Basic and Applied Research in Coal Utilization for Electric Generation

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Coal Utilization in South Africa

- 70% of primary energy consumption
- 90% of electricity generation
- 30% of petroleum liquid fuels

South Africa said it would lower its carbon emissions to 34% below current expected levels by 2020 and about 42% below current trends by 2025. "This undertaking is conditional on firstly a fair, ambitious and effective agreement," a South African government statement said. "And secondly, the provision of support from the international community, and in particular finance, technology and support."
Eskom is currently constructing two new coal fired power stations:

- **4764MW Medupi plant in the Waterberg** (to be supplied by Exxaro)
- **4800MW Kusile plant in the Witbank coalfield** (to be supplied mainly by Anglo Coal’s New Largo colliery).

These new power stations will use **supercritical technology**.

- Medupi is also the biggest dry-cooled power station in the world
- The boiler & turbine contracts were the largest Eskom had ever signed.
  - Hitachi Power Africa will supply the boiler and Alstom S&E has the turbine contract

- Medupi, situated in the remote Waterberg coalfield, will not initially have **flue-gas desulphurisation** (FGD), while Kusile, located in the more densely settled Mpumalanga Province, will have FGD fitted upfront.

- Both will be —**carbon-capture ready** — i.e. they could be retrofitted at a later stage.

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### Table 6: Eskom’s Coal-fired Power Stations: 2009

<table>
<thead>
<tr>
<th>Power station</th>
<th>Location</th>
<th>MW</th>
<th>Principal Coal supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afobatse</td>
<td>Middelburg</td>
<td>2040</td>
<td>Exxaro</td>
</tr>
<tr>
<td>Camden</td>
<td>Emelo</td>
<td>1440</td>
<td></td>
</tr>
<tr>
<td>Duvha</td>
<td>Witbank</td>
<td>3450</td>
<td>BHP Billiton</td>
</tr>
<tr>
<td>Grootvlei</td>
<td>Balfour</td>
<td>760</td>
<td>(1200)</td>
</tr>
<tr>
<td>Hendrina</td>
<td>Hendrina</td>
<td>1000</td>
<td>BHP Billiton</td>
</tr>
<tr>
<td>Kendal</td>
<td>Witbank</td>
<td>3640</td>
<td>BHP Billiton</td>
</tr>
<tr>
<td>Komati</td>
<td>Middelburg</td>
<td>(1000)</td>
<td>BHP Billiton</td>
</tr>
<tr>
<td>Kriel</td>
<td>Bethal</td>
<td>2650</td>
<td>Anglo Coal</td>
</tr>
<tr>
<td>Lebata</td>
<td>Sasolburg</td>
<td>3555</td>
<td>Anglo Coal</td>
</tr>
<tr>
<td>Majuba</td>
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<td>Mavumila</td>
<td>Leprahale</td>
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<td>Exxaro</td>
</tr>
<tr>
<td>Tutuka</td>
<td>Standerton</td>
<td>2610</td>
<td>Anglo Coal</td>
</tr>
</tbody>
</table>

Source: Eskom Annual Report 2010

(Bracketed data reflects mothballed capacity being returned to service)
Various Options for Cleaner Coal Utilization

- With Eskom and Sasol, synergy can be encouraged for IGCC or a combined coal & biomass in simultaneous fuel and electricity generation (polygeneration) with lowered CO₂ footprint (once-through coal-and-biomass to liquid fuel and electricity, Princeton Univ)
Formed NO (at high Temperature) and N₂O (at low Temp, such as in fluidized bed combustors) are then partially reduced to N₂.

- NO can be reduced by NH₃,
- N₂O can be decomposed due to temperature, and also
- NO and N₂O can be reduced either directly by char or through reactions with CO catalyzed char
Need for Improved Coal Utilization Technology

- South Africa’s domestic use of coal
  - Pulverized coal combustion (Eskom and Sasol)
  - Fixed-bed coal gasification (Sasol)
  - Grate-fired oilers (industry)

- Quality of coal
  - Expected to decrease because of lower grade coal (high ash) seams are being mined
  - Coal washing is being scaled down because of environmental concerns/legislations

- Hence, improved and new coal utilization technologies are required in future
Basic Research

- Research on coal Pyrolysis, Ignition & Combustion processes
- NOx formation and reduction

- Coal ignition phenomena through a controlled lab-scale test setup
  - Single coal particles
    - Homogeneous ignition
    - Heterogeneous (generally when D ~< 100 mic AND high heating rate)
  - Coal clouds (provides support for boiler design & engineering)
    - Homogeneous may still be important at high heating rate when volatiles are pyrolyzed before ignition of coal clouds

- Tools and Diagnostics
  - High-speed cam, pyrometer, etc
  - Cooled sampling probe
  - Laser diagnostics (LDV, LIF, etc)
  - Spectrometer
  - Modeling and numerical analysis (CFD)
  - Gas analyzers (GC, etc.)
  - etc
NOx Reduction Strategy in Burners

- Mostly from fuel-bound nitrogen and highly dependent on coal properties
  - Highly reactive coals (low Fixed-C/VM ratio) & coals with low N content → Low NOx
- Staging the addition of oxygen (in air) to produce an initially-fuel-rich zone near the burner exit
  - This will partially convert the fuel-bound nitrogen to N₂
  - Regulate rate of air introduction during early stages of combustion (use of multiple air zones and hardware to control “mixing rates”) →
    - reduces the O₂ availability as coal devolatize and
    - reduces peak flame temperatures
  - Undesired outcome: reduced flame stability and increases unburned carbon (UBC)
    - Multiple air zones make it possible to create sufficient swirl (or recirculation) for good flame stability using just s portion of the air flow
    - Remainder of the air (10% to 30%) is more gradually introduced downstream to complete combustion

- Reduction of temperature during the early stages of combustion

- Potentially additional NOx reduction can be achieved by adding extra HC downstream of the fuel in the post-flame area (called “reburning”)
NOx Reduction Strategy in Burners

- **Ignition chemistry**
  - Maximum VM release
  - Optimum \([m_1+m_2]/A_{VM}\)

- **Aerodynamics**
  - Maximum NO\(_x\) reduction area
  - Optimum relative velocity between fuel and air
  - Optimum \(V_2/V_1\)

---

\(A_{VM}\): required airflow rate for complete combustion of VM content in coal

\(m_0\): Coal flow rate, \(m_1\): primary air velocity, \(m_2\): secondary air flow, \(m_3\): tertiary air flow

\(V_1\): Primary air velocity, \(V_2\): secondary air velocity, \(V_3\): tertiary air velocity
NOx Reduction Strategy in Burners

- Sample industrial burners
- Similar NOx reduction strategy
- There is plenty of room for further innovation in burner design

Concept of in-flame NOx reduction. It is reduced under high temp and fuel-rich conditions just after the ignition point (Hitachi)
Sub-Scale Burner Research

- Build a modular single- or dual-burner (subscale) facility for burner studies

- Design a “new” burner based on past information and author’s ideas/experience

- Test the “new” and/or the existing (Eskom’s interest) burners using the following tools
  - Flow field visualization (high speed imaging, etc)
  - Gas sampling and analysis
  - Particle sampling & ash analysis
  - Velocity field measurements using nonintrusive laser methods
  - Particle field measurements
  - Computational methods
  - etc

- Consider effects of the following parameters
  - Coal types
  - Coal particle size distribution
  - Swirl intensity
  - Air flow distribution
  - Recirculation zone
  - Heat flux
  - etc
Pilot-Scale Furnace Studies

- Potentially feasible with collaboration and financial support from industry players (Eskom, Sasol, and others)
- Provides a unique information set from a combined single (or dual-) burner furnace and a more realistic (pilot) facility
- Provides valuable information on scaling
- For other relevant studies (burner & OFA, etc)

- Facility is to be equipped with
  - OFA ports
  - Fuel, air and water supply system
  - Flue gas & ash handling system
  - Fiber optic access
  - Gas sampling
  - Gas and particle analysis
  - Etc.

Real Models = Real Results (CS 108 & CS 112)
- 1/12 scaled replica of the combustion air & FGR system for a 330 MW Utility Boiler in Northern California
- 24 Burners & 12 Over Fire Air (OFA) Ports
- FGR supplied by 4 airfoil spargers
- Improved airflow distribution from +/- 16% to +/- 7.5%
- Increased FGR flow by 5%
- Increased OFA flow from 8 to 12%
- Along with the new Dynaswirl-LN burners this reduced NOx from 73 to 36 ppm
Basic & Applied Research Roadmap

- Basic research on coal combustion process
- NOx formation and reduction

- Research and development of fundamental technologies for low NOx combustion
- Laboratory scale test furnace
- Fluid dynamics
- Numerical analysis

- Pilot scale combustion test (< 100 kg/h)
- Study of burner structure design for adopting the fundamental technology

- Large scale combustion furnace test (~3500 kg/h)
- Performance confirmation by actual scale burner
- Confirmation test of burner’s devices

- Field test of actual existing boiler furnace
- Performance confirmation of candidate burner design by actual verification

Implications for emission and efficiency improvements for existing and new coal-fired power stations

In collaboration with the Eskom at its facilities
Coal cleaning is the key process in coal preparation to reduce mineral matter content and inorganic sulfur content.

Current commercial coal cleaning methods are invariably based on physical separation;

Chemical and biological methods tend to be too expensive.

Typically, density separation is used to clean coarse coal while surface property-based methods are preferred for fine coal cleaning.

Figure 1. Preferred size ranges of feeds to major coal cleaning devices

Figure 2. Typical efficient separating gravity ranges

Density-based coal cleaning
The Ash Situation

- **Density-based processes,**
  - coal particles are added to a liquid medium and then subjected to gravity or centrifugal forces to separate the organic-rich (float) phase from the mineral-rich (sink) phase. Density-based separation is the most common coal cleaning method and is commercially accomplished by the use of jigs, mineral spirals, concentrating tables, hydrocyclones, and heavy media separators. The performance of density-based cleaning circuits is estimated by using laboratory float-sink (F-S) tests.

- **Surface property-based processes,**
  - ground coal is mixed with water and a small amount of collector reagent is added to increase the hydrophobicity of coal surfaces. Subsequently, air bubbles are introduced in the presence of a frother to carry the coal particles to the top of the slurry, separating them from the hydrophilic mineral particles. Commercial surface property-based cleaning is accomplished through froth or column flotation. To estimate the performance of flotation devices, a laboratory test called release analysis is used.

- **Other physical cleaning methods:** **selective agglomeration,** heavy medium cycloning, and **dry separation** with electrical and magnetic methods
  - In **selective agglomeration,** the coal is mixed with oil. The oil wets the surface of coal particles and thus causes them to stick together to form agglomerates. The agglomerated coal particles are then separated from the mineral particles that stay in suspension because they do not attract oil to their surfaces. A version of selective agglomeration, called the **Otisca T-process,** was reported to reduce the ash content of some coals, ground to about 2 μm, below 1% with a high recovery of the heat content.
  - **Dry methods** that take advantage of the differences between electrical or magnetic properties of minerals and coal particles have not developed enough for commercial applications.

- **Theoretically,** the efficiency of physical cleaning should increase as particle size decreases (because of the improved liberation of the mineral matter from the coal matrix).
  - Therefore, recent research on advanced coal cleaning has focused on improving fine-coal cleaning.
Patented ultrasonic coal-wash (aqueous-based or reagent-based) process for de-ashing (US Patent # 4741839 and http://www.advancedsonics.com/)

- Ultrasonic vibratory energy coupled through the tray to the flowing slurry has a “microscopic scrubbing” action on all particles and agglomerates, breaking the surface tension on the particle, cleaning particle surfaces, and separating different constituent particles and coatings of gels, slimes, algae, clay or mud.
- Mixtures of fine particles of coal or other valuable minerals with ash, clay, rock or sand particles are separated with high efficiency by these techniques.
- Simultaneous removal of ash and sulfur is feasible

- Extraction of alumina from coal fly ash with sulfuric acid leaching method

Various reagents used to remove Ash and Sulfur from coal
Supercritical Studies

- New power stations in South Africa are based on supercritical steam
  - Boiler design
  - Supercritical steam turbine design and operation

- Yuda and Ayse [40] investigated the effect of supercritical ethyl alcohol/NaOH on the solubilization and de-sulfurization of lignite.
  - Supercritical experiments have been done in a 15 ml micro reactor at 245 °C for 60 min, by changing the ethyl alcohol/coal ratio from 3 to 20 under a nitrogen atmosphere. Increase in this ratio increased the yield of solubilization and desulfurization. Higher yields of extraction in the case of ethyl alcohol/NaOH experiments may be due to the fact that alcohols can transfer hydrogen more easily in the presence of bases.
  - As the ethyl alcohol/coal ratio was increased from 3 to 20, the sulfur content of the coal decreased to 0.75%.

- Supercritical heat transfer coefficients are not well characterized
Carbon Nanotubes & Ignition Enhancement

Effect of Pulse Duration on Dry SWCNTs’ Minimum Ignition Energy

Energy Flux for all laser studies in coal particles were greater than 800 W/cm².

Energy Flux for carbon nanotubes is at 20 W/cm², which is more than 40 times less required intensity.
Ignition of a Liquid Fuel Droplet
Towards Distributed Ignition of Fuel Sprays or Pulverized Coal Jets from Burners

For the first time, Chehroudi et al. demonstrated:

- Applications of nanostructured materials in fuel ignition and
- Ignition of liquid droplet via nanostructured materials

Accomplished by a camera flash using SWCNTs as ignition agents

Paving the way towards Distributed Ignition of gaseous fuel-air mixture, liquid sprays, and pulverized coal jet from burners
Thank you

Questions?
Technology Applications of SWNT Ignition: HCCI Engines

**NewScientist (Nov 19, 2005)**

**By Chehroudi, et al.**

**Attributes of the HCCI engine**
- Highly fuel-efficient operation
- Low emission of nitric oxides, soot, CO, and CO₂

**Rationale**
- Fuel-lean, homogenous fuel-air mixture, autoignition, no flame propagation, chemistry-controlled rather than turbulence-controlled combustion

**Technology barriers addressed**
- On-demand autoignition of homogeneous gaseous fuel-air mixture

**HOMOGENOUSLY-CHARGED COMPRESSION IGNITION (HCCI) ENGINE**


B. Chehroudi, PhD
Additional Information
structure – a burner built around a center jet of air, encircled by the fuel stream, and then wrapped in additional combustion air.

With the AireJet burner design structure, ignition takes place from the inside out and from the outside in. Combustion is intensified by supplying oxidant directly to the core of the flame rather than waiting for air around the exterior to mix with the fuel stream. The AireJet burner was specifically developed for use with overfire air (OFA) to create an integrated system for the most effective overall NOx reduction.

Mechanically, the AireJet burner assembly is similar to the DRB-42® burner configuration, B&W PGG's most recent low NOx burner, with an excellent reputation for durability. The coal nozzle/core air assemblies are lined with ceramic materials to resist wear.
2.1. Thermal NO

Thermal NO is primarily formed from the nitrogen present in air following the reaction mechanism given below [11-13]

\[
\begin{align*}
\text{N}_2 + \text{O} & \xrightarrow{k_1} \text{NO} + \text{N} \quad (4a) \\
\text{N} + \text{O}_2 & \xrightarrow{k_2} \text{NO} + \text{O} \quad (4b) \\
\text{N} + \text{OH} & \xrightarrow{k_3} \text{NO} + \text{H} \text{ (in a fuel-rich mixture)} \quad (4c)
\end{align*}
\]

The reaction rate coefficients \((k_1, k_2, k_3, k_2, k_3, k_3)\) are expressed in Arrhenius form as [14]:

\[
k_i = AT^\beta \exp\left(-\frac{E}{RT}\right) \quad (5)
\]

where \(i\) corresponds to the reaction steps of the mechanism (Eqs. 4a-4c), \(T\) is the universal gas constant, \(T\) is the temperature (in K), \(E\) is the activation energy, \(A\) and \(\beta\) are the kinetic parameters. The influence of the third reaction (Eq. 4c) in a pulverized coal flame is negligible [15]. The overall rate of formation of NO through the thermal route may be calculated from the rates of formation of the forward and reverse reactions given in Eq. (4a) and (4b). The assumptions often employed for the calculation are: (i) \(O_2\) and \(N_2\) are in equilibrium concentrations, (ii) the N atom concentration is at steady state and (iii) the O atom concentration is at partial equilibrium with \(O_2\) in the dissociation reaction [16].

\[
\frac{1}{2} \text{O}_2 \leftrightarrow \text{O} \quad (6)
\]

Hence, the rate of thermal NO formation can be expressed as [14]:

\[
\frac{d[\text{NO}]}{dt} = \frac{2[O]\left(k_1k_2[O_2][N_2] - k_{-1}k_2[\text{NO}]^2\right)}{k_2[O_2] + k_{-1}[\text{NO}]} \quad (7)
\]

where, the terms in the third bracket (\([\cdot]\)) represent the molar concentration of the corresponding species. The value of \([O]\) is found from the equilibrium constant for the dissociation of molecular oxygen (Eq. 6) with the rate constant proposed by Westenberg [16].

In the thermal NO formation mechanism, the activation energy of the forward reaction of Eq. (4a) is very high. Therefore, the thermal NO formation rate is highly dependent on the temperature and oxygen atom availability and is associated with long residence time [8]. It has been shown that thermal NO formation is significantly reduced in fuel rich systems and at temperature below the range 1600-1800 K [17]. However, the temperature fluctuations in the turbulent combustion system of a pulverized coal fired boiler can extend the importance of the thermal NO formation even at a lower mean gas temperature [18].

B. Chehroudi, PhD
2.2. Prompt NO

Prompt-NO is formed by reactions of $\text{N}_2$ with fuel derived radicals such as $\text{CH}$ and $\text{CH}_2$ in regions near the flame zone of a hydrocarbon fuel [19]. The general scheme of the prompt NO mechanism is that hydrocarbon radicals react with molecular nitrogen to form amines and cyano compounds. The amines and cyano compounds are then converted to intermediate compounds that ultimately form NO. Ignoring the processes that form CH radicals to initiate the mechanism, the prompt NO mechanism can be written as

\begin{align*}
\text{CH} + \text{N}_2 & \rightleftharpoons \text{HCN} + \text{N} \\
\text{C} + \text{N}_2 & \rightleftharpoons \text{CN} + \text{N} \\
\text{HCN} + \text{O} & \rightleftharpoons \text{NCO} + \text{H} \\
\text{NCO} + \text{H} & \rightleftharpoons \text{NH} + \text{CO} \\
\text{NH} + \text{H} & \rightleftharpoons \text{N} + \text{H}_2 \\
\text{N} + \text{OH} & \rightleftharpoons \text{NO} + \text{H}
\end{align*}

Where $n$ is the number of carbon atoms in the fuel, $C_1$, $C_2$, $C_3$, $C_4$ are 8.19 $\times$ 10^{-3}, 23.2, 32 and 12.2, respectively. In Eq. (9), $T^\#$ represents the non-Arrhenius behaviour of the equation at conditions where the maximum flame temperature is exceptionally high or low. $A_{Pr}$ is the pre-exponential factor, $a$ and $b$ are reaction order constants for the oxygen and the fuel, respectively, where $E$ is the activation energy.

However, the NO formation through the prompt route does not contribute more than 5% of the total NO formed in a coal fired boiler and is often neglected in the evaluation of NOx emissions from boiler [20].
2.3. Fuel NO

Coal contains 0.5-2.5% nitrogen depending on its origin and rank [21, 22]. Formation of NO from the oxidation of fuel-N is termed as fuel NO. It is the main source of NOx emissions in coal combustion, constituting 70-90% of the total NO [10, 23], and therefore has received considerable attention [21]. When the combustion of a pulverized coal particle begins, the nitrogen present in the fuel is partitioned between the volatile matter and the char. The split of nitrogen between the volatile matter and char depends on the fuel structure, temperature and residence time [21, 23]. Fig. (1) shows the partitioning of nitrogen between char and volatiles (in the form of tar and light gases like HCN and NH3) during devolatilization of coals of different ranks [21].

The results show that a major share of the total nitrogen is retained in the char after devolatilization. Basu et al. [24] found that the fraction of nitrogen in the volatile matter increases with the oxygen content in the fuel. The furnace temperature has a key influence on the nitrogen partitioning. At low temperature and residence times, the nitrogen is preferentially retained in the char, while at high temperatures char nitrogen is depleted [25-28]. Fig (2) shows the nitrogen concentration in char versus temperature for a range of coal using various experimental techniques [21].

In coal combustion, the nitrogen present in the char is a major source of NOx formation. [4, 38, 39]. But, there have been comparatively fewer studies on the conversion of char nitrogen at temperatures relevant to the pulverized coal fired boilers and therefore the subject remains less understood. Char oxidation involves a number of complex physical and chemical processes [4]. These incorporate difficulties in performing experiments with char as well as interpreting the results. There has been uncertainties on the species released upon oxidation of char nitrogen and a number of species (like NO, N2O, HCN, NH3, HNCO and N2) have been reported in the literature [38]. In the literature, the reported conversion of char-N to NO has been found to vary from below 30% [40-42] to almost 100% [43, 44]. Combustion of a single char particle at high temperature (1000-1400 K) has shown that the char-N is oxidized to NO with a yield of 75-100% [43]. This indicates that in an oxygenated atmosphere the char-N tends to get readily oxidized to NO. It further leads to the proposal that the reduction in NO yield from the char combustion in batch is perhaps due to the subsequent reduction of NO on the char surface [44].

Molina et al. [38] reviewed different works on the mechanism of NO formation on the char surface. It is established that the NO forms through the reaction of O2 molecules with N on the surface of the char:

$$C(N) + O_2 \rightarrow NO + C(O)$$  \hspace{1cm} (13)

Here, C(N) and C(O) denote the concentrations on the surface of the char for the nitrogen and oxygen, respectively. The NO, which is formed, may be reabsorbed on the char surface through a dissociative chemisorption reaction as:

$$2C_f + NO \rightarrow C_f(N) + C(O)$$  \hspace{1cm} (14)

where, C_f is a free carbon site on the char surface and C_f(N) is a nitrogen surface species other than the char surface species. The molecular nitrogen (N2) may be formed through the reaction of C_f(N) with gas phase NO and also through the reaction between two C_f(N) species.
2.4. N₂O-intermediate Mechanism

The mechanism is important in fuel lean ($\Phi < 0.8$), low temperature conditions [5]. The three steps of the mechanism are:

\begin{align*}
O + N₂ + M \leftrightarrow N₂O + M & \quad (15a) \\
H + N₂O \leftrightarrow NO + NH & \quad (15b) \\
O + N₂O \leftrightarrow NO + NO & \quad (15c)
\end{align*}

This mechanism is important in NO control strategies that involve lean premixed combustion such that encountered in gas-turbines [45], and it is not significant in pulverized coal combustion.
Nitric oxide, NO, is formed in fuel-lean flames by the attack of O atom on molecular nitrogen ("thermal NO"). In fuel-rich flames it forms via capture of N\textsubscript{2} by hydrocarbon radicals, ("prompt NO"), and by the pyrolysis and oxidation of heterocyclic nitrogen compounds in coals and petroleum fuels ("fuel NO"). Fig. 7 illustrates chemical pathways of nitrogen compound interconversions in fuel lean and fuel rich flames. Examination of the chemical reaction paths of nitrogen oxides formation and destruction in flames led to the formulation of guidelines for primary measures of NO\textsubscript{x} emissions reduction in boilers:

- reducing the peak flame temperature by heat extraction, and/or by flue gas recirculation;
- diluting the reactant concentrations by flue gas or steam mixed with gaseous fuels and recirculated burned gas mixed with the combustion air;
- staging the combustion air to produce fuel-rich/fuel-lean sequencing favorable for the conversion of fuel bound nitrogen to N\textsubscript{2}; and
- staging the fuel so that the NO formed earlier in the flame is getting reduced by its reactions with hydrocarbon radicals ("NO reburning") (Wendt et al. [21]).

The reduction of NO\textsubscript{x} emission by combustion process modification, a science based technology, has been successfully applied in industry. More than 188 GW of electric power generating capacity currently in operation

**Fig. 7. Chemical pathways of NO\textsubscript{x} formation and destruction [20].**

Combustion technology developments in power generation in response to environmental challenges

J.M. Beir
Low NOx burners (LNB) (Fig. 8) represent the most cost effective method of achieving reduced NOx emissions from new plant boilers, and also from existing boilers by retrofit. Air staging in these burners is achieved by the aerodynamically tailored mixing of the fuel jet with air streams supplied through the burner, rather than by the use of over-fire air.

One of the problems of LNBs is the requirement of maintaining a fuel-rich environment close to the burner for the pyrolysis reactions to run their course, followed by the admixing of the residual combustion air to complete combustion. An example of an engineering solution of this problem based on first principles is the radially stratified flame core burner (RSFC). The process of turbulence damping through radial density stratification in rotating flows demonstrated by Emmons and Ying [23], and Chigier et al. [24] has been employed in the design of this LNB. Premature air-fuel mixing is prevented by the damping of turbulence in the near burner region followed by the vigorous admixing of the residual burner air issuing from the outer annulus of a triple annular burner. Toqan et al. [25], Shiaideh et al. [26], and Barta et al. [27] reported NOx emissions achieved with the RSFC burner burning natural gas, heavy fuel oil, and coal, respectively, in the 1.5 MWth MIT combustion Research Facility. In Fig. 9, measured NOx concentrations are plotted for pulverized coal [27]. The straight line in the middle of the graph represents the case without external air staging. The top line refers to uncontrolled conditions, and the lowest line to the use of the RSFC burner with over-fire air.

The RSFC burner has been scaled up and commercialized by ABB under license from MIT. LaFlesh et al. [28] have recently given an update on ABB-CE’s RSFC Low NOx wall burner technology.

![Low NOx Burner Schematic](image)

**Fig. 8.** Low NOx burner schematic.

![Exit NOx Concentration vs. First Stage Stoichiometric Ratio](image)

**Fig. 9.** RSFC burner NOx emissions with HV bituminous coal [27].

Combustion technology developments in power generation in response to environmental challenges

J.M. Bees*
In “NO reburning,” the secondary fuel is usually natural gas (Fig. 10) [29], but fuel oil or even coal can also be used. In the latter case, the coal volatiles are the main reactants, but carbonaceous solids may also react to reduce NO to N₂ (Chan et al. [30]). The reburning technology has been successfully applied in the USA for slagging cyclones (Borio et al. [31]), for wall and tangentially fired pulverized coal combustion with dry ash removal (Folsom et al. [29]), and in both oil and coal fired boilers in Italy following computational studies, and laboratory and pilot plant experiments at ENEL’s R&D Laboratories in Pisa (DeMichele et al.[32]; LaFlesh et al. [33]). NOₓ reductions reported with coal and natural gas as reburn fuel in a coal fired boiler by Payne et al. [34] are shown in Fig. 11.

The modeling of the reburn process represents a special challenge because it requires detailed descriptions of both the nitrogen chemistry and the controlled mixing of relatively small mass flows of reburn fuel and tertiary air with the bulk flow of the combustion products in the furnace.

Ehrhardt et al. [35] have developed a model in which following a CFD calculation of the spatial distributions of flow, major species-concentrations, and temperature, the combustion space is subdivided into a relatively small number (say one hundred) of volume zones which then permit the application of more detailed chemistry than would have been possible in CFD models. Comparison with experiment showed good agreement with computations for an axisymmetric oil fired reburn system [35].
Because of the low combustion temperature in fluidized combustion, the NO is formed mainly by the conversion of coal-nitrogen, a process which lends itself for minimizing emission by the application of staged air introduction (Gibbs et al. [36]). However, a difficulty due to the low combustion temperature is that nitrous oxide, \( \text{N}_2\text{O} \), an intermediate product of NO formation, survives and is emitted from FBC at concentrations ranging from 40 to 100 ppm [22]. Nitrous oxide is a specially unpleasant pollutant; it is a greenhouse gas which also depletes stratospheric ozone. The raising of the gas temperature before the convective section of the boiler to above 1200 K could eliminate \( \text{N}_2\text{O} \) emissions, but the temperature rise adversely affects sulfur capture in the fluidized bed (Tullin et al. [37]). It is noteworthy that pressurized fluidized beds also emit \( \text{N}_2\text{O} \), except the second generation pressurized fluidized bed in which the gas temperature is raised by a topping combustor before entry to the gas turbine, thereby eliminating the \( \text{N}_2\text{O} \) in the combustion products [38].

In gas turbine (GT) applications, large amount of excess air is used to cool the combustion products before entry to the gas turbine to a temperature limited by the structural integrity of gas turbine blades. In the conventional method of combustion, the fuel and air are separately injected into the combustor and mix in the course of combustion (diffusion flame). This process is prone to the formation of thermal NO because of the near stoichiometric conditions which prevail on the boundaries of fuel-rich and fuel-lean eddies in such flames. To overcome this problem, the fuel gas and air are premixed prior to their entry to the combustor creating a strongly fuel-lean mixture corresponding to the combustor exit gas temperature (presently about 1573 K).

This so called ultralean premixed combustion gives very low \( \text{NO}_x \) emissions, typically less than 15 ppm at 15% \( \text{O}_2 \) with natural gas as fuel, but is left with the problem of flame stability. The latter is generally solved by the injection of a small percentage of the fuel, say 10%, to produce a fuel jet pilot flame as a stable source of ignition. Fig. 12 illustrates the opportunities and some of the problems of ultralean premix combustion (Maghon et al. [39]). The figure shows the measured variations of \( \text{NO}_x \) and CO emission data as functions of the air/fuel ratio and of the adiabatic flame temperature of a natural-gas/air diffusion flame, and for 92% and 100% premixing. In the case of 92% premixing, the rest of the fuel (8%) burns in the form of a pilot diffusion flame. \( \text{NO}_x \) and CO emissions are very low in the range of state of the art turbine entry temperatures (1573 K), but the flame stability is not ensured without the pilot flame. As the air/fuel ratio increases, the CO emission rises steeply. Most of the major gas turbine manufacturers are offering lean burn premix combustors capable of 15 ppm \( \text{NO}_x \) (15% \( \text{O}_2 \)) dry or with minimal water injection (Beer) [40]. As examples, ABB’s Double Cone burner is illustrated in Fig. 13 (Sattelmaier et al. [41]), and Siemens’ KWU in Fig. 14 (Becker et al. [42]). As new materials permit raising the turbine inlet gas temperature beyond 1800 K, the opportunity to reduce \( \text{NO}_x \) emissions by lean premixed combustion will become limited. This will present a new challenge to combustion R&D in gas turbine applications.
(2): Char burning [Field et al.]
(6) Zeldovich (Thermal NOx): For coal ~20%
(9) & (8) Fuel NOx: Found-bound nitrogen with combustion air. For coal ~ 80%
(7) Prompt NOx: Minor amount formed early in the combustion process through complex interactions of molecular nitrogen with hydrocarbon free radicals to form reduced nitrogen species that are later oxidized to NOx
NO and N₂O Chemistry for Coal

![Diagram showing NO and N₂O chemistry pathways in coal combustion](image)

**Figure 2. NOx production pathways in coal combustion**

Staged Low NOx Combustion Systems for Coal Fired Boilers and Corrosion

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