind size of the limestone. Because limestone dissolution in the spray tower contacting zone plays a substantial role in SO_2 removal by providing "instant" alkalinity from the solid phase to replenish any lost dissolved alkalinity, either technique can be satisfactory for recovering the lost utilization.

4. The Importance of Limestone Grind Size

Fast limestone dissolution in the contacting zone is important for liquid-phase alkalinity renewal. It can be expected that a more finely ground limestone will allow the system designer to decrease the recycle pumping rate, or L/G, while still achieving the same high degree of SO_2 removal. Limestone surface area is directly related to "undissolved" alkalinity, with the larger particles of limestone contributing relatively little to surface area but much more to the unreacted limestone passing out with the byproducts.

ABB has conducted pilot plant tests that show dramatically the impact of grind size on utilization. In the data shown below, a "fine" grind is 99.5% or more less than 325 mesh (44µm), while a "normal grind" is 80 - 90% < 325 mesh.

ABB has investigated the various means for achieving ultra-fine grinds of limestone (>99% < 325 mesh) and has determined that either dry roller-mill type pulverizers or tower mills offer power advantages over ball mills. Roller mills offer the additional advantage of accepting larger feed sizes (up to 40 mm stone size), thus reducing the intensity of precrushing required. Of course, roller mills can also produce normal grinds. Consequently, in the demonstration project described in the next section of this paper, ABB has elected to use a roller mill to produce limestone grinds over a very wide range (for evaluation purposes).



III. The LS-2 Advanced Scrubber Demonstration Project

A. Demonstration Plant Features

ABB's Stealth technology features substantial capital and operating cost savings for open spray tower FGDS:

- Higher gas velocity allows smaller absorber diameter, lower capital cost
- Compact spray contacting zone, lower tower height, reduced power cost
- Smaller reaction tank, lower height and diameter, lower capital cost
- More efficient use of slurry "undissolved" alkalinity, reduced power cost

In addition, ABB has identified some project and construction efficiencies that can substantially reduce the overall system cost without significantly compromising quality. These have been employed on other projects by ABB and others with a great deal of success. They are

- Use of standardized design to meet performance specification.
- Pre-approval of standardized design. Owner review required only for interface points, materials of construction, component redundancy, and operating/maintenance procedures.
- Accelerated schedule resulting from streamlined design procedures and pre-engineered construction package.

It is ABB's contention that a retrofit FGDS of the Stealth design can be built and placed into operation within 20 months of engineering release when a project embodies the principles outlined above. If these project criteria are in effect, the cost savings discussed in this paper will be readily realized.

To demonstrate both the innovative technology and the improved project efficiency, ABB has entered into an agreement with Ohio Edison to build a demonstration plant at the Niles Generating Station. The project was mobilized for engineering in November, 1993. It is anticipated that startup will occur in August, 1995.

The Niles project is called the LS-2 Advanced SO_2 Scrubbing Demonstration Project. The LS-2 plant embodies all the technical features of ABB's Stealth technology with the following additional cost effective and/or environmentally significant features:

- LS-2 is capable of taking the flue gas from either Unit 1 or Unit 2, or both simultaneously. The LS-2 plant is sized to process all the flue gas from one boiler (each boiler nominally rated at 110 MW). However, it is "cross-connected" in order to keep the gas processing rate and FGDS capacity factor high. The reasons for doing this will be discussed in the economics section at the end of this paper.
- LS-2 uses the existing power plant stack with its carbon-steel lined flue. LS-2 employs a novel, low cost method of reheat to prevent corrosion of the liner: a Ljungström reheater with horizontal shaft and with conventional gas recirculation for dirty-to-clean leakage control. The horizontal shaft orientation greatly reduces the amount and cost of expensive interconnecting ductwork.
- LS-2 uses unscrubbed flue gas for drying of the limestone in the dry pulverizer. The spent flue gas is returned to the scrubber to be processed.
- LS-2 uses a novel method for injecting the dry limestone into the absorber, avoiding dust entrainment.

- LS-2 employs a drop out bin under the centrifuges to eliminate problems and costs with conveyors. Wallboard-grade gypsum is loaded from these drop out bins directly onto trucks for transport to the end user.

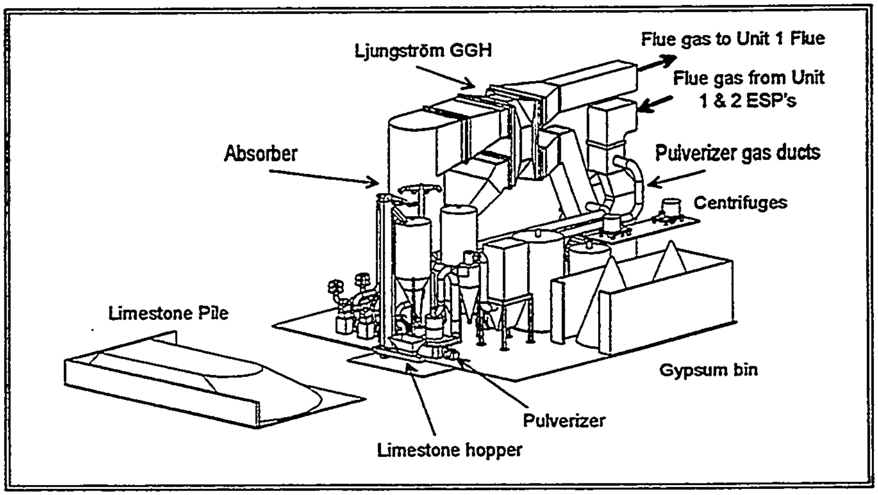
- LS-2 employs a PC-based, data highway control system with local PLC nodes performing the control and monitoring functions. PLC's are supplied and pre-programmed by each major subsystem supplier. The programs are checked out by ABB prior to final installation at the site, to ensure proper logic and acceptable man-machine interface.

In addition, several site-specific enhancements have been incorporated into the LS-2 project. The plant will be operated by only two full-time personnel: a control room operator and a rover. These individuals are also slated to operate the SNOX plant which is located next door. The SNOX controls (man-machine interface) will be moved to the LS-2 control room. Some plant maintenance and utility personnel augmentation will be required to handle the additional equipment and to load gypsum, limestone , and sulfuric acid (from the SNOX plant).

LS-2 is completely enclosed (except for the limestone pile and loading areas) to facilitate ease of operation and maintenance, even in the cold, northern Ohio winters. It is expected that loading of gypsum and limestone will require no more than five hours of outside activity for one person per day.

Since these features are site-specific, they are not considered in the economic projections discussed later in this paper.

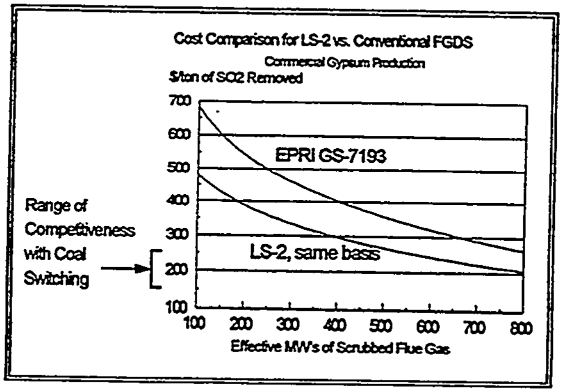
A 3-D view of the demonstatration plant is shown below.



IV. Cost Projection for LS-2 Scrubbing Relative to Fuel Switching

Detailed estimates for engineering, design, and construction of the LS-2 FGDS at Niles have been completed, and much of the equipment has been procured. Construction is well under way.

On the basis of actual cost projections, a relatively detailed estimate model has been formulated to project the cost of an LS-2 plant relative to EPRI projected costs for similar state-of-art FGDS as published in EPRI report GS-7193, "Economic Evaluation of Flue Gas Desulfurization Systems", Volume 1, February 1991. On an apples- to-apples project arrangement, whereby the customer chooses to incur typical engineering specification and evaluation costs, the projected cost savings for LS-2, embodying ABB's Stealth technology, are substantial. In fact, while the EPRI estimates show conventional FGDS costs never quite achieving cost competitiveness with fuel switching up to 750 MWe, LS-2 falls into a competitive cost range at or above 550 MWe size.



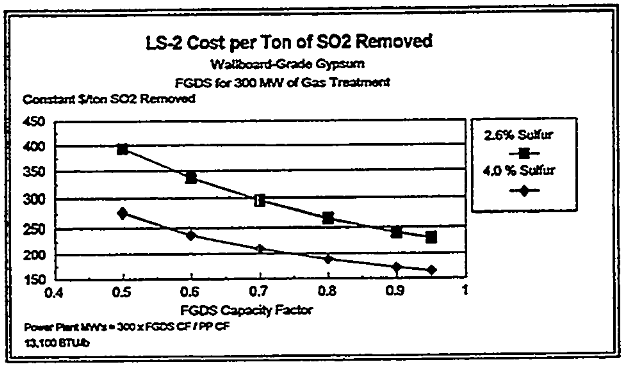
These economics can be further improved if some of the project and schedule economies being demonstrated at Niles are employed to engineer and construct the plant. To review, the project strategies are as follows:

- Use of standardized design to meet performance specification.
- Pre-approval of standardized design. Owner review required only for interface points, materials of construction, component redundancy, and operating/maintenance procedures.
- Accelerated schedule resulting from streamlined design procedures and pre-engineered construction package.

Incorporating project efficiencies that result from using these strategies, the cost of an LS-2 system can be further reduced. The LS-2 technology costs plotted on the curve above do not incorporate the project efficiencies mentioned above and are about 10% higher than LS-2 with the project efficiencies.

It is noteworthy that the cost projections shown above are for the EPRI basis 65% power plant capacity factor and for 2.6% sulfur bituminous coal. If higher sulfur coal is economically available, then the cost for scrubbing decreases on a $/ton of SO_2 removed basis. Further, and this is a big consideration, if the FGDS capacity factor is higher than 65%, the cost per ton of SO_2 removed decreases.

FGDS capacity factor is defined here as the average annual gas treatment rate divided by the design gas treatment rate. The capital cost of any FGDS is highly sensitive to design gas treatment rate. On a \$/ton of SO_2 removed, the capital recovery portion of the cost of scrubbing can be reduced by increasing the FGDS capacity factor. The impact of this effect on an LS-2 project for a nominal 300 MWe coal fired power plant is shown below.



It is very important to note that it is not necessary for the overall power plant capacity factor to be improved to achieve lower SO_2 removal costs. The lower costs can be achieved if the FGDS is smaller than required for full power plant operation. In this arrangement, the smaller LS-2 plant can be operated at its full rated gas flow even though the power plant may be turned down for evening or seasonal load reductions. With a smaller LS-2 system, the capital cost is lower and as a result the overall cost for scrubbing a ton of SO_2 decreases with increasing FGDS capacity factor.

A similar reduction in cost for scrubbing can be achieved if an LS-2 plant is cross-connected with several boilers and is smaller than the size required to take all the gas from all boilers simultaneously.

A most significant finding of these projections is that the cost of scrubbing with LS-2 project economics at 300 MWe is competitive with fuel switching when the economical base coal contains 2.6% sulfur or more and when the FGDS capacity factor is 90% or greater.

V. Conclusions

With Stealth technology, ABB has developed a landmark improvement in open spray tower FGDS that promises to reduce the cost of scrubbing dramatically over state-of-art systems. The improvements are to be demonstrated at the Niles Generating Station of Ohio Edison, with startup slated for mid 1995. Together with project execution enhancements demonstrated at Niles, LS-2 technology should offer a viable, economic alternative to fuel switching for many coal-fired boilers that have to comply with Phase II rules of Title IV of the Clean Air Act Amendments of 1990.

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Externally-Fired Combined Cycle: An Effective Coal Fueled Technology for Repowering and New Generation

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ABSTRACT

The Externally-Fired Combined Cycle (EFCC) is an attractive emerging technology for powering high efficiency combined gas and steam turbine cycles with coal or other ash bearing fuels. In the EFCC, the heat input to a gas turbine is supplied indirectly through a ceramic air heater. The air heater, along with an atmospheric coal combustor and ancillary equipment, replaces the conventional gas turbine combustor. A steam generator located downstream from the ceramic air heater and steam turbine cycle, along with an exhaust cleanup system, completes the combined cycle.

A key element of the EFCC Development Program, the 25 MMBtu/h heat-input Kennebunk Test Facility (KTF), has recently begun operation. The KTF has been operating with natural gas and will begin operating with coal in early 1995.

The US Department of Energy selected an EFCC repowering of the Pennsylvania Electric Company's Warren Station for funding under the Clean Coal Technology Program Round V. The project focuses on repowering an existing 48 MW (gross) steam turbine with an EFCC power island incorporating a 30 MW gas turbine, for a gross power output of 78 MW and a net output of 72 MW. The net plant heat rate will be decreased by approximately 30 percent to below 9700 Btu/kWh. Use of a dry scrubber and fabric filter will reduce sulfur dioxide (SO_2) and particulate emissions to levels under those required by the Clean Air Act Amendments (CAAA) of 1990. Nitrogen oxides (NO_x) emissions are controlled by the use of staged combustion. The demonstration project is currently in the engineering phase, with startup scheduled for 1997.

The anticipated near-term market for the EFCC is repowering of existing coal fueled power generation units. Repowering with an EFCC system offers utilities the ability to match existing steam conditions and improve the efficiency of existing plants by 30 to 50 percent, while reducing NO_x and carbon dioxide on a per megawatt (MW) basis. Furthermore, the EFCC concept does not require complex chemical processes, and is therefore compatible with existing utility operating methods and experience.

The long-term market for EFCC includes new power generation facilities using advanced combustion turbines in combined cycle operation. A conceptual design of a greenfield 300 MW EFCC plant has been developed. The facility has a net plant heat rate on a higher heating value (HHV) basis of less than 7000 Btu/kWh (over 49 percent efficiency), with very low SO_2, NO_x, and particulate emissions. The plant exhibits a highly competitive cost of energy.

EFCC Description

The Externally Fired Combined Cycle (EFCC) is an emerging technology for indirectly firing a gas turbine with coal or other ash bearing fuels. The EFCC concept offers power generators a highly efficient, cost-effective technology for repowering existing plants and for new capacity additions. EFCC plants are relatively simple in concept for design, construction, and operation, compared with other emerging technologies because most components are similar to those used in conventional power plants.

The EFCC Development Program is a cost-shared program between the US Department of Energy (DOE) Morgantown Energy Technology Center and a consortium of US and foreign utilities, industry, and state agencies. The EFCC Consortium is led by Hague International.

In the EFCC concept, shown on Figure 1, fuel is burned in an atmospheric combustor. The hot flue gas flows through a slag screen, which removes ash particles greater than 12 microns in size which might foul the air heater. The flue gas flows into a ceramic air heater, in which air from the gas turbine compressor is heated to turbine inlet temperature. After expansion through the gas turbine, the exhausted air flows to the combustor where it is used as combustion air.

Flue gas exiting the air heater flows to a heat recovery steam generator (HRSG), where steam for the bottoming cycle is generated. In some designs, the HRSG and the combustor are combined into an integrated steam generator (ISG). After flowing through the HRSG, the flue gas passes through flue gas desulfurization (FGD) and particulate removal systems before stack discharge.

The high efficiency of the EFCC concept offers significant potential in both new generation and repowering applications. In near-term new plant applications, this efficiency will exceed 45 percent (with heat rates less than 7,580 Btu/kWh) on an HHV basis. In the long-term, the EFCC has the potential to exceed efficiencies of 49 percent (heat rates less than 7,000 Btu/kWh). Furthermore, unlike other emerging coal fueled combined cycle technologies, the EFCC expands clean air rather than combustion gases through the gas turbine, increasing the service life of the turbine gas path. With existing FGD systems, sulfur emissions are maintained within regulatory requirements.

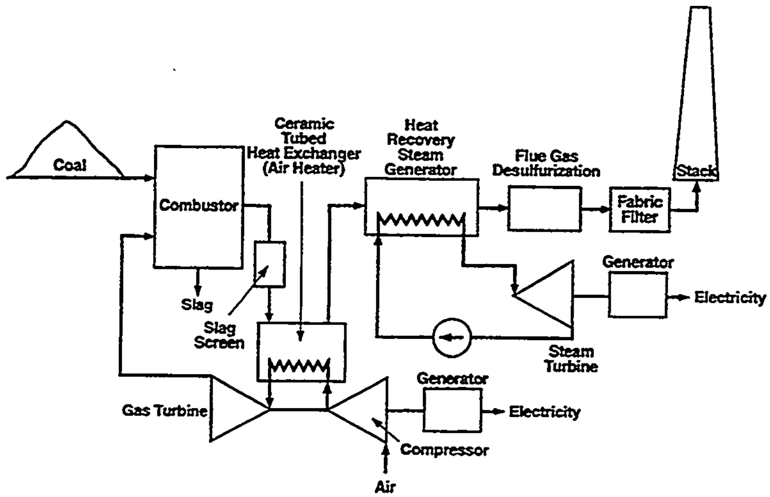

Figure 1. The Externally Fired Combined Cycle Concept

This paper discusses the background of the EFCC, the Kennebunk Test Facility (KTF), the Warren Station EFCC Clean Coal Technology Demonstration Project, the commercial plant concept, and the market potential for the EFCC.

EFCC BACKGROUND

Indirect fired gas turbine power plants have been studied since the 1930s, as summarized by Keller[1] in 1946. Applications of low rank coal and peat fired air heaters were reported by Keller and Gaehler.[2] In the 1950s, a 500 kW closed-cycle gas turbine with a peat fired, metallic air heater was built and successfully operated. This led to the installation of several cogeneration facilities which performed reliably. In 1950, Mordell[3] reported experimental studies at McGill University in Montreal, Canada, which showed promising results for an open cycle, indirect fired gas turbine, the predecessor to the EFCC. However, metallic air heaters used in these earlier versions of the cycle did not allow sufficiently high turbine inlet temperatures for economic power production.

During the 1960s, use of a ceramic air heater in indirect fired combined cycle applications was studied in concept, as summarized by LaHaye.[4] In 1971, Hague began a series of experiments with ceramic materials that culminated in the construction of the first ceramic air heater. Most of the work during this period was on heat recovery equipment (recuperators) for the secondary metals industry. By the early 1980s, about 50 low-pressure Hague units were in operation. These units have accumulated over 3 million hours of successful operation in corrosive, high-temperature, industrial environments.

In the early 1980s, Hague initiated work to increase the pressure capability of the ceramic air heater. In 1987, the USDOE and the EFCC Consortium, a consortium of electric utilities and industrial organizations, began to further pursue the concept.

Phase I of the EFCC development program was summarized by LaHaye and Zabolotny.[5] A low-pressure ceramic air heater was exposed to the products of combustion of a coal/water slurry over intervals of up to 40 hours. Ash buildup occurred on the air heater tubes, indicating the need for an upstream ash collection system. However, the ceramic tubes exhibited good mechanical durability and corrosion-resistance under all test conditions, and a method was devised to alleviate and remove ash deposits on the ceramic air heater heat transfer surface. Phase I was deemed a success by the Consortium members and a decision was made to proceed with Phase II.

Phase II of the EFCC development program, discussed by Vandervort et al.[6,7], began in 1988. This ongoing program has included high temperature and pressure tests of single tube strings, ceramic coupon corrosion and erosion tests, and tube material development. Successful testing of air heater components led to the final activity of Phase II, system testing at the Kennebunk Test Facility.

KENNEBUNK TEST FACILITY

The Kennebunk Test Facility (KTF), located in Kennebunk, Maine, is the first completely integrated system test of the EFCC technology. The KTF, which is shown conceptually on Figure 2, comprises a coal handling system, a 25 MMBtu/h heat input combustor, slag screen, three-pass high pressure air heater, 500 kW gas turbine, and a heat rejection system for waste heat, plus controls and ancillary equipment.

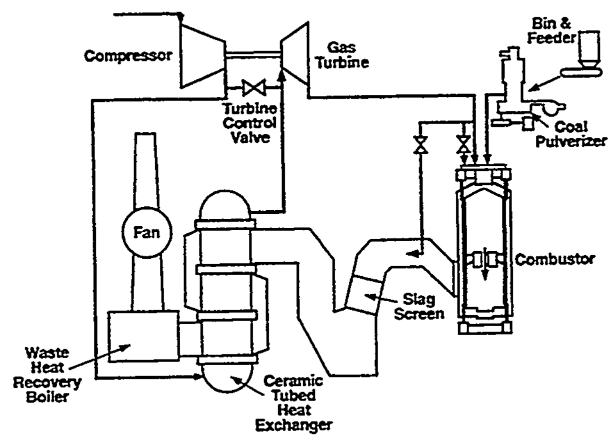

Figure 2. Kennebunk Test Facility

Combustor

The KTF is equipped with a low-pressure drop, air-cooled, staged combustor, shown on Figure 3. Staging is used for NO_x reduction. The combustor unit is down-fired into two cylindrical combustion chambers with the primary stage directly atop the second stage. The total height of the combustor, including the burner, is approximately 40 feet, and the outer diameter of the cylindrical casing is nominally 11 feet. Approximately 2/3 of the total volume is provided for the first stage, with the remaining 1/3 for the second stage. A collar divides the first zone from the second, and also provides convenient ports for the second stage combustor air. A cooling air annulus is built into the furnace insulating refractory. A slag tap is located at the base of the combustor.

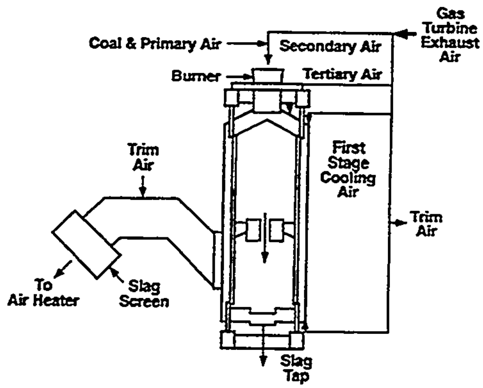

Figure 3. Kennebunk Test Facility Combustor

Screen

The slag screen consists of a staggered array of refractory tubes acting as an impact separator. A slag screen has been built and installed at KTF. Performance of the slag screen will be verified during KTF testing in 1995.

Ceramic Air Heater

The ceramic air heater designed for KTF is a three-pass shell-and-tube heat exchanger. A conceptual illustration of a three pass air heater is shown on Figure 4. The air heater has 72 vertically-oriented tube-strings for a total of 216 tubes. Tubes are supported vertically in compression, with the compressive forces developed by a spring-pack and bellows assembly on the cold end of the tube-string.

Ceramic air heater components being tested at KTF will permit air heater exit temperatures to approximately 1,810° F. However, to meet the goals of this program by the year 2000, a component optimization effort, focused on increasing the temperature capabilities of the ceramic components that comprise the air heater, will be performed as part of the future EFCC development program.

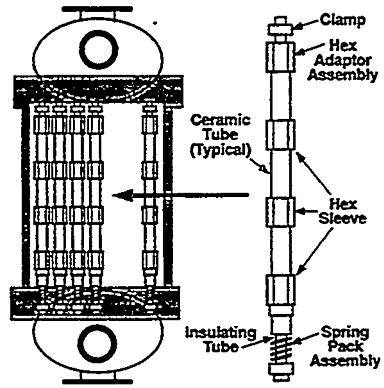

Figure 4. Air Heater Tube String Arrangement

Gas Turbine and High Pressure Piping System

The gas turbine at the KTF is a 500 kW Garrett Model IM831. The KTF air heater has a capacity to power a larger gas turbine; the 500 kW turbine was selected on the basis of availability to the project. As with most gas turbines used for indirect firing, the Garrett machine requires modifications for indirect firing. The conventional gas fueled combustor and associated fuel control system has been removed and replaced by a ceramic air heater fired by an external atmospheric coal combustor. The interface with the air heater requires a double-walled section of piping. The compressor discharge air flows to the air heater in the outer annular area, and the air heated in the air heater returns to the turbine section through the pipe section. The outer piping is fabricated from conventional metal materials and the inner liner from a fiber-reinforced ceramic material.

A turbine control valve system offers a key control of turbine output power. This system allows a portion of the compressor discharge air to bypass the ceramic air heater and mix with the hot discharge air to control the turbine inlet temperature. In this way, the ceramic air heater can be maintained as a nearly constant temperature heat reservoir, and gas turbine load variations are accommodated by control of the bypass flow. As the long-term heat duty of the exchanger varies, the gas inlet temperature can be modulated by regulating the coal firing rate and the combustion air.

Progress at the KTF

The KTF was fired in November 1994 with natural gas and with only metal tubes in the air heater, achieving an output of 300 kW. In February 1995, six metal tubes in the first pass were replaced with ceramic tubes. Firing with a mixture of natural gas and coal is planned for February. Initially, this cofiring will take place with six ceramic tubes in the first pass, and the remaining tubes being metal. The ratio of coal to natural gas will be increased and two full passes of ceramic tubes installed, leading to full firing of the KTF on coal by mid-April. The current goal is to operate KTF for a minimum of 100 hours of continuous operation and to accumulate a total of 300 hours of operation by May 1995. The KTF equipment is extensively instrumented to verify thermal performance, air heater pressure integrity, materials integrity, etc. Fouling or ash buildup will be monitored by video cameras, pressure drop measurements, and post-test evaluations.

WARREN STATION EFCC DEMONSTRATION PROJECT

The Warren Station EFCC Demonstration project, one of five projects selected by the USDOE in May 1993 under Clean Coal Technology Demonstration Program Round V, will repower the Pennsylvania Electric Company's (Penelec's) Warren Station Unit 2 with an EFCC unit. The repowered plant, which is expected to begin operation in 1997, will include a new combustor and HRSG (which are combined in an ISG), slag screen, ceramic air heater, gas turbine, scrubber, baghouse, interconnecting ductwork, and associated auxiliaries. The project team includes Penelec, Black & Veatch (B&V), and Hague International.

The Warren Station, shown on Figure 5, is in northwestern Pennsylvania, 2 miles west of the city of Warren, on the Allegheny River. Warren Station Units 1 and 2 began operation in 1948 and 1949, respectively. The station has four Erie City pulverized coal fueled boilers, each of which produces 225,000 lb/h steam at 875 psig and 885° F. Two Westinghouse steam turbine-generators, each rated at 48 MW, are in service. The units share a common stack, coal handling system, and circulating water system, which will continue to be shared by the repowered unit. The station is in good condition; repowering with EFCC will enable the station to produce energy at a competitive cost while complying with the 1990 CAAA.

The Warren EFCC unit will burn about 26 tons of pulverized bituminous coal per hour in a staged, atmospheric combustor. The combustor, which will be about 85 feet tall and 25 feet in diameter, is designed to reduce NO_x levels to 0.13 lb/MMBtu, well below New Source Performance Standard (NSPS) limits.

Hot flue gases will flow through a slag screen which removes ash particles greater than 12 microns in size. The gas will flow to a four-pass air heater comprising ceramic and metal tubes. The heat exchanger will be approximately 88 feet tall, 27 feet wide, and 8 feet deep. The exit air temperature will be 1,800° F.

Hot air from the air heater will power a 30 MW gas turbine which has been modified for indirect firing. Exhaust air from the gas turbine is used as combustion air in the combustor.

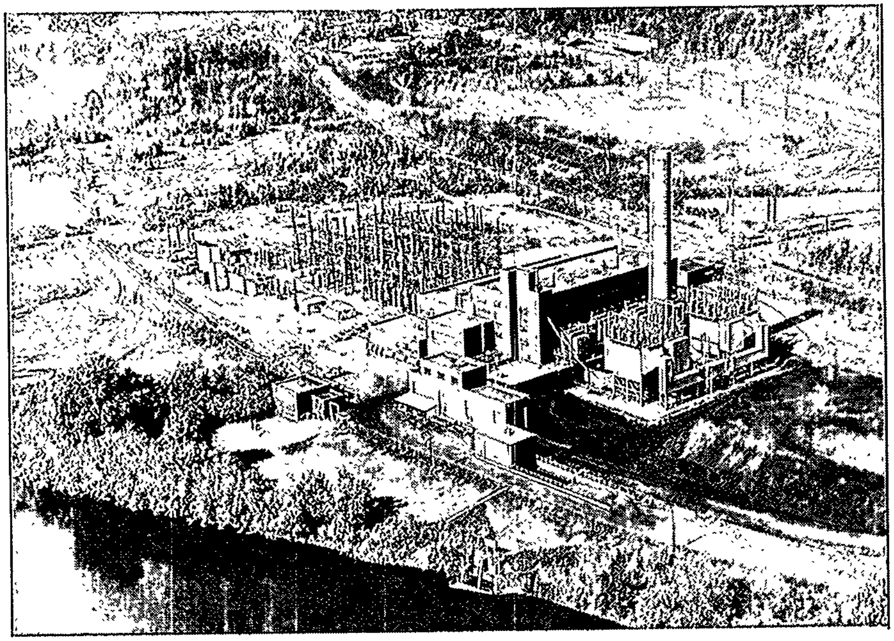

Figure 5. Existing Warren Station

Hot flue gas will exit the air heater and pass through the heat recovery portion of the ISG, which replaces two of the existing pulverized coal boilers. Steam from the ISG powers the existing Unit 2 steam turbine, producing 48 MW (gross). Flue gas exiting the ISG will be cleaned in a dry spray scrubber and baghouse system, reducing SO_2 by 80 percent and particulate to below 0.003 lb/MMBtu.

The projected capacity of the repowered Unit 2 is 78 MW gross (72 MW net), an increase of about 50 percent over that of the existing facility. The Unit 2 heat rate will significantly improve to below 9700 Btu/kWh which, in turn, will increase the dispatchability of the unit. The unit will exhibit very good part-load performance.

Phase I, Project Definition, activities to date include conceptual design, permitting, and work to obtain approvals associated with the National Environmental Policy Act. Detailed design and procurement are scheduled to start in June 1995, with initial construction to begin before the end of 1995.

The Warren EFCC Demonstration Project was reported in more detail in 1994 by Gray, et al.[8]

NEAR-TERM EFCC MARKET

The near-term domestic market for EFCC is likely to be repowering. The US has over 200 coal fueled power units in the range of 30 to 100 MW which are over 30 years old. Efficiencies of these plants range from 23 to 33 percent, with an average of 27 percent. Added to the coal fueled steam plants above 100 MW that are over 30 years old, the total exceeds 500 units. All of these are or will become candidates for repowering using the EFCC technology by 2010. The EFCC technology is particularly well suited to repowering these aging power plants for the following reasons:

- The cycle will boost the efficiency of the existing coal or oil fired units, increasing their dispatchability.
- The topping gas turbine with the steam generator sections can be tailored to match the steam conditions of virtually any of the candidate steam plants.
- Conventional flue gas cleaning systems can be employed, including wet or dry SO_2 scrubbers, fabric filters, or electrostatic precipitators. More advanced stack gas scrubbing and air toxic removal technologies can be used when they become commercially available.
- The dramatic improvement in fuel conversion efficiency reduces CO_2 emissions on a per MW basis.
- The coal currently in use, frequently from area mines, can continue to be used without beneficiation, maintaining a competitive cost with other energy sources.
- The concept remains competitive with other emerging technologies in the 50 to 100 MW range in terms of capital, maintenance, and operating costs.
- The EFCC technology offers an excellent opportunity for existing power generation sites to be used to generate power efficiently, avoiding the requirement of siting new plants.
- The EFCC plant is quite similar in concept to existing power plants and does not add new or complex chemical processes. Operators of existing utility plants can be easily trained for EFCC operation.

LONG-TERM EFCC MARKET

The long-term market for EFCC will include new coal fueled plants, both domestically and internationally. The domestic market for new baseload power generation remains small, with gas fueled generation capturing most of that market. The domestic market is expected to expand in the late 1990s as the current capacity surplus shrinks and existing plants age and retire. With likely increases in gas price, coal fueled plants will capture a larger share of the market with high efficiency, low emissions coal plants having a particular advantage. Because the worldwide growth of power generating capacity is four to five times that of the US, a significant international market potential is available for EFCC.

New EFCC plants will be extremely efficient. In 1992, Vandervort and Orozco[9] reported an EFCC design concept for such a plant. This design was based on the ceramic air heater providing 2,180° F air to a General Electric MS7001F gas turbine, resulting in a net plant efficiency of 44 percent (heat rate of 7,800 Btu/kWh on an HHV basis). The design at 2,180° F turbine inlet temperature is a conservative step in ceramic air heater development from the current KTF tests and the Warren Station design at 1,800° F air heater outlet temperature toward a mid-term goal of 2,300° F operation and a long-term goal of 2,500° F operation.

A conceptual design of an advanced, very high temperature, high efficiency, low emissions EFCC commercial plant was developed in early 1994 by Hague International and B&V, working with Manufacturing and Technology Conversion International (MTCI), Westinghouse, and Environmental Elements Corporation (EEC). This design requires significant developments in ceramic tube technology, beyond that currently available. The design is based on a Westinghouse 501G gas turbine, with an inlet temperature of 2,500° F. Sulfur removal is accomplished by sorbent injection in the combustor coupled with a backend dry scrubber, with the backend scrubber using carryover sorbent from the combustor. In addition to sulfur removal, the scrubber uses injected activated charcoal for mercury adsorption. The scrubber also serves as a conditioner for the electrostatic precipitator. NO_x reduction is accomplished through staged combustion in the combustor and through the use of a selective catalytic reduction unit in the HRSG.

Projected performance for the plant includes a net combined cycle plant capacity of 310 MW. At 100 percent load, the EFCC facility has a net plant efficiency exceeding 49 percent (7,000 Btu/kWh) on a higher heating value (HHV) basis. This is significantly higher than the efficiency of conventional pulverized coal plants (typically about 34 percent). This efficiency is also higher than efficiencies for integrated gasification combined cycle systems, which are typically in the 40 to 43 percent range. The EFCC plant exhibits good part-load characteristics.

Projected plant SO_2 and NO_x emissions are less than a quarter of the levels allowed by today's New Source Performance Standards. Removal of expected trace toxic heavy metals, excluding mercury, will exceed 99 percent. Expected mercury removal, including elemental mercury, will range from 90 to 95 percent.

CONCLUSIONS

The Externally-Fired Combined Cycle is an attractive emerging technology for powering high efficiency combined gas and steam turbine cycles with coal or other ash bearing fuels. Development of the technology continues with the startup of the Kennebunk Test Facility, leading to large scale demonstration at the Penelec Warren Station. Near-term commercialization will most likely focus on repowering applications, with long-term applications being very high efficiency, very clean new plants.

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COAL CLEANING: AN UNDERUTILIZED SOLUTION?

— by Robin L. Godfrey
Executive Vice President
Custom Coals Corporation

COMPANY BACKGROUND

Custom Coals Corporation is based in Pittsburgh, Pennsylvania. It is involved in the construction and operation of advanced coal cleaning facilities. The company holds patents on a suite of technologies which have the potential to convert over 200 million tons of U.S. mid to high sulfur coals, which cannot currently meet the arduous standards of the 1990 Clean Air Act Amendments, into a clean fuel which fully complies with these federal requirements. The company has initially chosen to focus on Pennsylvania's vast reserves of coal, because these coals provide a superior feedstock for the Technology.

In a $76 million project co-sponsored by the U.S. Department of Energy, Custom Coals is constructing its first coal cleaning facility. The DOE chose to participate with the company in the project pursuant to a competition it sponsored under Round IV of its Clean Coal Technology program. Thirty-one companies submitted 33 projects seeking approximately $2.3 billion of funding against the $600 million available. The company's project was one of nine proposals accepted and was the only pre-combustion cleaning technology awarded.

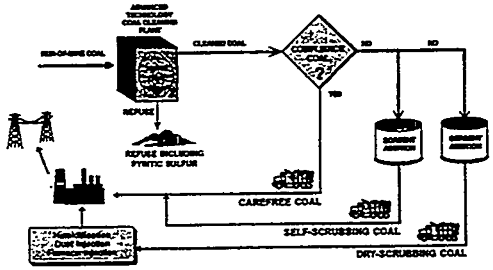
The project includes both the construction of a 500 ton per hour coal cleaning facility utilizing the company's proprietary technologies and a series of power plant test burns on a variety of U.S. coals during a 12-month demonstration program. Three U.S. coal seams — Sewickley, Lower Freeport and Illinois #5 — will supply the initial feedstock for the demonstration project. These seams represent a broad range of raw coal qualities. The processed coals will then be distributed to a number of generating stations for combustion. The 300 megawatt Martins Creek Plant of Pennsylvania Power & Light Co., near Allentown, Pennsylvania, will burn Carefree Coal; the 60 megawatt Whitewater Valley Power Station of Richmond Power and Light (in Indiana) and the Ashtabula, Ohio unit of Centerior Energy will burn Self-Scrubbing Coal. Following these demonstrations, the plant will begin full-scale commercial operation, providing two million tons of Pennsylvania compliance coals to electric power utilities.

CUSTOM COALS' SUITE OF COAL PRODUCTS

Custom Coals has a wide array of products for the compliance coal and other markets. The company's core products are Carefree Coal™ and Self-Scrubbing Coal™. Carefree Coal is a low ash, high Btu coal product produced through an aggressive, cost effective, physical beneficiation process. Beneficiation of coal refers to the removal of non-coal material from raw coal to produce a relatively clean coal product. Raw coal is composed of high purity coal material and non-coal material. Non-coal material in coal, commonly referred to as ash, normally includes pyrite, clays and other aluminosilicate materials. In producing Carefree Coal, approximately 90 percent of the pyritic sulfur contained in the coal's mineral matter (50 percent of the total sulfur) and most ash is removed with a innovative combination of recovering coarse clean coal, crushing and fine coal cleaning. For utilities burning non-compliance coals having pyrite that liberates easily and low organic sulfur levels, Carefree Coal can ordinarily reduce SO_2 emissions to 1.2 lbs/MMBtu thereby overcomplying with the 2.5 lbs/MMBtu Phase I standard of the 1990 Clean Air Act Amendments and meeting the more stringent Phase II standards. The unique process circuits required to produce Carefree Coal have been demonstrated at commercial scale. Custom Coals is already actively marketing Carefree Coal to utilities.

For utilities burning coal with moderate organic sulfur content and pyrite that liberates easily, Self-Scrubbing Coal may be the best compliance alternative. Self-Scrubbing Coal is produced by agglomerating (briquetting) a sorbent — dolomite, limestone, or dolomitic limestone — with the ultra-fine fraction of clean coal produced via the Carefree Coal process. These additives react during combustion to remove an additional 30 to 35 percent of SO_2 from the organic sulfur and remaining pyritic sulfur components. Because of the need to limit additives to avoid overloading boiler ash handling equipment, Self-Scrubbing Coal is most effective on coals having initial SO_2 levels of 4lbs/MMBtu or less. Several improvements result from using Self-Scrubbing Coal compared to earlier combustion trials by others in which the sorbent and coal were injected together through the burner. The positive effects of Self-Scrubbing Coal have been successfully demonstrated in test boilers but require a commercial scale Carefree Coal plant to produce the trainload quantities of feedstock necessary for full scale utility test burns. The completion of the Laurel plant will enable the company to perform such testing.

The characteristic of the feedstock coals and the requirements of the consumer determine whether Carefree Coal or Self-Scrubbing Coal is produced. Custom Coals also has another compliance coal in the development state. This product, Dry Scrubbing Coal™, is hoped to emerge as a cost-effective compliance option for utilities burning coal with high organic sulfur content or with pyrite that liberates only with difficulty. Dry Scrubbing Coal utilizes waste ash from the combustion of Self-Scrubbing Coal (basically calcined lime) as a hydrated sorbent in combination with any of several commercially proven, dry injection processes. Coupling Self-Scrubbing Coal with dry scrubbing technology allows nearly complete sulfur capture even in very high sulfur coals. Test data indicate removal of more than 95 percent of total sulfur from any coal at significantly less than the cost of conventional wet scrubbing technology. The significant savings result because sulfur is reduced prior to combustion and because refuse ash products are used as sorbents in lieu of costly commercial lime. Custom Coals has reviewed the dry scrubbing technologies which are presently available in the marketplace and identified those which are most compatible with Self-Scrubbing Coal technically and result in the lowest overall sulfur removal cost for high sulfur coals. Opportunities for an operating demonstration of Dry-Scrubbing Coal are being investigated and a more thorough evaluation of the market is underway.



Refined products which could be produced from Custom Coals' proprietary processes include coal water mixtures to be burned as a substitute for fuel oil, metallurgical coal for coking, pelletized stoker coal for industrial boilers, low ash-fusion coal for cyclone boilers, "smokeless" fuel briquettes for home heating in foreign markets and extremely low ash coal for activated charcoal.

CUSTOM COALS' TECHNOLOGY

Raw coal can be thought of as a physical mixture of four types of particles. Three of these are liberated. That is, they comprise more or less pure components. These components are organic material ("pure" carbon), which has a specific gravity of slightly less than 1.3; refuse, which has a specific gravity averaging about 2.6; and pyrite, which has a specific gravity of about 5.0.[1]

The fourth type of particle is locked, meaning that it consists of two or three of the pure components bound together. This locking of organic material with rock and pyrite gives rise to the spectrum of specific gravities characteristic of raw coal. For most raw coals, material which floats at 1.30 is nearly pure carbon; material which sinks at 2.0 is a combination of rock and pyrite; and material which sinks at 1.30 and floats at 2.00 is comprised of locked particles also called middlings. The amount of middlings in Eastern coals is substantial and varies considerably; fifty percent might be typical.

Most conventional coal cleaning sorts raw coal into two components: one less than and the other greater than a pre-selected gravity.[2] Therefore, conventionally, "clean" coal contains both free and locked particles. The locked particles that report to the clean coal bring sulfur (from pyrite) and ash (from rock) into the marketable "clean" coal product, reducing the quality of the product. Conversely, the refuse also contains both free and locked particles; these locked particles contain organic matter in this case constituting a loss of useful coal (heating value) and for the producers, a loss of revenues. Both outcomes are undesirable.

Custom Coals employs a three product separation as the starting point for Carefree Coal. The first separation at a low gravity floats the nearly pure coal and sinks all other particles. The second separation at a high gravity floats the middling particles and sinks the pyrite and refuse. The clean coal and refuse separated during this two step process are removed from the circuit and only the middling particles are passed along for further processing.

The Carefree Cleaning Process liberates the locked particles. This is the major factor distinguishing the Carefree process from conventional coal cleaning. The Carefree Cleaning Process crushes coarse locked particles to produce smaller particles. Most of the smaller particles are relatively free, depending on the type of raw coal. The washability of the coal — *i.e.*, the ease with which the rock can be separated from the coal — is a critical factor. This can only be determined through laboratory tests which will define the ash liberation characteristics of the coal. The company's goal is to reduce the ash level to 6 to 7 percent.

The principle steps in the Carefree Cleaning Process are:

✓ Recover a low specific gravity (1.30), coarse (plus ½mm) clean coal product.

✓ Reject a high specific gravity (2.0), coarse refuse.

✓ Comminute (crush) the middlings passed on by the three product separation (specific gravity 1.30 by 2.00) to minus ½mm to achieve additional liberation of the pyrite and other-ash forming minerals from the organic material. The extent to which the rock and pyrite liberated from the coal matrix upon crushing and grinding is a major factor determining the ease, and therefore cost, of producing a compliance coal. (Crushing and grinding to minus ½mm to achieve liberation of pyrite from the coal has not been

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1 Organic material or "pure" coal includes the various coal macerals. Pyrite includes two iron disulfide minerals, pyrite and marcasite. Rock, consolidated or unconsolidated mineral matter, embraces shales, clays, oxides, carbonates and accessory minerals.

2 One exception, froth flotation, separates the components on the basis of their surface properties. For hydraulic processes, *e.g.*, shaking tables, shape is also a separating factor.

generally practiced by the U.S. coal industry because there was no process for treating fines which efficiently separated coal from non-coal material.)

✓ Size and classify the resulting minus ½mm comminuted and natural material into three fractions — fines, ultra-fines and slimes. Discard the slimes; these are generally high in ash (50 percent or so) due to an abundance of clays.

✓ Clean the fines and ultra-fines in dense media cyclone circuits. In dense medium separation, raw coal is introduced into a medium having a specific gravity intermediate between that of coal and non-coal material. The dense medium may be a homogeneous liquid, but is more commonly composed of water and magnetic particles, such as ferromagnetic particles. Magnetite is a commonly used magnetic particle. To produce Carefree Coal, the company utilizes circuits which employ magnetite that is an order-of-magnitude smaller than conventional magnetite and cyclones of unique design. The magnetite is recovered in circuits designed for the size of the coal and refuse particles.

✓ Dewater all the clean coal fractions: coarse, fine and ultra-fine. Some thermal drying may be required depending upon the coal. For many coals, conventional dewatering of the coarser sizes coupled with thermal drying and agglomeration of just the ultra-fines is sufficient to meet market requirements regarding moisture and size consist. Thermal drying of the ultra-fines is achieved by indirectly heated dryers. The dried ultra-fines are briquetted. No binder is required, presumably due to the narrow size consist of the ultra-fines.

To achieve the above, there must be an efficient method for separating the resulting fine raw coal into a clean coal product essentially free of pyrite and refuse. Conventional technology does not achieve efficient separations at small particle sizes. Froth flotation, which is the only other commercially available technology, cannot distinguish coal from pyritic sulfur.

The widespread use of conventional dense media cycloning attests to its superior performance and versatility in beneficiating intermediate and small-size raw coal. Cleaning raw coal finer than ½mm in conventional dense media cyclones, however, gives poor results. Efficiency drops off sharply, and the separation gravity rises dramatically as particle size decreases. Both are undesirable. Both are also consequences of two theoretical limitations of commercial dense media cyclones for properly sorting fine particles. These limitations are:

- The medium is not homogeneous with respect to the fine size of the raw coal. That is, the particle size of the commercial magnetite comprising the media is too large. As the size of a particle of coal approaches the size of the magnetite comprising the media, the coal particle ceases to be submerged in media, which would buoy it up into the clean coal product. Rather, the coal particle is increasingly buoyed only by water in which it sinks, thereby being misplaced as refuse.

- The forces operating on the particles inside conventionally designed and operated cyclones are too weak with respect to the fluid resistance to impart the velocity required for separation.

To obviate these two theoretical limitations the following steps were taken.

- A new extraordinarily-fine magnetite was developed which is minus 5 microns (0.005 mm); one-tenth the size of conventional magnetite. This fine size eliminates the problem of conventional magnetite which is too coarse to be effective in cleaning fine and ultra-fine coal.

- Both the design and operating conditions of the cyclone were altered to overcome the problem of forces being too weak to effectively clean fine coal without, at the same time, overloading the cyclone.

The minus 5-micron magnetite and cyclone modifications constitute the heart of the Carefree Fine Coal Cleaning Process. All aspects of this novel dense media cleaning system, including minus 5-micron magnetite recovery, were demonstrated on a small but commercial scale at CQ Inc.

Self-Scrubbing Coal

Self-Scrubbing Coal is produced by agglomerating (briquetting) a sorbent — dolomite, limestone, or dolomitic limestone — with the ultra-fine fraction of clean coal produced via the Carefree Coal process. These additives react during combustion with the organic and remaining pyritic sulfur to remove an additional 30 to 35 percent of SO_2. Self-Scrubbing Coal attains year 2000 compliance with coals of moderate organic sulfur and pyrite that liberates easily. No additions to or modifications of the boiler are required with Self-Scrubbing Coal. It is received, stored, reclaimed, pulverized and burned the same as conventionally prepared coal.

Dry-Scrubbing Coal

Non-compliance coals that have difficult-to-liberate pyrite or high organic sulfur content can be prepared into a compliance product through Dry-Scrubbing Coal. While the Carefree and Self-Scrubbing Coal technologies can address reduction needs for many Pennsylvania raw coals, much of the Pittsburgh seam coal requires further treatment.

Dry Scrubbing Coal utilizes waste ash from the combustion of Self-Scrubbing Coal (basically calcined lime) as a hydrated sorbent in combination with any of several commercially proven, dry injection processes. Substantial amounts of unused calcium oxide are present in the flyash produced by burning the aggressively beneficiated coal to which sorbent was added. This lime is available to capture additional sulfur dioxide, either in the duct between the air preheater and the electrostatic precipitator or in an add-on spray dryer.

Two conditions are required for the capture of sulfur dioxide in spray dryers or in in-duct process. The temperature of the flue gases must be lowered to within about -9°C (15°F) to 2°C (35°F) of the adiabatic saturation temperature and an alkaline reagent, such as lime, must be present to react with the sulfur dioxide.

The percent removal of sulfur dioxide is good. For example, a capture of 43 percent attained by dry sorbent injection would be considered poor if viewed as a stand alone technology. When dry sorbent injection is integrated with Custom Coals' aggressive coal cleaning process, total sulfur reduction increases to 81 percent. This is sufficient to bring many coals into long-term compliance.

TESTING PERFORMED TO DATE

The merits of the technology described above were extensively evaluated at commercial scale during 1990 and 1991. The work was performed by independent experts in the related fields: Hazen Research for the production of fine magnetite; CQ Inc. for the performance of the fine coal cleaning circuits; Eriez Magnetics for the magnetics recovery circuits; Energy and Environmental Resources for the combustion testing of Self-Scrubbing Coal; and Teledyne Readco for the pelletization of the ultra-fine coal. The results of the pilot scale work are documented in a 3 volume study entitled, "A Technical and Economic Evaluation of Two Compliance Coal Technologies." Each of the advanced circuits was constructed and operated in CQ Inc.'s 30 TPH advanced coal cleaning research facility. The equipment sizes in the Laurel facility advanced circuits are identical to those used in the pilot plant testing. Following is a brief description of the work performed.

Magnetite Production. Several tons of fine magnetite were produced to conduct the coal cleaning and magnetite recovery tests. The properties of the magnetite were evaluated and the engineering data required to make an economic assessment of a magnetite production plant was secured.

Cyclone Performance Evaluation. Commercial size Custom Coals-style cyclones were fabricated, a suitable pump was secured and a test loop was constructed to assess the performance of the desliming and dense media cleaning circuits. Appropriate samples were obtained and analyzed to determine the performance of the desliming and cleaning systems.

Excellent (and essentially identical) separation efficiencies were obtained in both the pilot 2-inch, and commercial 10-inch diameter cyclones tested. Cleaning performance of the dense medium cyclones operating on small-sized feed is summarized below.

Description	Size	Probable Error, Ep
Fines	0.500 by 0.016	0.03
Ultra Fines	0.106 by 0.015	0.07

Magnetite Recovery Testing. Two systems were employed for recovering the fine magnetics from the fine clean coal and refuse; screening and magnetic separation. A series of fine screens was employed for recovering the fine magnetite from the ½mm by 150 mesh fine coal and refuse. Magnetic separators were employed for recovering the fine magnetite from the 150 mesh by 500 mesh fine coal and refuse. The separators were arranged in a rougher-cleaner-scavenger configuration. The rougher and cleaner magnetic separators employed relatively weak and inexpensive barium ferrite magnets. The scavenger magnetic separator employed a mix of the stronger and more expensive rare earth magnets with the barium ferrite. The conditions of feed rate, dilution water requirement and other variables affecting the system were determined. The products were assessed for both coal (or refuse) in the magnetite concentrate and magnetics in the coal (or refuse) product.

Thickening and Filtration. Each size fraction of clean coal and refuse produced ultimately must be separated from the large quantities of process water used. Screening, centrifuging, thickening and filtration either individually or in some combination are the most commonly used techniques for solid-liquid separation. Several types of solid-liquid tests were performed to provide design data necessary for determining optimum sizing of the equipment and establishing economics including (1) thickening and filtration tests for the fine magnetics, (2) thickening and filtration tests for the fine refuse; and (3) thickening and centrifugation tests for the fine clean coal.

Agglomeration. Agglomeration is the sticking together of many smaller particles to form larger particles. Briquetting is an example. Agglomeration requires pressure to bring the small particles into contact with each other and typically a binder is required to cause them to stick together when in contact. Briquetting tests performed in February 1993 established that the Carefree Coal fines can be agglomerated without the addition of a binder. The briquettes produced were weather resistant and of sufficient strength to withstand transportation, storage and power plant handling.

Combustion Testing. The objective of this work was to establish, at a significant scale of combustion, that Self-Scrubbing Coal works to remove SO_2 and that no negative effects on the boiler system result from its use. Self-Scrubbing Coal was burned at a firing rate of 1,000,000 Btu per hour in a test boiler with a time-temperature profile similar to an example utility power station. Slagging and fouling were assessed along with the effect of ash from Self-Scrubbing Coal on particulate collection.

ADVANTAGES OF THE TECHNOLOGY

Carefree Coal

In most cases, the extra cost will be more than offset by several considerations.

- ✓ *Higher Quality.* Carefree Coal is lower in sulfur, lower in ash, has a higher Btu content and is easier to handle than conventionally cleaned coal.
- ✓ *Higher Yields.* The Carefree Coal process will produce higher yields of finished coal from a given feedstock, 10 percent to 25 percent more. The value of this increase in yield typically exceeds the incremental capital and operating costs.
- ✓ *Higher Utility Plant Boiler Availability.* Burning low ash coal reduces boiler slagging and fouling resulting in less downtime for maintenance. Increases in power plant availability result in substantial savings.
- ✓ *Lower Transportation Costs.* By reducing ash, the Btu value of coal can be raised 10 to 15 percent, yielding proportional savings on transportation costs. Transportation frequently represents 30 percent of the delivered cost of the coal. The ability to use local coal to produce Carefree Coal also mitigates this expense.
- ✓ *Reduced Ash Disposal Costs.* Savings of as much as $15 per ton of fly-ash disposal can often be projected. This is a savings of $1 per ton of coal burned where markets for fly-ash by-products have not been developed.

The above factors can yield net savings for the utility far greater than the incremental coal cost, producing in a sense a "negative compliance cost." However, the real economic value of Carefree Coal lies in its ability to turn non-compliance coal into compliance coal, thereby transforming its market value. Historically, coal has been sold principally on the basis of its Btu value. Now, and increasingly in the future, it will be priced to reflect its sulfur content.

It is accepted wisdom that compliance coal will eventually command a market premium over non-compliance coal in the environment created by the 1990 Clean Air Act Amendments. The size of the premium is dependent on a number of facts, the most important of which may be the number of utilities which opt for an early installation of scrubbers as opposed to those who favor coal switching to lower sulfur coal from other regions. Based on market studies by the Research Data Institute, the 1995 premium for compliance coal over higher sulfur products is expected to be in the range of $5 to $10 per ton.

Self-Scrubbing Coal

There are several improvements that result from using Self-Scrubbing Coal, especially when compared to earlier combustion trial by others in which both the sorbent and the coal were injected together through the burner.

- ✓ *Less sintering occurs with low-NO_x burners, a requirement of the recent amendments to the Clean Air Act.* Sintering causes a loss of sorbent reactivity due to a reduction in the surface area of the sorbent. Greater sintering occurs at higher temperatures and less at lower temperatures. Sintering is minimized by low-NO_x burners that provide an improved time/temperature profile for SO_2 capture.

✓ *Slagging is reduced.* Ferrous iron aggravates slagging. Removal of 85 to 95 percent of the pyrite during coal cleaning substantially eliminates ferrous iron and therefore its fluxing action on siliceous constituents.

Most minerals found in coal are not volatile at the flame temperatures encountered during combustion. Illite and biotite, found in the shale and clay groups, are mostly removed by the unique desliming step, part of the aggressive beneficiation process.

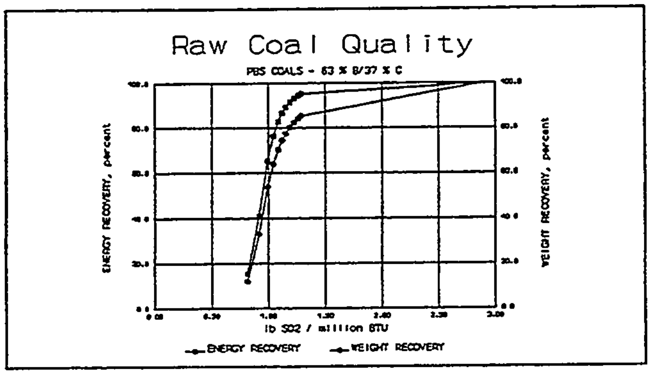
Organically bound calcium contributes to slagging. Calcium from dolomite or limestone is not volatile at the temperatures encountered at potential slagging surfaces.

✓ *The quantity of ash is not excessive.* Aggressively beneficiating the coal before introduction of the sorbent keeps ash levels near or below pre-established levels.

✓ *Higher removals of sulfur dioxide are possible due to greater calcium to sulfur stoichiometry.* The aggressive beneficiation reduces sulfur substantially. For a given quantity of sorbent, lower sulfur means greater calcium-to-sulfur ratios. And, proportionately greater capture of sulfur dioxide occurs with higher calcium-to-sulfur ratios.

✓ Water soluble alkalies are removed by the beneficiation process, thus reducing the potential for fouling.

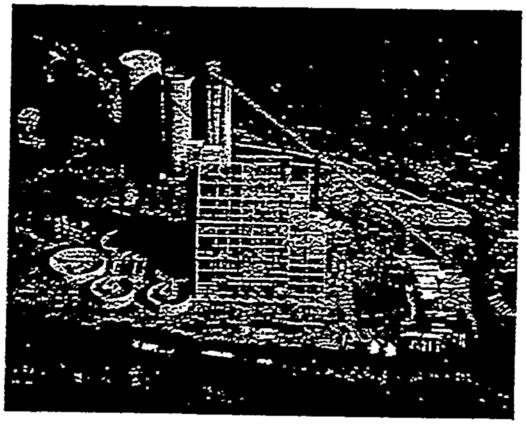
EXAMPLE WASHABILITY



Laboratory analyses of a Kittanning seam have been performed to simulate the impact of aggressive cleaning utilizing the Custom Coals technology. From this analysis, it is possible, through the use of various computer models, to predict the quality of the final clean coal product and the amount of that product that can be produced from a given ton of raw coal feed. This relationship is expressed in the form of a grade/yield curve and is shown on the following page. The grade/yield curves for this coal indicate that a Btu recovery of 92% and a weight recovery of 80% can be achieved when producing a 1.2 lbs SO_2 product.

THE LAUREL FACILITY

The Laurel facility is the flagship of Custom Coals' U.S. operations. This 500 ton per hour facility located in western Pennsylvania is the first commercial application of the company's patented advances in coal cleaning technology. Design engineering for the plant was completed by internationally renowned ICF Kaiser Engineers. All construction engineering was performed by Affiliated Engineering Technologies, Inc. a group of experienced coal preparation construction engineers. Riggs Industries, a company with over 20 years of experience in constructing coal preparation facilities, served as construction manager. The raw coal sources for Laurel come from the Kittanning Seams in Somerset County where, as previously noted, extensive washability and liberation studies have been performed on coals from a number of mines. The Laurel project will require approximately 2.9 million tons of raw coal per year for a total of 58 million tons over the project's 20 year life. A long-term contract has been signed with PBS Coals to provide 40 percent of this requirement for 1995 through 1999.

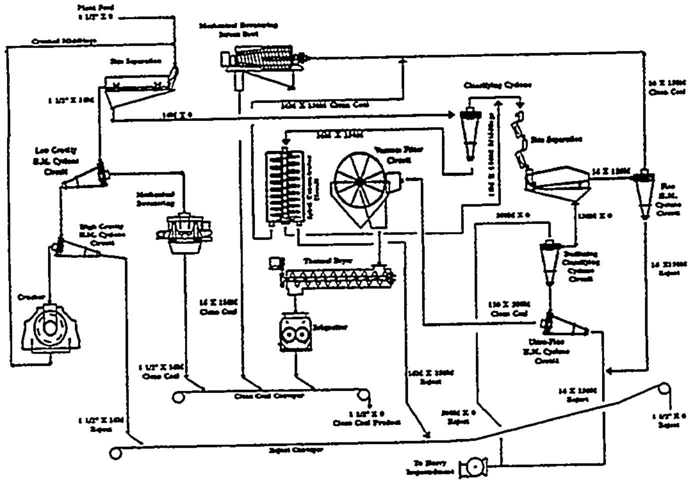


Aerial view of the Laurel facility at approximately 60 percent completion

The site can receive up to 40 trucks of raw coal per hour, or approximately one truck every ninety seconds. Raw coal is weighed and sampled before being dumped into one of four 60-ton capacity raw coal bins from which it is conveyed to stacking tubes. Each bin has its own vibrating feeder, and each pair of bins feeds a separate stacking tube, permitting two distinct raw coal feedstocks to be received and stockpiled at the same time. Coal can be reclaimed to the preparation plant at the rate of 500 tons per hour. A reinforced concrete reclaim tunnel with a total of ten draw-down hoppers and ten vibrating feeders permits the plant to be fed by a minimum of two feeders or by any desired combination of feeders. The feeders are equipped with variable frequency controllers to permit the rate of discharge to be controlled by the plant operator.

As previously discussed, the Larrel project employs a three product separation as the starting point for producing Carefree Coal. The first separation at a low gravity floats the nearly pure coal and sinks all other particles. The second separation at a high gravity floats the middling particles and sinks the pyrite and refuse. The clean coal and refuse separated during this two step process are removed from the circuit and only the middling particles are passed along for further processing. The middling particles are crushed, in closed circuit, to pass ½mm and then cleaned in two size fractions. The 16M x 150M size fraction is cleaned first in spiral separators, followed by advanced heavy media cyclones. The 150M x 500M material is cleaned in advanced heavy media cyclones.

Dewatering is accomplished by centrifuges for the coarse and intermediate size fractions. The finest coal is thermally dried and can be discharged to the clean coal conveyor or go instead to a briquetting process. The briquetting machine (compactor) uses very high pressures to form the fine clean coal into stable briquettes measuring 3" x 2" x 1⅝".



Flowsheet representation of the Laurel facility

The Laurel facility also includes state-of-the-art clean coal handling and sampling capabilities. A two-stage sampling system and an on-line elemental analyzer monitor and record the quality of clean coal being generated by the cleaning plant. The immediate availability of analytical information afforded by the analyzer allows the plant operator to make real-time adjustments in the processing circuits to maintain product quality within established limits.

Clean coal can be directed into either of two 5,000-ton clean coal silos leading to the railcar loadout facility or to the 5,000-ton silo that is part of the truck loadout facility. The railcar loading facilities have a rated capacity of 2500 tons per hour and a flood loading unit train loading bin. The automated truck loadout facility is capable of loading trucks at a rate of 750 tons per hour.

The clean coal product shipped from the plant will meet the 1990 Clean Air Act Amendments year 2000 SO_2 emission standard of 1.2 lbs SO2/MMBtu. It will have a heating value of 13,200 Btus/lb with 9 percent ash, 6 percent moisture and 17 to 18 percent volatiles. The size distribution of the clean coal product minus the briquettes would be as follows:

1½ inches x ¼ inch	30.2%
¼ inch x 100 M	62.2%
100M x 150 M	7.6%
-150M	0

LAUREL CAPITAL COSTS

The table below presents the construction cost estimates for the project by cost category. Design engineering was completed by ICF Kaiser Engineers in July 1993. The deliverables from this effort included balanced process flowsheets, site layout drawings, plant general arrangement drawings and piping and instrumentation drawings. A fixed price construction engineering contract has been signed with Affiliated Engineering Technologies, Inc.

A construction management agreement was executed with Riggs Industries who has 20 years experience in constructing coal preparation facilities. The total value of the contract is $1,000,000. The services to be provided under the contract include: (1) site coordination and oversight; (2) preparation of construction bid packages and review of bids; (3) scheduling; (4) coordination of change orders; and (5) site safety and security. Individual construction packages are being competitively bid and awarded as engineering is completed. All construction contracts are fully bonded and contain "no lien" provisions.

500 TON PER HOUR PROCESSING RATE

	Original Budget	Anticipated at Completion
Site Acquisition/Bonds	2,450,000	1,789,129
Engineering	1,109,525	1,200,000
Equipment	11,200,692	11,200,692
Structural Steel	2,500,000	1,700,000
Construction	18,950,842	18,950,842
Admin Building	620,000	620,000
DER Compliance Costs	500,000	500,000
	$37,331,059	$35,960,663

LAUREL OPERATING COSTS

Custom Coals has estimated the operating costs and the estimate has been reviewed by an outside consultant. The total commercial operating cost of producing Carefree Coal™ at the Laurel facility has been estimated as follows:

Tph	500
Hours	5,800
Raw Tons	2,900,000

	Dollars ($)	Raw Ton ($)
Plant Labor & Fringe Benefits	2,121,416	0.732
Refuse Disposal	298,759	0.103
Mobile Equipment Rental	172,800	0.060
Laboratory	148,435	0.051
Electricity	1,499,279	0.517
Magnetite	707,600	0.244
Plant Security	22,620	.008
Dryer Fuel	696,619	0.240
Chemicals & Flocculants	333,971	0.115
Operating Supplies	110,466	0.038
Maintenance Supplies	317,389	0.109
Insurance & Licenses	49,611	0.017
Other	82,478	0.028
TOTAL	6,561,443	2.263

EVALUATION OF SULFUR REMOVAL ECONOMICS

A processing cost/ton estimate was developed using the capital and operating cost estimates and assuming a 15 year amortization of the capital. It was also assumed that the long-term processing contract would support 80% debt financing at an 8% interest rate.

	$/YR	$/RC TON	$/CC TON
Operating Cost	6,561,443	2.263	3.017
Capital Recovery	4,153,333	1.432	1.910
Total	10,714,776	3.695	4.927

The utility industry frequently ranks compliance alternatives based on the $/ton of SO_2 removed. To make that calculation for an advanced coal cleaning compliance solution, it is necessary to compare the incremental expenditure on coal cleaning to the decreased emissions of the clean coal product. The proposed processing cost of $4.927 per clean ton represents an increase of approximately $2.427 per clean ton over conventional cleaning. The tons of SO_2 emitted drop from a rate of 2.5 #SO_2/MMBtu to 1.2 #SO_2/MMBtu or 36,758 annual tons of SO_2 assuming the combustion of 2,175,000 tons. Therefore:

$$(\$2.427 \times 2{,}175{,}000) \div 36{,}758 = \$144/\text{Ton } SO_2 \text{ removed}$$

Coal Fueled Diesels for Modular Power Generation - Operating Experience with 1.7% Ash Coal-Water Slurry Fuels, *K.R. Benedek, R.P. Wilson, Arthur D. Little, Inc., J. Parkinson, CQ Inc., and A.K. Rao. Cooper Bessemer Reciprocating, U.S.A.*

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Recent Development of CWS Combustion Technology In China

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Introduction:

China is the largest producer and consumer country of coal which is the most principal elementary energy in China. One of the major factors in restricting national economy development is the uneven distribution and intense transportation of coal. It is a tremendous energy consumption to burn 30,000,000 tons of oil each year. Therefore, the important tactics in developing national economy in China is to realize the replacement of oil by coal in the near future and coal transportation in pipeline at a specified future date.

Just as the above saying, China has been keeping on studying and developing CWS technology in recent years, though the commercial applications of CWS technology ceased one after another with the international petroleum price dropping. The development of CWS combustion technology is introduced in particular here.

CWS technology research started in the early 1980's and was concentrated in such scientific research institution as the Chinese Academy of Sciences and Zhejiang University to conduct few experimental study. It was listed in national "6.5" key task project in 1983. And experimental research and test work was accomplished basically in the early six months of 1984.

The ignition and combustion test on 1.5 mw boiler was done successfully in Zhejiang University in May, 1983. Many combustion tests had been done on 20t/h boiler in Beijing No.1 Paper Mill using combustion technology explored by Zhejiang University by the end of 1985 and the desired requirements was achieved with 687 hours of total operating period 143 hours of longest continuous operating period and 2400 tons of CWS burned in total. The remake of burner nozzle and boiler was formed initially, which paved the way for the further expanding application.

One of the national "7.5" key task projects had been implemented since 1986, whose emphasis was laid upon improving CWS--firing technology on the 60t/h oil--fired boiler in Beijing No.1 Paper Mill. Large--scale tests were conducted many respects such as short--distance pipelines systems in front of furnace, technology, burner technology and furnace remake technology etc. in early 1990 through near 5--year effort. While all technical targets attained international commercial requirements and standards and relatively systematically technology of combustion and application was formed, CWS application in industrial boilers was expanded apparently and achieved successfully.

The research center upon CWS--firing technology exploration on utility boilers was listed in the national "8.5"key task project and CWS--firing application scope was further enhanced. Now many CWS application projects are in the testing and implementing process, which includes CWS--firing application on 230t/h oil--fired boiler in Bai Yanghe generating plant, 75t/h coal--dust--fired boiler, 35t/h CWS-fired boiler, 35mw tunnel oil--fired boiler and other industrial boilers etc. This paper mainly introduces the developing situation in this respect.

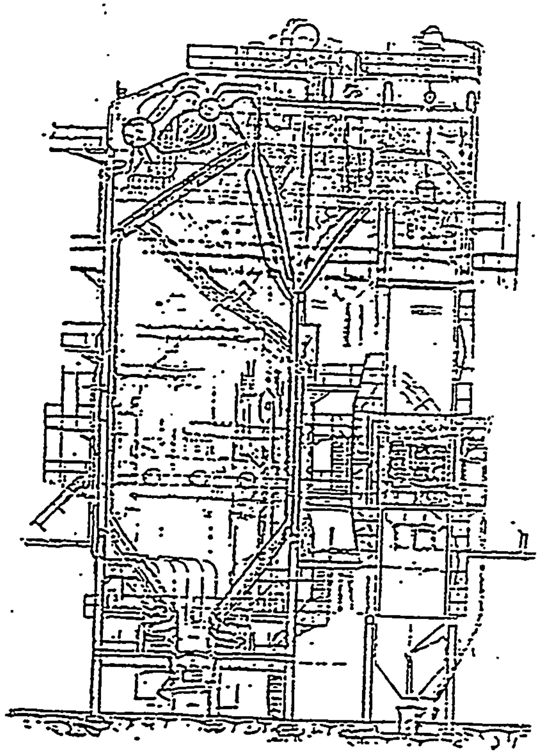
Development of CWS Combustion Technology on Utility Boiler

1. Technology of retrofitting 230t/h oil--fired boiler into CWS-fired one in Bai Yanghe power plant.

The No.3 230t/h boiler in Bai Yanghe power plant was designed to burn coal and was changed to burn oil when installed. Its construction was showed in Figure 1. This boiler belong adopt coal suspension combustion dry slag drawing system way and has a rectangular chamber whose section area is 10 m × 7.6 m with water--cooling wall arranged fully at four sides. Slagging catching water tubes are fixed up at outlet of furnace; Double superheaters are arranged in horizontal exhaust pass and two economizers and two air preheaters are installed in heat recovery area. In the original design burners were fixed up (symmetrically) in both side walls. Having been changed to burn oil, tangential firing way and tangential burners were adopted with 3 mechanical atomizing oil nozzles arranged vertically in every burner. The air registers were employed in order to match to the system.

The main technological properties on the originally designed boiler are as follows:

Boiler capacity	230 t/h
Superheated steam pressure	101 at
Superheated steam temperature	510 °C
Feed water temperature	215 °C
Exhaust gas temperature	140° C
Boiler efficiency	91.5 %
Hot--air temperature	365° C
Fuel	PingDingShan Coal (70%) and XingMi Coal (30%)
Fuel consumption	30230 kg/h
Furnace outlet temperature	1107 °C
Heat liberation per unit furnace volume	114×10^3 kcal/m^3•h



(1) burner (2) drum (3) slagging catcher

(4) superheater (5)economizer (6) air preheater

Figure 1 No.3 230 t/h utility boiler (original design)in Bai Yanghe power plant

Tangential fired burners are adopted after transforming to burn CWS in order to ensure steady CWS ignition and combustion for the ratio of furnace section length to width is relatively large which is equal to 1.33. And CWS burners with side secondary air arrangement are selected at each angle showed in figure 2. It is feasible to use CWS only as fuel, or oil only, or burn the blend of CWS and heavy oil.

Burners are separated into 7 layers from bottom to top successively No.1 layer for the lower secondary air nozzle; No.2,3,4 layers for CWS burners with side secondary air arrangement in which the No.4 layer can also be used for oil firing; No.5,6 layers for oil burners in which No.5 can also be used as up--secondary oil nozzle when firing CWS; No.7 layer--the top for third air nozzle .

The oil burners located No.4,5,6 layers are put into operation with other nozzles using stopped at rated load when firing CWS.

Mechanical atomizing nozzle is adopted for each oil--fired nozzle whose designed capacity is 1.25 t/h. The dashing multi-atomizing CWS nozzle, which is designed by the Institute For Thermal Power Engineering in Zhejing University.

Boiler capacity 230 (t/h)

Overheated steam pressure 101(ata)

Overheated steam temperature 501(501) °C

Feed--water temperature 215(215) °C

Exhaust gas temperature 136(131) °C

Boiler efficiency 89.94(93.69) %

Hot--air temperature 335(312) °C

Fuel Bayi CWS (heavy oil)

Fuel consumption 33278(14782) kg/h

Heat release rate at furnace volume 125×10^3 (120×10^3) kcal/m^3 .h

Remake the no.3 angle oil--fired burner of the boiler to a burner which can be used for both CWS-firing and oil--firing in order to get experimental date of CWS burner design with side secondary air arrangement.

It is the successful promise of CWS combustion to ensure the continuous normal operation of CWS system in front of the furnace showed in figure 5, which was designed and installed for test of burning CWS .

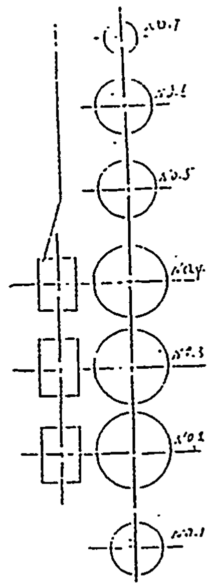


Figure 2 CWS burner with side

secondary air diagram

The main technological properties of CWS or oil--fired boiler at rated load after having been transformed to burn CWS as follows (the date for oil--firing is in the parentheses)

The CWS transported from CWS plant is poured into 100m^3 CWS storage tank by CWS discharge pump. Pump CWS in the tank to the stirring tank by transferring pumps, then transport it to the nozzle of the CWS burner through regulating valve in CWS feed--in pipe after CWS is stirred and poured into revolving CWS fitter by the pump in front of furnace. Two sets of double transferring pumps, stirring tank, pump in front of the furnace and revolving filter are designed operating and one stand--by CWS manometers are fixed behind pump in front of furnace, revolving fitter, CWS feed--in regulating valve and before each CWS nozzle. The atomizing medium used in test is steam from boiler itself and wash water is from the mother pipe of industrial water in the boiler house.

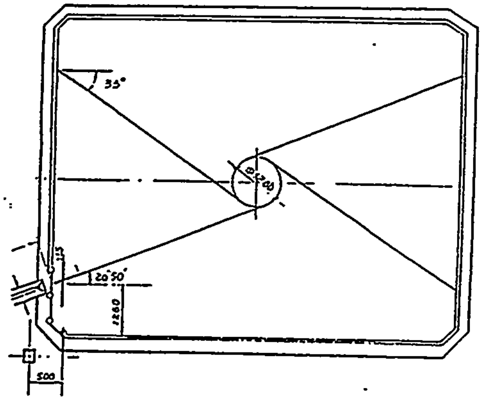


Figure 3 The diagram of the furnace

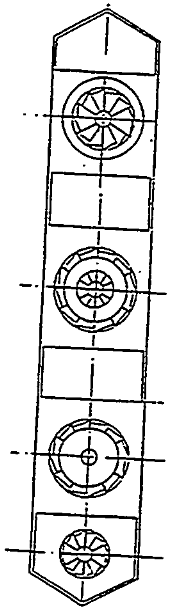
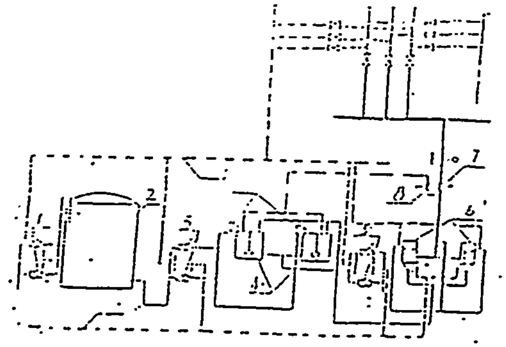


Figure 4 The diagram of the single CWS burner at No. 3 corner



atomizing steam pipe
CWS feed--in pipe
CWS circulating pipe
wash water and waster water pipe

(1) CWS discharge pump (2) CWS storage tank (3) Run pump (4) stirring tank (5) pump in front of furnace (6) CWS revolving filter (7) regulating valve in CWS feed--in pipe (8) regulating valve in CWS circulating pipe

Figure 5 CWS system in front of furnace

CWS used in the test, which is prepared according to industrial adapted condition in ShanDong 8.1 CWS plant, has been stored for 4 months in 100m tank and suffered freezing. Have been unfreezed and stirred by compressed air. CWS is used 59.1 % and whose low heating valve Qdw is 4000 kcal/kg.

The results of the No.3 single angle burning test are listed in table 1. The observing results indicate cws can be ignited and burned steadily under each operating load; no black exhaust occur; The flame is complete and bright; No coal pellets descend; Igniting distance is less than 600mm away from burner outlet. The main conclusions are as follows.

1. The quality of CWS prepared by ShangDong 8.1 CWS plant is good and accord with the demands of transportation, storage, conveyance and combustion. CWS is proved to be a kind of good fuel to replace oil in utility boiler.

2. The temporary CWS feed--in system in front of furnace used in the test operated normally. It is very convenient to regulate CWS used for combustion. Both CWS pump in front of furnace and CWS revolving fitter can be operated successively and normally during the whole test process.

3. CWS which is poured to the single angle, whether it concludes 1, 2 or 3 nozzle, can be ignited and burned steadily. The combustion process is good.

4. The rated load of boiler is reached on No.3 CWS single angle burner under the test condition of oil--firing or CWS firing. The generating load is 15 mw when fire CWS only on single angle.

5. The dashing multi--atomizing CWS nozzle is designed by Institute for Thermal Power Engineering Zhejiang University, whose capacity is 1.9--3.57 t/h when regulating test. The capacity has scope decided according to the engineering design of remaking the 230 t/h oil--fired boiler to CWS-fired one in Bai Yanghe generating plant.

6. The combustion test testifies that the structure design of the oil CWS dual--purpose burner and CWS burner with a relative little gradual expending CWS top--burning chamber selected for the engineering of remaking 230 t/h oil--fired boiler to CWS-fired one in Bai Yanghe power plant matches to the demands of CWS-fired properties.

7. The combustion test testifies: Since flame is very close to water--cooled wall at back plate when 230 t/h oil--fired boiler whose ratio of length to width of furnace section is 1.33 is remade to CWS-fired on in Bai Yanghe power plant which may cause flame stick to the wall, burner with side secondary air plan selected for the CWS-fire burner is reasonable.

Design and Operation of 35 t/h CWS Boiler for Special Use

The idea of studying and exploring special CWS fired industrial boiler is put forward after a vast amount of studying and analyzing on the basis of the successful remakement of 20 t/h and 60 t/h industrial oil--fired boilers to CWS-fired ones in Beijing No.1 Paper Mill. It is the first time to design special CWS-fired boiler. The success will not only promote vigorously the spread of oil--economizing CWS-fired technology on Chinese oil--fired boiler, but also set up broad market for Chinese clean fuel. The selected design load of CWS boiler is 35 t/h and oil also can be burned in this boiler with transferring oil--firing and CWS-firing one another very conveniently in order to make CWS-fired boiler have advanced, demonstrated function and higher testing value in design.

The 35 t/h boiler design utilizes comprehensively design and experience of 20 t/h and 60 t/h remakement and combines the riper developing idea of coal--boiler and oil--fired boiler. The principles of CWS-fired boiler design are proposed after analyzing and summarizing:

(1) The 35 t/h CWS--fired boiler should be able to be transferred to fire oil besides firing CWS. Burner should have authentic safe, stand by and alternative function.
(2) Load regulating scope is from 60 % too 100 % and has stronger adaptable and adjustable function.
(3) The standard of firing CWS should reach the same as the corresponding coal--boiler and oil-fired boiler. The circumstances such as severe block--up, wear and tear and sintering of nozzle.
(4) Sintering and ash deposit on furnace heated section must be avoided.
(5) Furnace design should have advanced, demonstrated function and strong test ability, which can provide much valuable experience and date of hot test and operation for designing large--scale CWS boiler.

Combined Chinese CWS combustion technology development, the following measures are adopted on burner and furnace design according to the above design principles.
(1) In CWS steady combustion technology respect: First in furnace arrangement, primary air and secondary air of the prepositive steady combustion chamber burner with adiabatic wall are arranged to be revolving flow. Impeller of primary air is axial impeller and that of secondary air is axial movable impeller. Secondary air can mix primary air to form high temperature recirculating exhaust gas area with adjustable size, width and abstracted volume by regulating its impeller. The recirculating area not only provide steady heat source for CWS igniting and burning, but also ensure CWS steady igniting and burning under low load. Second, according to the CWS characteristic of about 30 % water content, water content must be vaporized promptly and volatile matter should be separated out and ignited and burned fast. After the combustion experimental data of remaking 20 t/h, 60 t/h and 230 t/h oil--fired boilers to CWS--fired ones is analyzed. It proves that overfeeding primary air does not benefit water content vaporizing and CWS igniting steadily, but cause atomizing CWS with water content not having be vaporized fully to reach heat--absorbing surface to result in sintering in furnace. Therefore, the formed circulating area by secondary air should be used fully and primary air should be reduced in air allocation to make CWS burn and ignite steadily. And increase primary air when shifting to burn oil to ensure enough root air when firing oil. Oil can be ignited and burned promptly through reasonable air allocation. Third, while third is designed and arranged, bottom offering air and top offering air arrangement is adopted. Bottom offering air can hold big unburned carbon articles to avoid them descending to hopper and make them burn again in combustion area so unburned carbon loss is reduced; Third air also is adopted for the test of U--type flame combustion form organized by direct--flow burner arranged on top--firing in front wall in order not only to provide air force to form U--

type flame and avoid flame dashing to the hopper, but also to lengthen CWS retention period in furnace to make combustion more sound. Top offering air can strengthen after burning to make up for the defect of bad--mixing afterwards and make unburned carbon articles burn again in combustion area, so the combustion efficiency of coke is raised. The arrangement of bottom offering air and top offering air and a counter--clock big recirculating air force area in furnace with burners arranged in front--wall intensify steady ignition and combustion, which raises CWS combustion efficiency and furnace heat transfer, realizes staged air, lowers temperature in flame area reduces hot NO_x production and reaches the goal of reducing produce and exhaust of NOx.

(2)Two rows of stirring burners with 2 in each row are arranged in front--wall to operate boiler safely and adjust load conveniently. A CWS atomizer, a oil gun and a survey hole may be arranged in the center pipe of each burner. The load adjusting scope of CWS nozzle is form 0.6 t/h to 1.5 t/h. CWS can be burned at full load and it can be shifted to fire oil very conveniently. Reading experimental steady combustion, spare and testing function. Two direct flow burners are fixed in front arch with U--type flame organizing combustion test adopted which are spare for firing CWS and oil, so CWS U--type flame combustion test can be carried on. The full load when firing CWS can attach 50 % of the total load. It is southentic in boiler reserve and operation is safe when adopting this kind of arrangement. It embodies characteristics of demonstrated, experimental, safe function of this boiler.

(3) One of the main facts which affect furnace normal operation is sintering and ash--build--up of furnace. Reasonable air allocation is adopted in the 35 t/h boiler design to ensure that CWS is burned steadily in the air force area in furnace. Little swirl angle is adopted in pre positive main burner to make gas--flow have enough air flow. Strengthen its tumult utilize bottom offering air and top offering air fully to make combustion more sound and adopt other measures to prevent furnace from sintering and ash buildup. At the same time, multi--air feed--in is used to lower the furnace outlet temperature, The furnace is separated to two top and low layers in design. Different q_v and q_F are adopted to intensify water content of CWS vaporizing and atomizing CWS igniting and burning. The designed total furnace properties is

$$q_v = 132 \times 10^3 \text{ kcal/m}^3.\text{h}$$
$$q_F = 1.17 \times 10^6 \text{ kcal/m}^2.\text{h}$$
$$q_H = 75.8 \times 10^3 \text{ kcal/m}^2.\text{h}$$

The properties of low furnace is

$$q_V = 206 \times 10^3 \text{ kcal/m}^3.\text{h}$$
$$q_F = 132 \times 10^3 \text{ kcal/m}^2.\text{h}$$

In low furnace q_V is bigger and q_F is less than the same kind of boiler, which can reduce the temperature in combustion area of furnace and prevent sintering.

(4) The hopper is designed to remove ash and prevent ash deposit.

The gross arranging figure of 35 t/h CWS--fired boiler and the designed properties of burners are proposed after theory analysis and calculation, which is showed in figure 6.

The boiler is single drum and natural circulation one whose furnace adopts T1--type structure with pre positive steady combustion chamber furnace. It can be used for firing CWS and oil. The rated vaporizing volume of the boiler is 35 t/h, the rated steam pressure is 3.82mpa, the rated steam temperature is 450 C, the working pressure of the drum is 4.31mpa, the feed water temperature is 105 C. Four stirring main burners are fixed in front wall and 3 of them can reach 100 % load. Each burner has a oil gun. Two spare burners are fixed in front arch. The designed capacity is 50 % of the total load, which is used when operating under low load. When firing oil, spare burners can be used as oil--fired burners and cooperated with main burner to regulate overheat temperate. When firing CWS, use burner to feed air and bottom offering air , top offering air are adopted to adjust combustion. Adiadic wall is laid in front wall of steady combustion chamber, adiabatic walls are built with refractory bricks at both side walls and smooth steel tube structure exists in other parts of the furnace.; The total volume furnace is 210m , which is separated to top and low layers. The width and depth of top furnace (from water--cool wall centerline) are 44900 mm and 3350 mm respectively and that of low furnace whose volume is 134.2 m is 4490 mm and 5050 mm q_V =206 × 10^3 kcal/m^3.h. The structure of less at top and big at provides CWS enough time of water content vaporizing and CWS burning, which benefit CWS ignition and combustion. The retention period of exhaust gas in furnace is 3--3.5s. B is equal to 5581kg/h by thermal calculation. The ranges of temperature and entropy reduce are 44 C and 25.7kcal/kg respectively. By thermal balance calculation the boiler coefficient η=87.66 %

Now , two special boilers of this kind had been provided to Beijing No.1 Paper Mill, which had been finished installing in Jan. 1994. Regulating test is carrying and elementary test has reached designed properties. Another boiler is provided to Bai Yanghe generating plant and is being installed. Regulating test to generate will start in June, 1994 according to estimating.

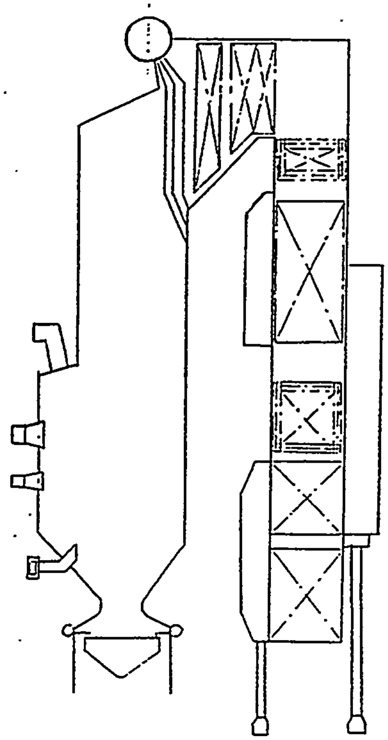


Figure 6 The Figure of the 35 t/h CWS Boiler.

THE COAL-WATER SLURRY COMBUSTION TEST ON THE 3MW HOT-WATER BOILER IN SHENGLI OIL FIELD

by

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INTRODUCTION

ShengLi oil field is the second greatest one in China. In recent years, with the constant augmentation of its magnitude, public utilities, residence and staff quantity, the oil-firing consumption for manufacture and living is also increasing steadily. The oil Field Administrative Bureau is going to adopt CWS to replace partial fuels in order to cut down the expenses of valuable petroleum resources. As a new type of oil-substitute fuel, CWS is paid wide attention to in the world. A lot of research works on CWS combustion technology had been done in many countries such as Russia, Japan, Swede, Italy and USA

Being one of the first units who work on CWS combustion, Zhejiang university, which had engaged in the CWS combustion tests on the 4T/h-230T/h industrial and utility boilers, has accumulated abundant experience and possessed many pieces of patents since 1981.

The Oil Field Administrative Bureau and Zhejiang university cooperated to study CWS combustion technology in order to observe the feasibility of shifting to burn CWS on oil-fired boilers in oil fields and to provide basis and operating experience for spreading CWS combustion technology.

CWS used in this test is produced in Yanri CWS plant. The data of coal industrial analysis and ultimate analysis is showed in table 1.

Table 1. The CWS analytical data

A^y	W^y	C^y	H^y	O^y	N^y	S^y	V^r	Q^y_{dw}
%	%	%	%	%	%	%	%	kJ/kg
6.1	32	51.56	3.33	6.03	0.68	0.3	38.43	19440

The properties of CWS are as follows: the concentration is 69%; the ash content is less than 6%; the calorific value is 21MJ/Kg; the viscosity is less than 1.5 Pa.s.

The combustion experiment is done in a tunnel oil-fired boiler.

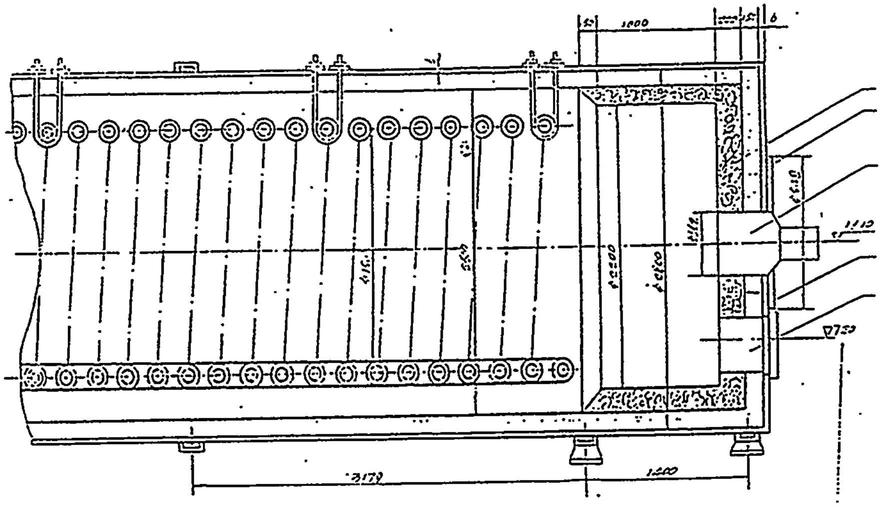

Figure 1. 3MW tunnel boiler diagram

BRIEF INTRODUCTION OF EXPERIMENTAL SYSTEMS

1. FUEL SYSTEM IN FRONT OF FURNACE

The flow chart of fuel system in front of furnace is showed in Figure 2. CWS is transported to the test spot in tank trucks and pumped into storage tanks, then to nozzle through the on-line filtration in front of furnace by two parallel connecting CWS-offering pumps. Then CWS is atomized though nozzle and burned in the boiler.

```
                                          Wash Water
                                               |
CWS Tank ---> CWS Deliver Tank ---|---> CWS Pump -------->   CWS Storage Tank
                                               |
                                               |          CWS Offering
                                  Stirring Tank------>   Pump        -----> Filter
                                                           ↑                  |
                                                           |                  |
                                                       Wash Water             ↓
                                                                          Atomizer
                                                         Boiler   <-----   Burner
                                                                             ↑
                                                                             |
                                                                        Compressed air
```

Figure 2. the flow chart of fuel system in front of furnace

The system is fitted with circulating lines in order to assure the smooth process of the test and to abate the CWS stratified phenomena. The circulating flow system is installed on the mother pipe to make the Adjustments of CWS flow more easily.

The compressed air is adopted as atomized medium and an $3M^3$/min air-compressor is selected in the test.

The system is fitted with a water-wash system whose task is to wash the whole system after the test is finished.

.2. THE EXPERIMENTAL BOILER

The experimental boiler is a horizontal tunnel coil pipe oil-fired boiler whose heat output is 3MW and which is used for heating. The temperature on the spot of hot-water exit is 70-95°C. A CWS steady combustion chamber is in the preceding arrangement of the boiler, which is showed in Figure 1.

3. EXPERIMENTAL EQUIPMENT

The CWS burner of the twin-swirling precombustion chamber is adopted in the experiment. The primaryand secondary airs of rotating flow out from the burners formed a recirculation region with high temperature at the exit of the burners, in which vehement heat and mass exchange are formed between the CWS gas flow and the smoke with high temperature, so it is possible to intensify the ignition and combustion. At the same time, the new precombustion chamber construction is also used to intensify the ignition process for the strong radiation area can be formed. The cold field measurement about air dynamic field manifests that sound recirculation properties can be obtained and the steady ignition and combustion can be achieved using this kind of burners.

The CWS atomized nozzle selected is DZ series of CWS nozzle. It has advantages such as good atomized properties , blockproof, applying safety and long service life etc. The atomized medium can be steam or compressed air.

The main technological properties of DZ-600A-type CWS nozzle selected are as follows:

The designed rated load	600kg/h
Load adjustment scope	300-750kg/h
The designed air pressure (pre-nozzle)	0.70MPa
The designed CWS pressure (pre-nozzle)	<=0.8MPa
The nozzle atomized size SMD	<=95μm

The atomized spray angle of the nozzle is 60° which must be matched to the air dynamic field of the CWS burner, or the air-dynamic field would be spoiled, which would result in damaging of the CWS igniting condition and slagging etc.

Since it is inevitable to mix few foreign matters during the process of preparation, transportation, load and unload and application, dry scars of CWS will on the wall with the rising and dropping of the CWS operating time. These

dry scars which are not easy to transform to slurry again after they come off from the wall are easy to block nozzles. So the on-line filter is installed in the system to prevent foreign matters and dry scars from blocking nozzles.
Mono-screw pump is selected to pump CWS. Two parallel connecting pumps are installed, for one operating, the other standby.

SYSTEM OPERATING AND COMBUSTION ADJUSTING

1. SYSTEMS AND THE OPERATING SITUATION OF THE MAIN EQUIPMENT

After installation of system, the CWS combustion test was conducted in March, 1994. The total operating hours is about 100 hours.
The flow and pressure of CWS out of strew-pumps are steady and easy to be adjusted. The process is safe and reliable.
Two parallel connecting CWS on-line filters are applied, for one operating, the other standby. During operation, the pressure difference between the inlet and the outlet of filters is less than 0.01MPa. Each system for CWS discharge, storage and transportation functioned normally and nozzle's block did not occur during the whole process of test.

2. REGULATING TEST OF COMBUSTION

The target of steady ignition and combustion was obtained though burning regulating and revising in several days.
CWS start-up and ignition:
It is usual to use diesel oil, heavy oil or natural gas to ignite CWS. To small-scale boiler or industrial boiler, fire wood also can be used for ignition, and it is employed in this test with subsidiary fuel of natural gas because of applying simplified systems for the exemplary short-term combustion test and the flow of small amount for the low pressure in the existing natural gas system.
Certain amount of firewood is thrown into the steady combustion chamber and ignited by natural gas. CWS is pumped into burner through nozzle atomizer after starting the air-blower and ignite all firewood. Then CWS burns very promptly. The whole process needs only 10 minutes or less. Firewood direct-ignition without natural gas support was realized finally. Electric breakdown--the CWS pump interruption--caused the fire to go out in the burner during process. The breakdown was fixed in 6 minutes and the CWS pumped was ignited without any other fuel support by using of the remaining heat with high temperature in the steady combustion chamber after fire went out.
According to the designed rated load of the boiler, the CWS flow needed is 600kg/h. And the load must be cut down since the load for heat descends with the weather getting warmer and the highest temperature of the outlet hot water should be 110°C. During the test process the ordinary CWS flow was 400-500kg/h and would be regulated to 300kg/h when the temperature of outlet water was undue high or in evenings, so the virtual operating load was 50%-70% per cent of the rated one. The temperature at surveying hole 1 which is 400mm from the outlet of the burner was 950-1050°C and that of surveying hole 2 which is 2000mm from the outlet of the burner was 1050-1150°C. CWS can be ignited and burned steadily under the 1/2-3/4 of the rated

load and adjustment is also very simple by adjusting the CWS circulating flow and the revolving velocity of pumps. Therefore there is no much difference on operating control between using CWS and crude oil as fuel.

THE MAIN RESULTS OF THE COMBUSTION TESTS

To evaluate the results of the application of the coal water slurry combustion in the tunnel hot water boiler, the combustion efficient of the boiler, the pollutants in the exhaust gas and the flame temperature profiles in the furnace. The gas concentrations are measured with the MSI2000 multi-composition analysis. The unburned carbon is collected with the fly ash collector. The temperature in the furnace is measured with the platinum-rhodium platinum thermos-couple.

1. COMBUSTION EFFICIENT

The Combustion efficient are measured to understand the characteristics of the atomizer, the burner and boiler. Table 2 shows the main results of the combustion tests. It shows that most of the combustion efficient are higher than 98% and the average combustion efficient is 98.39%. To the coal fired boilers with the same capacity, the combustion efficient are only about 90%. It means that the combustion efficient is near to the level of the oil fired boiler.

Table 2 The Combustion Efficient Measured

Item	CO(ppm)	Carbon contents in fly ash(%)	CO unburned loss (%)	Carbon unburned loss(%)	Combustion Efficient(%)
1	252	18.16	0.06	1.34	98.6
2	182	18.28	0.04	1.36	98.60
3	241	24.44	0.06	1.97	97.97
4	173	15.59	0.04	1.13	98.03
5	184	23.22	0.04	1.84	98.12
6	178	20.61	0.04	1.57	98.39
7	271	22.34	0.06	1.75	98.19
8	201	17.72	0.05	1.31	98.64
9	251	22.21	0.06	1.74	98.20
Average	215	20.29	0.05	1.56	98.39

2. THE TEMPERATURE RISE PROCESS WITH THE START-UP OF THE BOILER

The ignition process of the boiler is very fast. The furnace temperature rises rapidly to reach the demands of the stable combustion after the coal water slurry combustion. Figure 3 shows the furnace temperature rise line of the boiler. It shows that the furnace temperature reaches about 800°C after 10 minutes which is the limit of the coal water slurry spray combustion. About 2 hours later, the furnace temperature reaches its stable value.

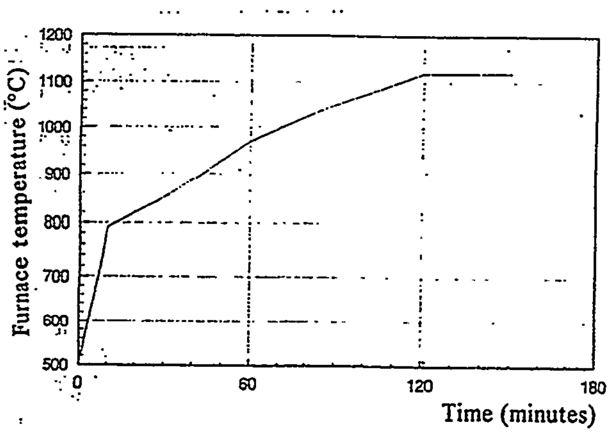

Figure 3 The temperature rise line of the furnace at the start-up of boiler

3. THE LOAD CHARACTERISTICS OF THE BOILER

Figure 4 shows the regulation relationship of the furnace temperature with boiler load. To understand the load characteristics of the boiler, several load shifts tests are carried out. The loads range is 50% to 100%. At the 50% of the MCR, the furnace temperature is about 870°C. If the lowest stable ignition and combustion temperature of the coal water slurry is about 800°C, the lowest load can be 40% without any support fuel.

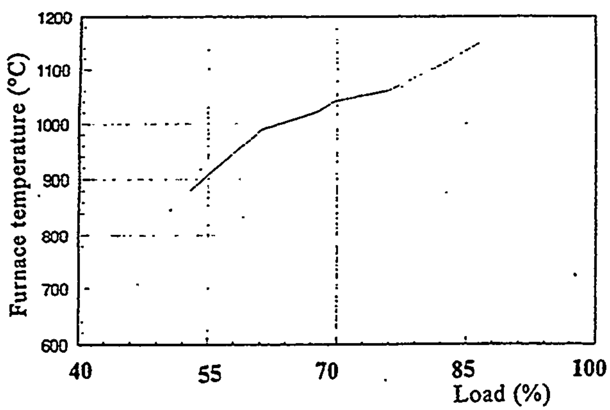

Figure 4 The relationship of the furnace temperature and the boiler load

4. THE TEMPERATURE PROFILES IN THE FURNACE

Figure 5 and 6 show the relationship of the furnace temperatures along the axial distance of the furnace from the exit of the burner. It shows that the temperature of the furnace rises first and reaches the top point at the distance of 1 to 1.5 meters from the burner exit. This is the position of the exit of the precombustion chamber. After this position, the furnace temperature begins to reduce for the heat absorption of the heat exchangers. At low load the temperature reduces faster than the high load. This is due to the same heat transfer condition and this brings the average temperature of the furnace at high load is higher than that of the low load. Therefore, the combustion of coal ware slurry at higher load is more stable.

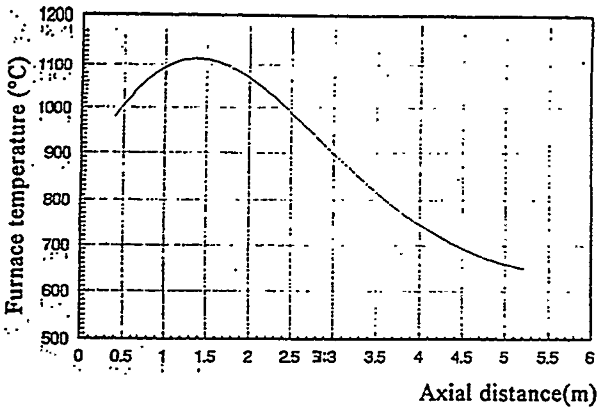

Figure 5 The furnace temperature along the axial distance at high load

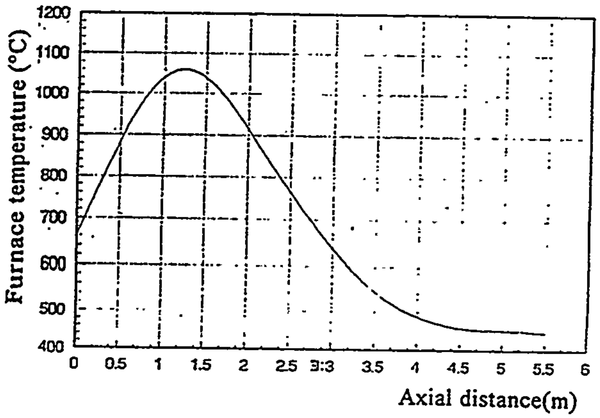

Figure 6 The furnace temperature along the axial distance at low load

Figure 7, 8 and 9 show the temperature profile with the radical distribution at the different axial position. The different temperature distribution characteristics are observed. Figure 7 shows the temperature profile at the front part of the furnace where the distance from the exit of the burner is about 400 mm. The temperature of the furnace profile is in the shape of a saddle. It means that the coal water slurry spray has ignited at this position. The temperature at the edge of the spray is the highest and the spray is ignited here. Figure 8 shows the temperature profile at the distance of 2000 mm from the exit of burner. Only half of the profile is measured and it shows that the highest temperature is in the center of the furnace. There is also another high temperature zone near to the furnace wall where there is an outside recirculation zone. It shows that the coal water slurry spray is ignited due to the inner and outside recirculation zones. Figure 9 shows that the temperature profile is in the shape of parabola at the distance of 3200 mm. For the reason of heat transfer the temperature at two sides is lower than that of the temperature at the center of the furnace.

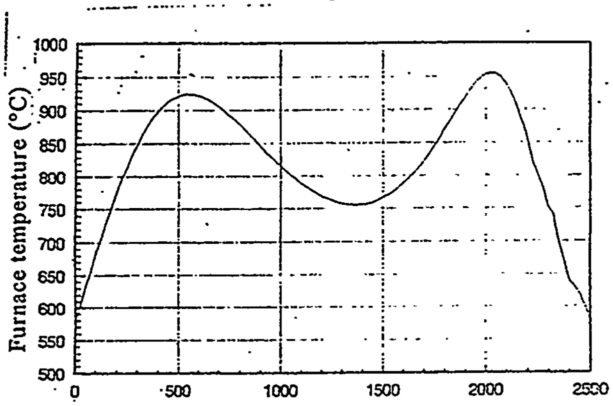

Figure 7 The furnace temperature profile along the radical distance at the front part of the furnace.

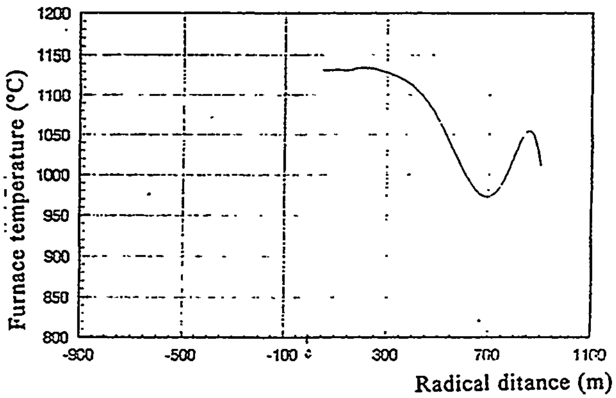

Figure 8 The furnace temperature profile along the radical distance at the central part of the furnace.

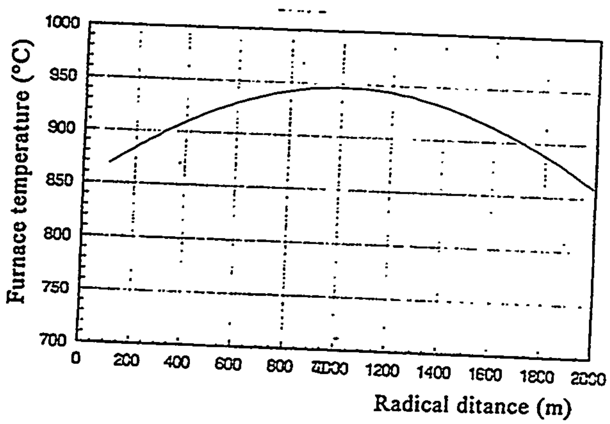

Figure 9 The furnace temperature profile along the radical distance at the rear part of the furnace.

5. MEASUREMENT OF THE GAS EXHAUST

Table 3 shows the typical CO, NO and SO_2 measured results of the exhausted gas. It shows at the excess air coefficient of 1.6 CO is about 200 to 300 ppm, NO is about 100 to 200 ppm and SO_2 is about 90 to 170 ppm. These values are all very low.

Table 3 The gas exhaust results (α=1.6)

Item	CO(ppm)	NO(ppm)	SO_2(ppm)
1	276	98	129.3
2	267	97.6	90.8
3	238	177.4	166.4
4	276	199.4	147.8
5	301	163.6	121
6	230	226.9	107.3
7	234.4	235.2	66.2
Average	260.3	171.2	108.9

CONCLUSION:

Though the above test and measurement analysis, some conclusions can be obtained as follows:

1. The combustion using CWS as fuel is successful. Steady ignition and combustion are realized in the tunnel coil pipe hot-water boiler and the operation is safe and reliable and can be controlled very easily. Therefore, the target of replacing oil by CWS can be achieved.

2. The CWS combustion efficiency reached 98% or more which exceeds that of the ordinary burning coal way and attains or approaches the level of burning oil.
3. The emission of pollutants NOx and SOx is lower apparently than that of oil or coal as fuels when burning CWS, so CWS is one kind of clean fuels.
4. Systems of CWS discharge, storage and transportation are designed and installed successfully.
5. Some crucial technology and equipment are applied such as CWS on- line filter, nozzle burner, steady combustion chamber and mono-strew pump etc. Their properties of CWS supplied by CWS plant are good.
6. The ignition process is convenient without any support fuel. The ignition period is only about 5 minutes.

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A LOW EMISSION TECHNOLOGY---LOW COST COAL WATER MIXTURE FIRED FLUIDIZED BED COMBUSTION

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ABSTRACT

In this paper, low cost coal water mixture(CWM) FBC technology is described. Low cost CWM may be coal washery sludge or the mixture of water and coal crashed easily. This technology is featured by agglomerate combustion of low cost CWM. Experimental results in 0.5MW FBC test rig are reported. The effects of bed temperature, excess air, staged combustion on combustion and emission performance has been studied. The comparison combustion tests by using dry coal and CWM are made in 0.5MW FBC test rig. Also coal washery sludge of different origins are also tested in the test rig. Based on the test rig experiments, a demonstration AFBC boiler with capacity of 35 T/H steam for utility application (6 MW) is designed. The design features will be presented in this paper. Both the operation experience of test rig and demonstration unit show the developed low cost CWM FBC technology is of high combustion efficiency and low emission. This technology is being commercialized and applied in China in top priority by Chinese government.

INTRODUCTION

Coal is the main energy resource of China. In the industrial branches attached to production, preparation, transportation, and utilization of coal, there are many sources of coal-water mixture(CWM). But only two ways we can make the CWM low cost.

One of the important sources of CWM is coal washing plants. At present, Chinese coal washing plants produce about 10 million tons of coal washery sludge a year. The main features of low-grade washery sludge are of high ash content (about25--30%), small in solid particle size, high in viscosity and low heating value. It is also difficult to dewater the sludge in large capacity. If the coal washery sludge is not properly disposed, it will cause serious environmental problem as well as energy wasting.

Another way of low cost CWM is produced before dosing boiler. At first coal is crashed under 2mm, then water is added in mixture to make CWM at about 25--30% water content. This kind of CWM is easily produced and pumped to transport to boiler.

The Institute for Thermal Power Engineering of Zhejiang University has been actively involved in the development and commercialization of low cost CWM fluidized bed combustion technology since early 1980's. Some other investigations can be found from Cooke,et al(1975),La Nauze et al(1982 and Terade et al(1982).

DESCRIPTION OF LOW COST CWM FLUIDIZED BED COMBUSTION TECHNOLOGY

When Low cost CWM is fed into a fluidized bed combustor in a lumped mass, it generally does not return to fine particles after drying, but forms solid agglomerates even though low cost CWM

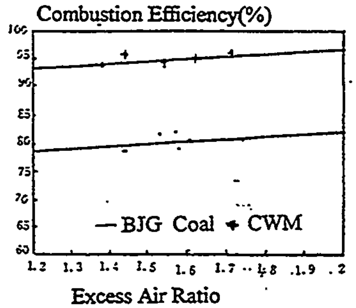
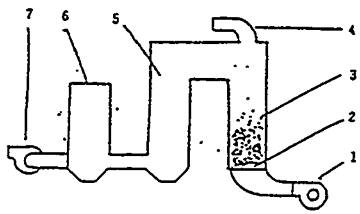


Figure 1 Comparison on combustion efficiency between CWM and dry coal

Figure 2 Microscopic structure of low cost CWM agglomerate under SEM



1. F. D. fan 2.distributor 3.fluidized bed combustor
4. fuel feeder 5. back pass 6. bag filter 7. I. D. fan
Figure 3 0.5 MWe FBC test rig

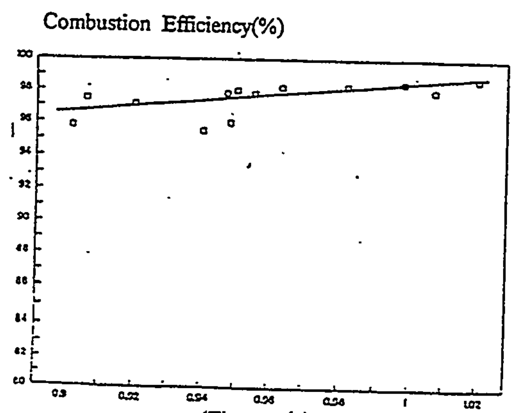


Figure 4 Combustion efficiency at different bed temperature

consists fine particles. This process or property is named as agglomeration. Figure 1 is the microscopic structure of coal washery sludge agglomerate under SEM.

As reported by other investigators, the agglomeration of low cost CWM is often harmful to the stable operation of fluidized bed combustors. Big agglomerates tend to deposit at bottom of the bed and eventually damage the fluidization and eventually damage the fluidization of the bed. To overcome this problem, some earlier researchers place restrictions on the top size of agglomerates formed in the fluidized bed. But such restrictions always complicate the fuel feeding and combustor operation. Furthermore, restricting top size generally increases the quantity of fine fuel particles and therefore raises the elutriation loss of fuel.

The Institute for Thermal Power Engineering of Zhejiang University developed a new technology of CWM in early 1980's(Cen, et al, 1982). The features of the new technology can be summarized as follows:

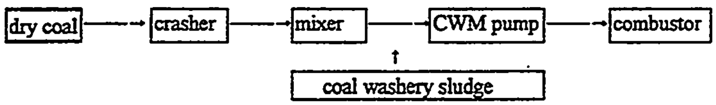
--Using big CWM feeding size to make the agglomerates relatively large so that the elutriation loss of the fuel is greatly lowered;

--Using dense bed material to prevent big agglomerates from depositing at bottom of the fluidized bed so that to ensure the stable operation;

--Adopting non-overflow operation of fluidized bed material and increase the residence time of fuel agglomerates in the bed for complete burn-out.

TEST RESULTS FROM THE 0.5 MW FLUIDIZED BED COMBUSTION TEST RIG

Figure 2 schematically shows the 0.5 MW fluidized bed combustion test rig at the Institute for Thermal Power Engineering of Zhejiang University. It consists of the fuel preparation and feeding system, the combustor, the convective backpass and the baghouse. The cross section of combustor is 500 by 500 mm. The combustor height is 4.5 meters. Secondary air ports are arranged along the furnace height. The low cost CWM preparation and transportation system is shown in the following:



The main features of the system is pipeline transportation and pump feeding.

The low cost CWM tested are given in table 1. Before low cost CWM is burned, the water content is controlled in the range of 25--30%. The bed material are summarized in table 2.

Table 1 Low cost CWM analysis

item	Bijiagang coal	Yongrong Sludge	Yanzhou Sludg
Mad ,%	4.48	2.80	2.39
Aad,%	18.29	51.65	40.60
Vad,%	30.4	16.41	26.31
FD,%	46.83	29.14	30.70
Cad,%	66.94	36.14	44.27
Had,%	4.40	2.53	2.97
Oad,%	7.07	5.49	7.85
Nad,%	1.39	0.67	0.78
Sad,%	0.3	0.72	1.14

Table 2 Bed Material

	sand	coal rejects
mean size,mm	1.301	1.996
bulk density, Kg/m^3	1561	1254
real density, Kg/m^3	2788	2342
U_{mf} Nm/s	0.62	0.55

For comparison, experiments were done in 0.5MW test rig by dosing dry coal with low cost CWM. From figure 3, it can be seen that while the combustion efficiency with all particles fed in dry state is only 80% present. The combustion efficiency with low cost CWM is nearly 95%. The increase of combustion efficiency is 15% which is much higher than the latent heat loss(about 1.6 present) caused by mixing water in low cost CWM.

It is also reported that the combustion efficiency is very high(>96%) while coal washery sludge is burned in 0.5MW FBC test rig(shown in figure 4). During single stage combustion, the combustion efficiency is a little lower(about 94%). The reason for high combustion efficiency of low cost CWM is the combustion process is well organized in present technology. As mentioned earlier, the developed technology is featured by agglomerating combustion of low cost CWM.

One of the distinguished advantage of fluidized bed combustion is low NOx emission. Figure 5 shows the NOx emission level when coal washery sludge is fired. In the tested bed temperature range, the NOx emission can be controlled within 200 ppm by staged combustion. If the bed temperature does not exceed 950 ℃ ,the NOx emission is lower than 150 ppm. Compared with single stage combustion, the NOx emission is reduced by 25--40% by staged combustion.

Figure 6 gives the NOx profiles along the furnace height during combustion test. During the staged combustion, the bed zone is under reducing condition and the NOx level is low because of lowered conversion of nitrogen in fuel to NOx. When the secondary air is introduced at above the bed surface, the NOx emission increases at first, and decreases greatly along the bed height as the reaction of NOx with char and some gas species.

Figure 7 shows the NOx emission under different bed zone excess air. The total excess air ratio is maintained at about 1.25 during all tests. It can be concluded from the test results that the optimum bed zone excess air ratio for NOx emission is in the range of 0.85--0.95.

Sulfur retention tests are also carried out by mixing limestone particles directly to the low cost CWM before combustion. Figure 8 shows sulfur retention under different Ca/S mole ratio. Figure 9 gives the sulfur retention when different low cost CWM is fired. The sulfur retention increases with the sulfur content of fuel. For the tested low cost CWM, the sulfur retention is over 80% when the Ca/S mole ratio equals to two.

6MWe COAL WASHERY SLUDGE FIRED FBC BOILER FOR COGENERATION APPLICATION

Based upon the pilot plant tests and operating experience accumulated from a 10t/h steam coal washery sludge FBC boiler(Cen, et al,1987). A 6MW coal washery sludge fired FBC boiler for cogeneration application is designed and installed. The cogeneration plant is situated in a coal mine in Shandong Province of China. This plant is next to the coal washing plant of the coal mine. The coal washery sludge discharged from the coal washing plant is transported to the boiler by a belt conveyer. The cogeneration plant was put into operation in the end of 1990.

The boiler is a bubbling fluidized bed boiler. The design parameters are summarized in Table 3. Figure 10 is the simplified section view of boiler. The coal washery sludge is fed to the combustor in lumped size from the top of the furnace. The fly ash separated from the convection pass are recirculated to the furnace for further burnout. To protect immersed tube surface from erosion, the immersed surface are finned tubes.

Table 3 35t/h FBC boiler design parameters

steam capacity, t/h	35
steam pressure, MPa	3.82
steam temperature, ℃	450
feeding water temperature, ℃	150
bed temperature, ℃	962
fluidizing air velocity, m/s	3.66
fuel feed rate, kg/h	9475
water content of fuel, %	25
low heating value of fuel, kj/kg	12351
flue gas exit temperature, ℃	168
combustion efficiency, %	92
boiler efficiency, %	81

The first trial operation of the boiler was on Nov. 19,1990. From May 10, 1991, the boiler is on full load operation. During May 1991 to Dec. 1994 the accumulated operation hour is more than 20000 hours. The longest continuous operation lasted for 1416 hours. The measured combustion efficiency at base load is 96%. The boiler efficiency is 83.5%. The SO2 and NOx emission at the exit of chimney are 308.56 mg/Nm3 and 78.5 mg/Nm3. Coal washery sludge with water content of 20% to 30% can be steadily burned.

Figure 11 shows the temperature distribution along the furnace height. Figure 12 gives the combustible gas profiles. The results shows the combustion is mainly finished in the bed zone and splashing zone. The calculated combustion fraction within the fluidized bed is 0.86 to 0.87.

SUMMARY

1. By using the developed low cost FBC technology, high combustion efficiency and low NOx and SO_2 emission can be got compared with dry coal burned on bubbling fluidized bed combustor. The combustion efficiency is over 96%. The NOx emission is lower than 150 ppm. The sulfur retention is over 80%(Ca/S)=2).

2. The coal washery sludge discharged from coal washing process can be disposed by fluidized bed combustion technology. For a 35T/H FBC boiler, the daily disposal capacity of coal washery sludge is over 200 tons. This technology is being commercialized applied in China in top priority by the Chinese government for the disposal and energy recovery of coal washery sludge.

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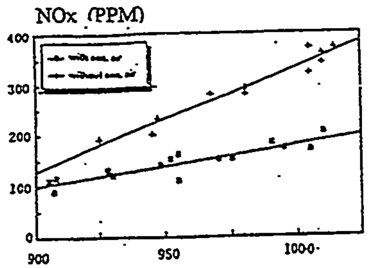

Figure 5 NOx emission at different bed temperature

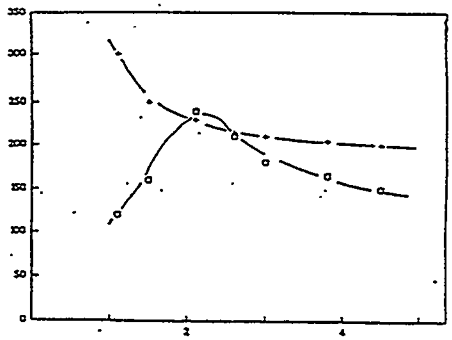

Figure 6 NOx profiles along the furnace height

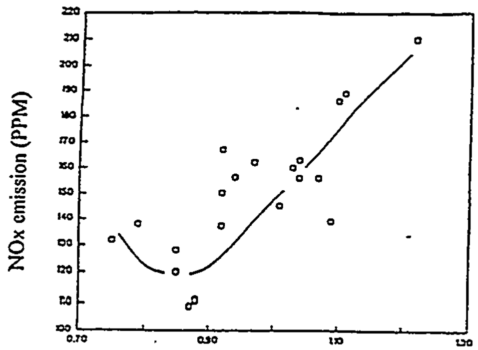

Figure 7 NOx emission under different bed zone excess air

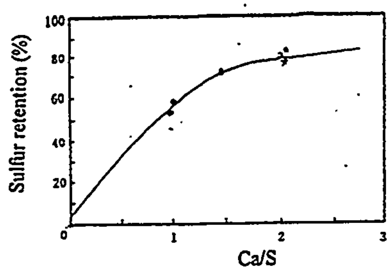

Figure 8 Sulfur retention under different Ca/S mole ratio

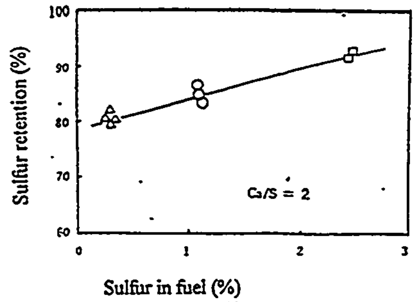

Figure 9 Sulfur retention under different sulfur content coal

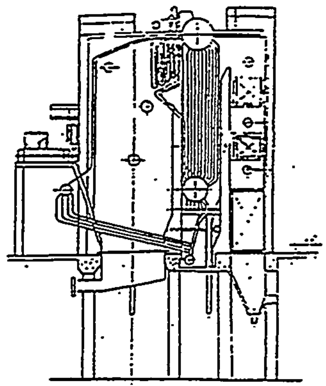
Figure 10 35t/h FBC boiler

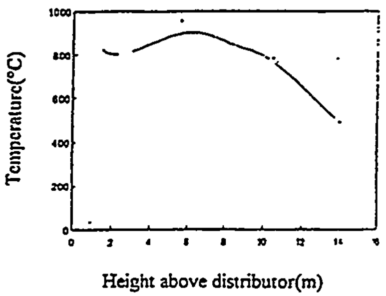

Figure 11 Temperature distribution in the furnace of 35T/H FBC boiler

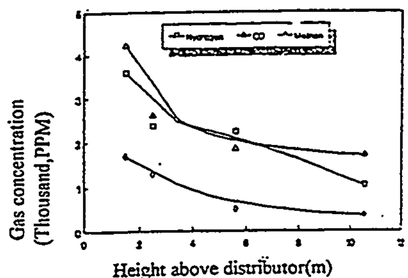

Figure 12 Combustible gas profiles in the furnace of 35T/H FBC boiler

CLEAN & EFFICIENT POWER WITH HIGH ASH COALS THROUGH RETROFITTING

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INDIA

ABSTRACT

The paper deals about retrofitting an existing thermal power plant with a coal gasification plant, a matching gas turbine and a waste heat boiler. The criteria for selection of thermal power plant, choice of coal gasification process and size of retrofit plant are described. The techno economic analysis show that the proposal is technically and environmentally attractive, but economically not comparable with a pulverised coal fired thermal power plant may be because of small size of the retrofit plant. However the economics are comparable with a natural gas based combined cycle plant.

INTRODUCTION

A substantial number of coal fired thermal power plants in the range of 20-100 MW capacity installed in India during the sixties and the seventies are operating at lower efficiencies (18%-26%) and at low plant load factors (35% - 55%) [1,2]. Regular overhauling and revamping of these plants would be necessary to maintain them in running condition but the increase in efficiency may be marginal. The environmental laws are stringent now compared to the situation existing when the plants were installed 2 to 3 decades ago. Also at the time of installation, especially in the sub-urban locations, habitation around the plant was negligible. With the passage of time, the cities have expanded and the population around the thermal power plant became dense. The environmental aspects assumed importance. The stack emissions from the plants are above the prescribed limits and replacement or retrofitting of high efficiency electrostatic precipitators is required to reduce the level of air pollution. Quality of coal is deteriorating which is increasing the maintenance cost, affecting performance and increasing the pollution. Thus large investments are needed to maintain the plants in running condition and limit the stack emission, which increases the cost of power generation. Sulfur in coal is generally low (<0.6%) and hence a flue gas desulfurisation unit is not required.

The equipment of these old power plants which still have sufficient residual life could be utilised in the following manner through retrofitting

* In power plants where the boiler and steam turbine are not in working condition and have out lived their life, but electric generators are in good condition and have sufficient residual life, a coal gasification plant and a matching gas turbine can be installed to serve as simple cycle power plant.

* In power plants where steam turbines and electric generators are in working condition having sufficient residual life, a coal gasification plant, a gas turbine and waste heat boiler can be installed to operate the plant in combined cycle mode.

In both the cases, the existing facilities like coal handling, ash disposal, water systems, cooling towers, control and instrumentation, fire protection, switch yard, power transformer and distribution network and othergeneral infrastructure can be utilised. They approximately cost 50% of the total power plant cost.

SELECTION OF POWER PLANT FOR RETROFITTING

A suitable thermal power plant for retrofitting with a coal gasification plant, a matching gas turbine and a waste heat boiler is selected based on the following criteria.

* The residual life of Steam Turbine Generator (STG) unit should be more than 5 - 6 years.

* The support facilities like coal handling, ash disposal, utilities and power evacuation etc., should be in good working condition and adequate with minor modifications, if required.

* Availability of adequate space for erecting the coal gasification, gas turbine and waste heat boiler units of the retrofit plant.

* Proper approach to the site for movement of equipment and machinery.

* Site constraints, if any, and relocation of the existing facilities like electrical lines, raw water and ash disposal pipelines, should be minimal.

* Dust concentration in the vicinity of selected site should be less to prevent the outside dust affecting the performance and life of gas turbine.

* Availability of coal, raw water, DM water and construction power.

* Ease in the integration of water and ash disposal pipelines, power evacuation and coal feeding etc. from the retrofit plant to the existing systems in the main thermal power plant.

* After retrofitting, the plant load factor (PLF) and overall thermal efficiency should improve resulting in better economics of power generation.

The thermal power plant selected based on the above criteria is operating at a PLF of 35% and a thermal efficiency of 25.8% [2,3]. There are 4 units of 15 MW steam turbo generator (STG) sets installed during 1953-59. Out of 4 STG's, 3 are in working condition and one of them was operated for about 5000 hr. in 1992-93 [3]. The electrostatic precipitator needs replacement. The approach roads are wide and the site is clean. Dust concentration is less. The existing facilities of water, coal feeding and ash disposal are close to the battery limits of retrofit plant. Additional coal, raw water, DM water, potable water and power for construction are available. The plant authorities are willing to participate and meet a portion of capital cost. The manpower for operation and maintenance will be provided by them.

The plant authorities have agreed to bear the cost towards the following items of work.

* Clearing and leveling the site.

* Supply of primary crushed coal, DM water, soft water and power at the appropriate locations within the battery limits of the retrofit plant.

* Shifting of 15 MW STG unit alongwith condenser and its auxiliaries and accessories including circulating water system, cooling tower, control & instrumentation to the site of retrofit plant.

* Power evacuation from gas turbine generator transformer onwards.

* Cost of insurance of equipment of the existing power plant located in the vicinity of retrofit plant against accidental damages caused during erection, testing and commissioning.

RETROFIT PLANT

It is proposed to retrofit the thermal power plant to operate in a combined cycle mode with a,

* Secondary coal crusher

* Coal gasification plant including gas cleaning system to produce clean fuel gas suitable for utilisation in gas turbine.

* Gas turbine generator set of 30 - 35 MW output with associated transformer and auxiliaries.

* Waste heat boiler (WHB) with associated auxiliaries to utilise the sensible heat in the exhaust gases from the gas turbine to produce steam which will be fed to the existing 15 MW steam turbogenerator.

* Control & instrumentation, all interconnecting piping, valves and fittings.

Choice of Coal Gasification Process

A feasibility study [1] was carried out for establishing the relative techno-economic merits of power generation with high ash coals (ash content 35%) through combined cycle mode based on four generic types of gasification processes (dry entrained bed, slurry entrained bed, fluidised bed and moving bed) and compare the economics with a pulverised coal fired (PC) thermal power plant for a capacity of 600 MW. The study had shown that the fluidised bed and the moving bed processes are suitable for IGCC power generation and economics are comparable with a PC plant. Out of the two, former process is techno-economically more attractive. Threfore the IGCC retrofit plant is based on fluidised bed process.

Choice Of Size

Size of the retrofit plant is fixed at 45 MW (30 MW from gas turbine + 15 MW from steam turbine) keeping in view the present level of confidence, scale up factors for coal gasification plant, ease of retrofitting in an existing power plant and the capital investment. The objectives of the retrofit plant include demonstration of the coal gasification process on commercial scale with high ash coals, combustion of lean gas in gas turbine and integration of gasification and power islands. These can be achieved at minimum capital cost by installing one train consisting of a coal gasification plant, a WHB and a gas turbine in an existing thermal power plant. After it is successfully demonstrated, higher capacity coal gasifiers can be designed based on the data generated from this plant.

Another criterion is that there are a number of natural gas based power plants in the country having unit sizes of 30 MW. The resources of natural gas are limited in India compared to coal. Natural gas is also required for other important sectors such as fertilisers and chemicals besides power generation. Therefore natural gas can be replaced in near future by coal gas by retrofitting the combined cycle plant with a coal gasification plant. The size of gasifier for a thermal power plant and a combined cycle plant will be same because the size of gas turbines is same.

Plant Description

The block flow diagram is shown in fig. 1. Primary crushed coal will be supplied from the thermal power plant to the battery limits of the retrofit plant. The coal will be dried if necessary and crushed in the secondary crusher to required size and fed to the gasifier. The gasifier is based on fluidised bed gasification process and operates at a pressure of 24 kg/cm^2. The gasification media are air and steam. Air is extracted from the air compressor of the gas turbine and steam is drawn from the plant itself. The raw fuel gas coming out of the gasifier is cooled in a heat exchanger to produce steam which is integrated into the process. The raw fuel gas is then scrubbed with water to remove particulate matter. The fuel gas after scrubbing with water is at room temperature and the quality is suitable for combustion in a gas turbine without further cleaning.

The clean fuel gas after preheating is fed to the gas turbine where chemical energy in the gas upon combustion is converted into electrical energy and thus power is generated at first stage. The hot exhaust gas leaving the gas turbine at 600°C is fed into the waste heat boiler to generate steam at required pressure, temperature and quantity to suit the 15 MW STG shifted from the thermal power plant. Power is generated from steam turbine at second stage. There is steam integration between gasification island and WHB.

The fuel gas has high nitrogen content which acts as diluent to suppress the flame temperature in the gas turbine combustor preventing the formation of oxides of nitrogen (NOX). As a result, steam injection into combustor is not required for NOX control. Solid waste is discharged into the existing ash disposal system in the thermal power plant. The plant will have relief and blowdown system to burn any combustibles that may be vented and to protect the plant from operating disturbances. The plant will also be equipped with a fire protection system.

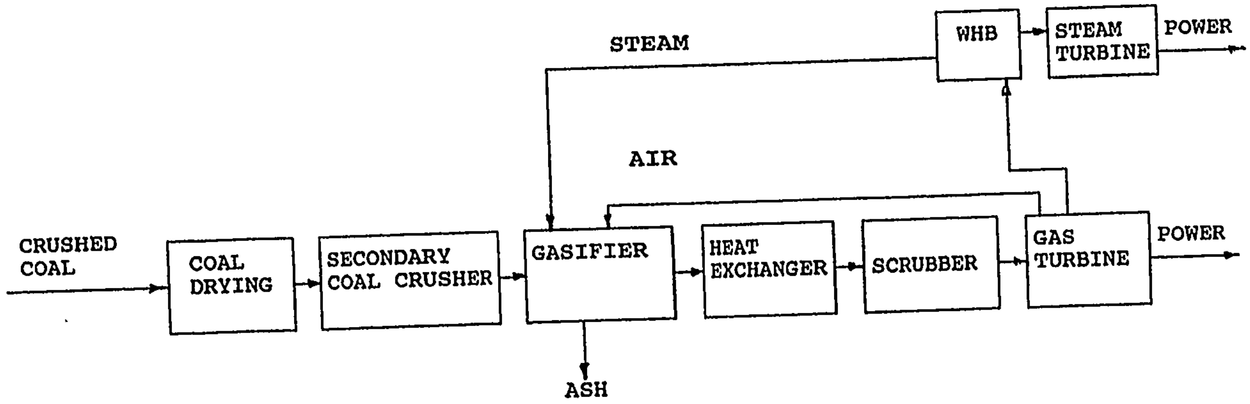

FIG. BLOCK FLOW DIAGRAM FOR IGCC RETROFIT PLANT

Environmental Aspects

One of the compelling reasons for seriously considering coal gasification for electric power generation is the capability of the gasification system to operate in an environmentally acceptable manner. Coal gasification offers a practical means of utilising coal while at the same time meeting clean environmental requirements.

In the gasification system, the major portion of ash is removed as bottom ash from the gasifier. The fly ash in the product raw gas from gasifier is either subjected to wet scrubbing or hot gas cleanup system to remove the particulate matter to the level well below the environmental standards, or is recycled to the gasifier to improve carbon conversion and removed as bottom ash.

The Integrated Gasification Combined Cycle (IGCC) system has the ability to control sulfur emissions to any extent necessary at reasonable cost. This results from the following characteristics.

* In any coal gasification system the bulk of sulfur in the coal is converted to H_2S and some to COS. The reduced forms of sulfur are much simpler to remove from a gaseous stream than SO_2, an oxidised form of sulfur.

* In a coal gasification system, the sulfur compounds are removed in situ during gasification or from the fuel gas prior to combustion. In a PC power plant the sulfur compounds are removed after combustion. The volume of gas treated in the former case is considerably lower.

* In the IGCC system, coal is gasified at high pressure, therefore removal of H_2S and COS from the fuel gas is easy and economical.

* Bulk of H_2S can be converted to pure elemental sulfur which can be sold as a by-product.

Nitrogen oxides (NOX) are not formed to any appreciable extent in the reducing atmosphere of coal gasification. With air gasification the presence of nitrogen during combustion of the clean gas results in lower temperatures and therefore low NOX formation. When oxygen is used in gasifier, the steam which is produced in the process can be injected in to the combustor to reduce NOX formation.

The emission from IGCC and PC plants are given below:

	IGCC	PC
Particulates, kg/h/MW	0.05	0.74
SOX emission, " " "	0.83	5.32
NOX emission, " " "	0.70	3.78

TABLE: 1

RETROFIT IGCC PLANT - PERFORMANCE & COST DATA

*	Power Output	
	Gross power, MW	49.68
	Auxiliary power consumed, MW	4.24
	Net power, MW	45.44
*	Net heat rate, kcal/kWh	3,081
*	Total capital, Rs.million	2,400
*	Unit capital, Rs/kw	48,309
*	Operating Cost	
	Fixed cost, Rs. million	434.70
	Variable cost, Rs. million	218.20
	Total, Rs million	652.90
*	Cost of power generation, ps/kWh	
	@ 5500 hr. annual operation	261
	@ 6000 " " "	239
	@ 7000 " " "	205
	@ 7400 " " "	194

IUS $ = Rs. 31.85

TECHNO ECONOMIC ANALYSIS

The power output, net heat rate, capital cost, operating cost and cost of generation for the retrofit IGCC plant are given in Table-1. The operating cost is calculated based on Rs.2400 million as capital cost.

1. The net heat rate of the IGCC plant is calculated as 3081 kcal / kWh which is lower than the heat rate of 3327 kcal/kWh for 15 MW STG [2].

2. The cost of power generation from the retrofit plant is varying from 261 to 194 paise/kWh for 5500 to 7400 hr. of annual operation. The cost of power generation from the thermal power plant is 160 paise / kWh at 6000 hrs of annual operation. The plant authorities are operating a natural gas based combined cycle power plant in the same city and the cost of generation is 210 paise/kWh [3]. It would be appropriate to compare the cost of generation from IGCC plant with that of a natural gas based combined cycle plant than a thermal power plant due to technological similarities. If so, it can be seen from the table that the cost of generation from retrofit plant is comparable for annual operation of 7000 hr. and above. However, cost of generation remains to be higher for the retrofit IGCC Plant compared to the PC plant.

3. The plant load factor is expected to increase from 35% to 70% after retrofitting [3]. The additional power generated after retrofitting is calculated as 258.65×10^3 MWH Revenue earned from additional power generated @ paise 210 / kWh Rs.543.20 million.

4. Out of the capital cost of Rs.2400 million, the cost of existing infrastructural facilities to be utilised from the thermal power plant is estimated at Rs.700 million. The fixed cost in computing operating cost is estimated based on capital cost of Rs.2400 million. Though the existing facilities are in working condition, they are old and their book value is marginal. It may therefore be appropriate for a retrofit plant to calculate the fixed cost based on the cash invested i.e. Rs.1700 million. If so, the fixed cost is estimated as Rs.273.7 million

5. Cost of coal consumption per annum in the boiler supplying steam to the 15 MW STG is Rs.52.70 million.

6. The variable cost of IGCC retrofit plant per annum is Rs.218.20 million. Net variable cost = 218.20 - 52.70 = Rs.165.50 million. The cost towards other utilities for 15 MW STG such as water is negligible.

7. Saving in the cost of oil support [2] in the 15 MW STG boiler per annum = Rs.0.80 million.

8. Saving in the annual maintenance cost [3] of the boiler = Rs.10 million.

9. Net Revenue earned from the retrofit plant per annum
= 3+7+8+ - (4+6) = Rs.114.8 million.

Pay back period for the investment of Rs.1700 million = 14.8 years.

CONCLUSIONS

Retrofitting of an old thermal power plant with a coal gasification island, a matching gas turbine and waste heat boiler improves the net heat rate and plant load factor and reduces the pollution effects. But the economics of operation are not attractive may be because of smaller size of plant. It is necessary that the steam turbine generator set should have a residual working life of 10 - 15 years, the capital investment on retrofitting should be minimum and the plant size needs to be 200 MW and above to have better economics of operation comparable with a new pulverised coal fired thermal power plant. Since the retrofit plant would drastically cut down the pollution effects due to emissions of particulate matter, sulfur and oxides of nitrogen, it would be ideal for cities / densely populated areas even for small sizes if economics is not a major criterion.

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Utilization of Czech Hard Coal for Clean Coal Technology.

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The fuel and energy base in Czech Republic is presently in a period of great structural change. The substantial problem is the evolution from a centrally planned system to a market economy model of extraction, production and consumption of fuel and energy sources.

The biggest contemporary problems are the following:

- very high energy consumption per GNP-unit as a consequence of the recent period of cheap energy subsidized by the government
- not existing programs for energy savings, regeneration, and renewable sources
- up until now, low energy price and its distortion by targeted subsidies don t allow us to estimate the alternative energy sources economically
- due to crude oil and gas import in the economy almost wholly dependent on unreliable sources in the former Soviet Union
- as a consequence of an oversized energy consumption there are relevant environment problems
- the current economic situation in the industry doesn t enable it to provide sufficient investment capital targeted to energy savings or utilization of renewable sources.

In the area of solid fuels management, the Czech economy will have to face unknown competitive forces on the free coal market, where increasingly Canadian, Australian, American and South Afrikan coals are pushed through. A specific problem appears to be the competition of some European coals that have a high rate of state subventions.

Total geological coal reserves in former Czechoslovakia amount to 28 billion tons. The location of these reserves in Czech republic is presented in Fig.1.

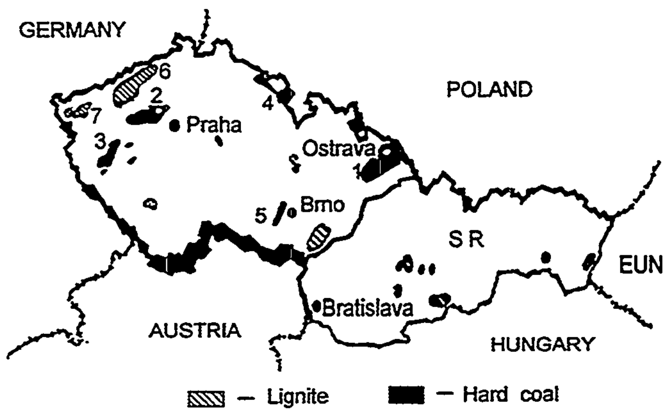

Fig.l: Location of coal reserves in Czech Republic

The geological reserves of hard coal amount to 6,3 billion tons, however, according to the contemporary valid regulations, the utilizable deposits are assessed as 21 per cent of geological reserves. A significant part of these leasable for extraction will remain unused. Recently due to the closure of the last remaining mines, coal has become inaccessible in the Ostrava-Karviná Basin. This amounts to 900 million tons of reserves in total including 116 million tons of utilizable reserves.

Contemporary utilizable reserves meeting current technical and economic requirements for utilization are designed to balance reserves. According to 1994-data for hard coal 4,3 billion tons are recorded. The long-term extraction and development of hard coal and lignite is shown in Table l.

Table l.: Long-therm development of coal production in CR. [mil.t]

Year	65	70	75	80	85	90	91	92	93
Lignite	65,7	74,5	78,6	87,2	92,6	77,2	75,2	66,7	65,6
Hard coal	27,8	28,2	28,1	28,2	26,2	22,4	19,5	18,4	18,3

From the data it is obvious that in the conditions of the Czech Republic there will be a several hundred years-perspective of coal as an energy source.

The dominant producer of electricity in the Czech Republic is the Czech Power Company, responsible for 80% of generation in 1993. Installed capacity is over 10 thousand MW, in this 70% from coal power plants, 27% from nuclear power plants and 3% from hydro power plants including two pumped storage plants.

The Czech Republic is in a very complex situation with regard to environmental protection. This situation is a consequence of extensive development of industry and agriculture, inefficient use of natural resources and high emissions of air and water pollutants. The root cause of the current problems is that for historical reasons, our country has had an ineffective economy which did not take account of environmental factors. The main source of air pollution is heat and power generating plants. Such plants account for around 55% of total ash, 82% of SO_2 and 21% of NO_x emissions. The proportion of air pollution in the Czech Republic due to energy production is much higher than the average for West European countries. The energy industry is mostly based on the use of domestic lignite - see Table 2.

Table 2.: Characteristics of energetic lignite

calorific value	10 - 14 MJ kg^{-1}
water content	30 - 35 %
ash content	20 - 30 %
sulphur content	0,9 - 2,7 %

The use of poor quality coal combined with 15 years delay in the construction of desulphurization facilities, has led to the present problems. In most regions, harmful emissions from power plants are not the main source of air pollution. Approximately 30-50% of air pollution in the lower atmosphere in a typical town near a 800 MW coal fired power plant should by attributed to that plant. The remainder is caused by a variety of other sources, such as surface mines, chemical plants, transport and above all, household boilers and small heat generating plants.

A new Clean Air Act from 1991 is valid in the Czech Republic. In accordance with the Act, all power plants must meet very strict emissions limits (see Table 3) by 1998.

Table 3.: Clean Air Act limits for burning of fossil fuels

	in $mg.m^{-3}$	SO_2	NO_x	CO	flue ash
Over 300 MW	Solid fuel	500	650	250	100
	Liguid fuel	500	450	175	50
	Gas	35	200	100	10
50 - 300 MW	Solid fuel	1700	650	250	100
	Liquid fuel	1700	450	175	50
	Gas	35	200	100	10
5 - 50 MW	Solid fuel	2500	650	150	150
	Liquid fuel	1700	450	175	100
	Gas	35	200	100	10

Construction of flue gas desulphurization facilities is a very significant element of air quality protection. This method will be used for 8 power plants with a total installed capacity of around 6000 MW. For power plants of the Czech Power Company in northern Bohemia the wet limestone desulphurization method will be used, while for plants in other areas the cheaper semi-dry method is being considered (see Table 4). Substitution of old boilers by fluidised bed combustion technology will be used in 4 small (55 - 110 MW) power plants and 3 new equipments are under construction in North Moravia.

Table 4.: Desulphurisation program of Czech Power Company. Planned FGD facilities.

Power Plant	Capacity [MW]	Method	Date
Tisová	1 x 110	wet limestone	1995-96
Ledvice	2 x 110	semi dry	1994-96
Tušimice	4 x 200	wet limestone	1994/97
Prunéřov	4 x 110 5 x 210	wet limestone	1992/96
Počerady	5 x 200	wet limestone	1991/97
Mělník	2 x 110 1 x 500	wet limestone	1995/98
Dětmarovice	4 x 200	semi dry	1995/98
Chvaletice	4 x 200	semi dry	1995/98

Reducing NO_x emissions is simpler than $DeSO_x$ programme through optimising the combustion regime and it is expected that emission limits can be reached by these primary measures alone. Figure 2 shows the situation in the furnace of a 200 MW boiler before and after optimising.

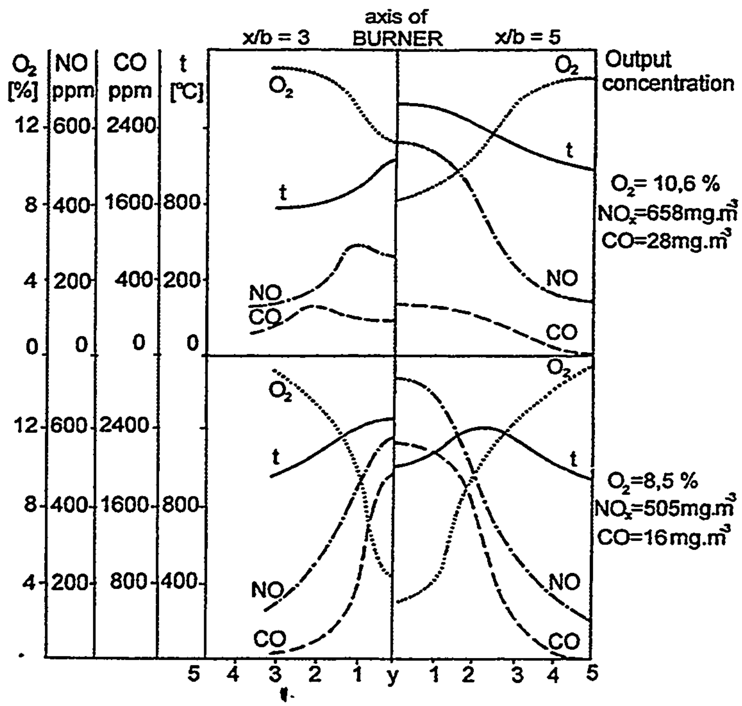

Figure 2.: Courses of NO_x formation in the furnace.

Only for the hard coal burning power plant Ditmarovice with its higher flame temperature is the combustion zone being implemented with reconstruction of burners by IVO Technology of Finland. At this time, most power plants in the North-Moravia region use a hard coal with calorific value about 24 $MJkg^{-1}$ and sulphur content about 0,6 %. Characteristics of hard coals - see Table 5.

Table 5. Characteristics of energetic hard coal.

calorific value	19 - 35 $MJkg^{-1}$
water content	0,8 - 6,6 %
ash content	8 - 40 %
sulpur content	0,4 - 0,9 %

From the point of view of local air pollution, it is the small boilers that are a great problem (the ones with thermal output of up to about 10 MW). There are thousands of them in operation in the Czech Republic and they comply with neither the economical nor the environmental requirements in any way. For economic reasons, their replacement with new boilers is out of the question, and there has been no way of modernizing them so far, so most of them are preparing for natural gas combustion. This will enable the power plants to comply with the emission limits, but because it will merely include equipping their combustion chambers with gas burners and doing only the necessary adjustments, their efficiency will be low and their operation costly with all the negative consequences. Being dependent on a sole foreign supplier does not make this solution more advantageous either. The solution to this difficult situation lies in these activities - education, research, development and implementation with support from the state.

Through the Grant Agency of the Czech Republic s coordinative work, the departments of three Technical Universities take part in this process. Technical University Ostrava in areas of coal science, combustion processes and equipment, creation of harmful substances in the furnace, minimization of harmful emissions and reconstruction of furnaces. Technical University Prague in areas of utilization of North Bohemian Lignite in power systems and burning stability in pulverised coal combustion, and Technical University Brno in areas of cogeneration units, combined cycles and ways of increasing efficiency of small gas boilers.

Meanwhile, the introduction of modern coal combustion technologies, flue gas cleaning, and utilization of solid residues from combustion processes is mostly a question of the transfer of existing technologies. The problems concerning the enhanced efficiency of economy and ecology of present stoker-fired boilers need to find optimal solutions with acceptable investment costs. The present situation is characterized by the following:

- no existing difference in furnace construction utilized for bituminous and brown coal combustion
- the lower output furnaces (several MW) expecially are constructed from membrane walls
- the most frequent type of boilers uses travelling grate firing systems with scatter coal transportation
- the air heat exchanger isn t utilized when the coarse-grained coal (0-30 mm) is fired (proportion of fractions less than 2 mm is 60%)

The results of this situation are mostly in lower temperature fields in furnace (max. 1000°C). This value is 250°C lower than projected temperature. Combustion with a high excess of air results in unburned solids carried out from the furnace with the gases. Due to the low temperature optimal combustion is not achieved. The content of the carbon in flue gases can sometimes be 60%, and if the bag houses are used, the danger of damage often occurs during textile firing.

What are ways we can improve this unsatisfactory state? In the first place, combustion of the prescribed quality coal. We are able to deliver sorted coal now, however, the price is much higher than the more usually fired coarsegrained coal. These higher prices are the biggest obstacle for many power and heating plants.

The second problem is that most stoker-fired boilers are designed for lignite, with a high content of volatile matter. For power industries located in bituminous mine areas it is therefore necessary to transport lignite for long distances. However, plants that burn lignite find it impossible to meet the mandatory emission limit for SO_2, because of the higher content of sulphur in the coal.

According to the "Cléan Air Act" of the Czech Republic all types of bituminous coal in Czech Republic are considered suitable ecological fuel. The content of sulphur in this coal guarantees that smaller industrial plants (less than 50MW) will meet the emission limit for SO_2. Decreasing of the NO_x emissions are more easy and investment costs are not too high.

Currently, ways to reconstruct present stoker-fired boilers with travelling grate are being examined, in order to find methods with acceptable investment costs. Final reconstruction is verified by combustion tests in power plants. The inlet and outlet boilers parameters are investigated. Special water-cooled probes are used for measuring the temperature and concentration fields in the furnace - see Fig. 3, 4.

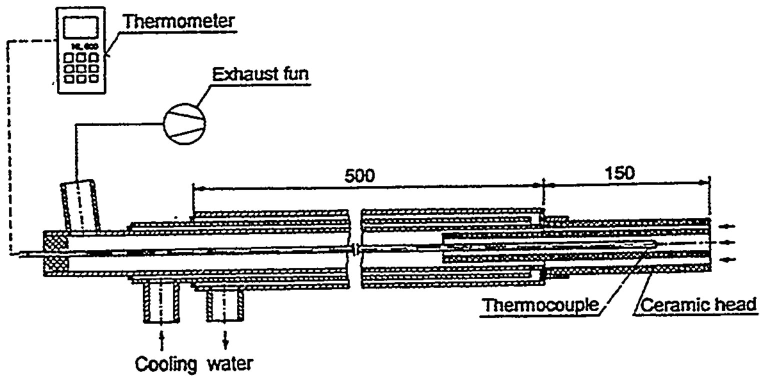

Fig.3. The probe for measuring of local temperatures in the flame.

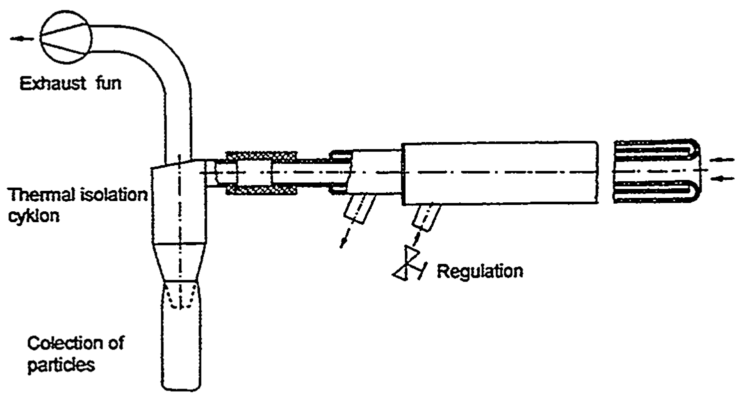

Fig.4. The probe for taking in solid particles.

The results of combustion tests demonstrate the correlation between maintainance parameters, as is for example shown in the Fig.5. Minimal excess of air is solved in respect to fulfilment of the emission limit of CO in flue gases.

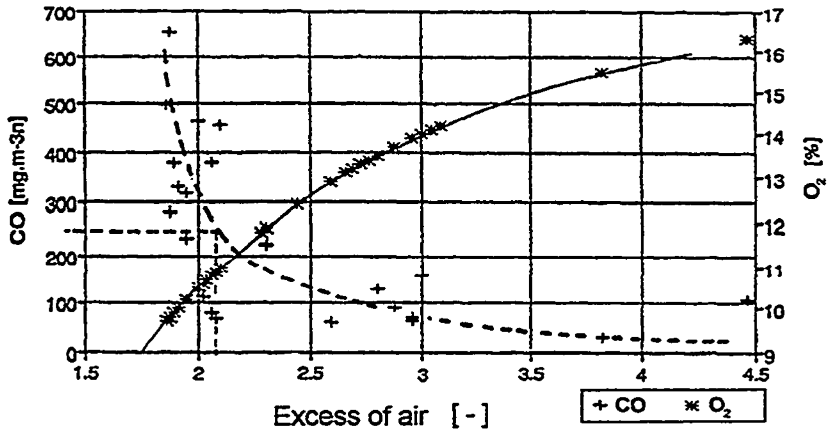

Fig.5. Limited excess of air for fulfilment of the emission limit of CO.

The main goal is to secure optimal ecological and economical firing conditions for bituminous coal in the furnaces designed for lignite. Then it will be necessary to increase combustion temperatures in the furnace. This can be provided by the following precautions. It is necessary:

- to use sorted coal of the prescribed quality and to decrease the content of fine particles
- to preheat and regulate the combustion air in the inlet of the furnace
- to provide suitable additional wall isolation in the lower part of the furnace
- to applicate the additional burner.

It is possible, also to recirculate the captured fly ash to the furnace for decreasing unburned carbon content.

The optimization of the combustion process can enhance a temperature in the furnace as is shown in Fig.6. A normal temperature in the furnace reached max. 1000°C. After optimization we can obtain projected values. According to measured concentration fields of CO_2 that have been obtained the acceptable combustion efficiency.

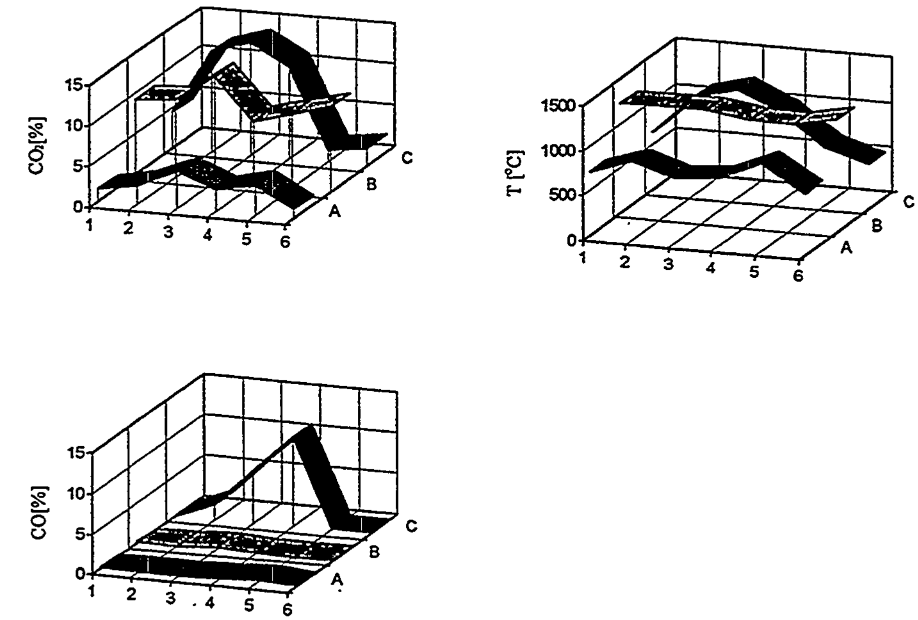

Fig.6. The temperature, CO and CO_2 concentration fields in stoker furnace after optimization.

A very intresting solution uses an additional burner. The experiments have been provided on the boiler with 8 MW-output. The 1 MW pulverized burner is located in the front wall.

This approach confirmed the suitability of this solution from the quality combustion point of view. The disadvantage of this method is the complicated grinding system requiring other equipment. The delivery of pulverized coal to the feeding system was not realistic in that time. The additional burner can use gas or oil. Many experiments proved that for optimal effect, it is nesessary to install a front wall burner with maximum the output 5% of the total boiler output.

We also proved the possibility to combust sorted waste oil. If the burner with the output 2% of total boiler output was used, the boiler could meet the mandatory emission limits. The combustion temperature increased about 150°C and the content of unburned carbon in the fly ash decreased about 75%.

Summary.

With respect to coal reserves in the Czech Republic, and given the lack of other fossil fuel resources, it is necessary to upgrade and modernize all coal power plants.

We have good results in power plants of large output, thanks to the Czech Power Company and others enterprises. The worst situation is in small industrial plants. They consist of a huge number of units, which have great impact on the local environment and on the total development of the energy sector. The main reason is the difficult economic situation of enterprises during the transformation of the Czech economy. There is still no offer for acceptable reconstruction of the small boilers.

The situation will be worse after full acceptance of the "Clean Air Act" in the year 1998. This problem is considered as a special chapter of the program "Clean Coal Technology" in the Czech Republic and other eastern European countries.

In order to address this problem, a Meeting of Experts on Clean Coal Technologies has been organised by the Economic and Social Council of the United Nations to be held in April 1995. Similarly, another meeting called the " Workshop of the Development of small-size boilers for industrial, household and farming sectors" will be held later that month. These problems are studied also in project CUSTNET (Coal Utilization Science and Technology Network), financed by the Directorate-General for Science, Research and Development of the European Commission in Brussels. This project constitutes in this time an international network of scientists and technologists, working in the area of coal utilization.

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