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Executive Summary

Coal is one of the world’s fastest growing energy sources. It fuels almost 40% of electricity worldwide, with even higher percentages in several countries. However, coal is also the most unclean energy source in the world. Upon burning, coal releases a number of problem pollutants such as mercury, sulfur, nitrogen, and carbon dioxide. These pollutants are not only harmful to breathe in, but are also avid greenhouse gases and contribute significantly to global warming.

Clean Coal Technologies (CCTs) are defined as ‘technologies that enhance both the efficiency and the environmental acceptability of coal extraction, preparation and use’. CCTs reduce emissions and waste, and increase the amount of energy gained from each ton of coal. CCTs can reduce greenhouse emissions from any industrial or mining process involving coal, but the international priority is reducing carbon dioxide emissions from coal-based electricity generation. There are two basic strategies to achieve this:

- Increasing the efficiency of electricity generation plants (a one percent improvement in thermal efficiency can yield two to three percent reduction in greenhouse gas emissions). This approach will not work in isolation because a short-term reduction in emissions will be counteracted by the increasing demand for electricity;

- Capturing emissions and storing them underground (sequestration). This strategy is the most important in terms of achieving large reductions in greenhouse gas emissions from coal-based power generation. Sequestration is supported by coal gasification technologies, which can deliver a relatively pure stream of carbon dioxide, lending itself to capture and storage.

Clean Coal Technologies - the products of research and development conducted over the past 20 years - have resulted in more than twenty new, lower-cost, more efficient and environmentally compatible technologies for electric utilities, steel mills, cement plants and other industries.

Looking at the growing popularity of these technologies and of this industry, Energy Business Report presents an in-depth analysis of all the various technologies involved in cleaning coal and protecting the environment. This report on Clean Coal Technologies analyzes upcoming and present day technologies such as gasification, combustion, and others. This report looks at the various technological aspects, economic aspects, and the various programs involved in promoting these emerging green technologies.
Industry Background

What is Coal?

Coal is a fossil fuel extracted by underground mining or open-pit mining (surface mining). It is a readily combustible black or brownish-black rock. Coal is a sedimentary rock, but the harder forms, such as anthracite coal, can be regarded as metamorphic rock because of later exposure to elevated temperature and pressure. It is composed primarily of carbon along with other assorted elements, including sulfur. Often associated with the Industrial Revolution, coal remains an enormously important fuel. It is the largest single source of fuel for the generation of electricity worldwide, and a vital component in the reduction of iron ore.

Historical Background of Coal

Coal has a lengthy and diverse history. Evidence suggests that coal was first used commercially in China, where a mine in northeastern China provided coal for smelting copper and casting coins around 1000 BC. Meanwhile, Greek philosopher and scientist Aristotle was one of the first to refer to coal as a charcoal like rock.

The demand for coal increased drastically during the Industrial Revolution in the 18th and 19th centuries, primarily due to the improvements made in 1769 to the design of James Watt’s steam engine.

Throughout history, coal has been used to produce gas for gaslights, also known as ‘town gas’. This gradually led to the process of coal gasification, which was responsible for the development of gaslights in metropolitan areas at the beginning of the 19th century. The use of coal gas in street lighting was eventually replaced by the invention of modern electric techniques.

With the advancement of electric power in the 19th century, coal was primarily used to generate electricity. In 1882, Thomas Edison’s first coal-fired electric generating station went into operation. The station was used for supplying electricity for household lights.

However, with the gradual rise in the transportation sector, oil overtook coal as the largest source of primary energy in the 1960s. Though coal continued to play a fundamental role in the world’s primary energy market, it accounted for only about 23.5% of global primary energy needs in 2002 and 40% of the world’s electricity.

The history of coal in the U.S. dates back to colonial days when blacksmiths used small amounts of fossil or stone coal to supplement the charcoal burned in their forges. Farmers mined coal from beds exposed at the surface and sold it in large quantities. Although most of the coal for the larger cities along the eastern seaboard was imported from England and Nova Scotia, some also came from Virginia. Figure 1 illustrates an estimated timeline showing the development of coal in the U.S.
Composition of Coal

Carbon accounts for more than 50% by weight and 70% by volume of coal (this includes inherent moisture). This is dependent on coal rank, with higher-ranking coals containing less hydrogen, oxygen and nitrogen, until 95% purity of carbon is achieved at Anthracite rank and above. Graphite formed from coal is the product of the thermal and diagenetic conversion of plant matter (50% by volume of water) into pure carbon.

Coal usually contains a considerable amount of incidental moisture. Coals are usually mined wet and may be stored wet to prevent spontaneous combustion. The carbon content of coal is quoted as both an 'as mined' and a 'moisture free' basis.

Lignite and other low-rank coals still contain a considerable amount of water and other volatile components trapped within the particles of the coal, known as macerals. This is present either within the coal particles, or as hydrogen and oxygen atoms within the molecules. Coal is converted from a carbohydrate material, such as cellulose, into carbon, which is an incremental process. Therefore, coal carbon contents also depend heavily on the degree to which this cellulose component is preserved in the coal.
Other common constituents of coals include silicate minerals such as clays, illite, and kaolinite, as well as carbonate minerals like siderite, calcite and aragonite. Iron sulfide minerals such as pyrite are also common. Sulfate minerals are also found, as is some form of salt, trace amounts of metals (notably iron, uranium, cadmium), and, on rare occasions, gold.

Methane gas is another component of coal, produced from methanogenesis. Methane in coal is dangerous. It can cause coal seam explosions, especially in underground mines, and may cause coal to spontaneously combust. It is, however, a valuable by-product of some coal mining, serving as a significant source of natural gas.

Coal composition is determined by specific coal assay techniques, and is performed to quantify the physical, chemical and mechanical behavior of the coal, including whether it is a good candidate for coking coal.

Some of the macerals of coal are:

- Vitrinite: Fossil woody tissue, likely often charcoal from forest fires in the coal forests;
- Fusinite: Made from peat made from cortical tissue;
- Exinite: Fossil spore casings and plant cuticles;
- Resinite: Fossil resin and wax;
- Alginite: Fossil algal material.

**Types of Coal**

There are several different types of coal, each with different properties dependent on age and depth from the surface. In some parts of the world, coal development is accelerated by volcanic heat or crustal stresses. Heating value, ash melting temperature, sulfur and other impurities, mechanical strength, and many other chemical and physical properties must be considered when matching specific coals to a particular application.

Coal is classified into four general categories, or “ranks”. They range from lignite through sub-bituminous and bituminous, to anthracite, depending on the progressive response of individual deposits to increasing heat and pressure. The carbon content of coal supplies most of its heating value, but other factors also influence the amount of energy it contains per unit of weight. (The amount of energy in coal is expressed in British thermal units per pound. A Btu is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit.)

About 90% of the coal in the U.S. falls in the bituminous and sub-bituminous categories, which rank below anthracite and usually contain less energy per unit of weight. Bituminous coal predominates in the Eastern and Mid-continent coalfields, while sub-bituminous coal is generally found in the Western states and Alaska.
Lignite ranks the lowest and is the youngest of the coals. Most lignite is mined in Texas, but large deposits also are found in Montana, North Dakota, and some Gulf Coast states.

**Anthracite:** Discovered in 1769, anthracite is the hardest of the four types. Anthracite is coal with the highest carbon content, between 86-98%, and a heat value of nearly 15,000 Btus-per-pound. It is a hard, black, shiny form of coal that contains virtually no moisture and very low volatile content. Subsequently, it burns with little or no smoke and is sold as a "smokeless fuel". Most frequently associated with home heating, anthracite is a very small segment of the U.S. coal market. Anthracite is mined in only a few areas in the U.S., mostly in the eastern Pennsylvania region. It is used extensively in municipal water purification and treatment plants and for home heating.

**Bituminous:** The most plentiful form of coal in the U.S., bituminous coal is used primarily to generate electricity and make coke for the steel industry. The fastest growing market for bituminous coal is supplying heat for industrial processes. Bituminous coal has a carbon content ranging from 45-86% carbon and a heat value of 10,500-15,500 Btus-per-pound. In addition to being used for electrical generation, bituminous coal is also used in making coke or coking coal, an essential ingredient in making steel. Most production of bituminous coal in the U.S. occurs from the east coast to the mid-west states, and Alaska.

**Sub-bituminous:** Ranking below bituminous is sub-bituminous coal, with 35-45% carbon content and a heat value between 8,300-13,000 Btus-per-pound. Reserves are located mainly in a half-dozen Western states and Alaska. Although its heat value is lower, this coal generally has a lower sulfur content than other types, which makes it attractive for use because it is cleaner burning. In the U.S., it is produced mainly along the east side of the Rocky Mountains, and from eastern Montana to the four corners area where the states of Arizona, Colorado, New Mexico and Utah join.

**Lignite:** Lignite has the lowest carbon content, 25-35%, and a heat value ranging between 4,000-8,300 Btus per pound. Often referred to as brown coal, it is mainly used for electric power generation. Lignite is the result of millions of tons of plants and trees that decayed in a swampy atmosphere 50-70 million years ago. Geologically, it is very young (upwards of around 40,000 years). It is brown and can be soft and fibrous, containing discernible plant material. It also contains large amounts of moisture (around 70%) resulting in low energy content. The material on top of the lignite deposits in North Dakota and Montana - called overburden - was deposited by runoff from the west as the Rocky Mountains formed.

Coal rank has little to do with quality, and as a coal matures, its ash content actually increases proportionately, due to the loss of moisture and volatiles. Lower ranking coals may have lower energy contents, but they tend to be more reactive because of their porosity and higher surface area.
Environmental Effects of Coal

Although laws enacted in the 1970s resulted in improved pollution controls on new power plants, coal is still the most unclean source of energy in the world. Upon burning, coal releases a number of problem pollutants:

- Mercury - a known nervous system toxin;
- Sulfur - which leads to the formation of acid rain;
- Nitrogen - which also contributes to acid rain and smog;
- Carbon dioxide - the chief global warming gas.

Coal is the largest source of mercury contamination in the air, and also the biggest contributor to the greenhouse gases that cause global warming. Coal burning also results in the emission of fine particles into the atmosphere. Nitrogen oxide and fine airborne particles aggravate asthma, reduce lung function and cause respiratory diseases and premature deaths across the world.

The available emissions-scrubbing technology can clean up about 90-95% of the mercury, sulfur and nitrogen emissions, but current laws in the U.S. only require these scrubbers for new plants or for major upgrades in capacity. The latter requirement was recently weakened so that more upgrades can be made without triggering the need to use state-of-the-art pollution controls.

Another problem with coal is mining procedure. In the past, coal was extracted by digging tunnels into the ground. The new approach involves the removal of the “overburden”, which is the layer of dirt and rock on top of the coal, taking the coal out, then replacing the overburden. Above this layer of overburden, trees, animals, and often entire ecosystems are destroyed completely. In spite of reclamation laws that were passed in the 1970s to ensure reclamation of strip-mined land, the ecosystem on a reclaimed piece of land is seldom as rich as the original.

Mountaintop removal is another manner of strip mining in which a mountain peak is removed to access the coal underneath. This is achieved by filling in a nearby valley, thus burying any stream and habitat that exists there. This method of strip mining has had a particularly devastating effect on the homes and their communities near the operations; on rivers, streams, lakes and water supplies; and on the environment in general. While such coal operations do supply many locals with jobs, the increase of mechanization has caused the number and quality of the jobs to decrease.

Regardless of method, coal mining causes many problems for locals, including water contamination; coal-dust permeating the air, coating everything inside and outside houses; and the health problems related to both of these issues. It also leads to severe erosion, resulting in the leaching of toxic chemicals into nearby streams and aquifers, which destroys their habitants.
Meanwhile, combustion of coal, like any other fossil fuel, produces carbon dioxide (CO2) and nitrogen oxides (NOx) along with varying amounts of sulfur dioxide (SO2), depending on where it was mined. Sulfur dioxide reacts with oxygen to form sulfur trioxide (SO3), which then reacts with water to form sulfuric acid. The sulfuric acid is returned to the Earth as acid rain.

Emissions from coal-fired power plants represent the largest source of carbon dioxide emissions, which have been implicated as the primary cause of global warming. Coal mining and abandoned mines also emit methane, another cause of global warming. Since the carbon content of coal is much higher than oil, burning coal is a more serious threat to the stability of the global climate, as this carbon forms CO2 when burned. Many other pollutants are present in coal power station emissions, as solid coal is more difficult to clean than oil, which is refined before use. A study commissioned by environmental groups claims that coal power plant emissions are responsible for tens of thousands of premature deaths annually in the United States alone. Modern power plants utilize a variety of techniques to limit the harmfulness of their waste products and improve the efficiency of burning, though these techniques are not subject to standard testing or regulation in the U.S. and are not widely implemented in some countries, as they add to the capital cost of the power plant. To eliminate CO2 emissions from coal plants, carbon capture and storage has been proposed, but not commercially utilized.

Coal and coal waste products including fly ash, bottom ash, boiler slag, and flue gas desulphurization contain many heavy metals including arsenic, lead, mercury, nickel, vanadium, beryllium, cadmium, barium, chromium, copper, molybdenum, zinc, selenium and radium; all of which are dangerous if released into the environment. Coal also contains low levels of uranium, thorium, and other naturally occurring radioactive isotopes whose release into the environment may lead to radioactive contamination. While these substances are trace impurities, enough coal is burned that significant amounts of these substances are released, paradoxically resulting in more radioactive waste than nuclear power plants.

**Managing Wastes from Coal**

Burning coal gives rise to a variety of wastes that must be controlled or at least accounted for. So-called "clean coal" technologies are a variety of evolving responses to late 20th century environmental concerns, including that of global warming due to carbon dioxide releases to the atmosphere. However, many of these methods have been applied for years, and will only be mentioned briefly here:

- **Coal cleaning by 'washing'** has been standard practice in developed countries for some time. It reduces emissions of ash and sulfur dioxide when the coal is burned;

- **Electrostatic precipitators and fabric filters** can remove 99% of the fly ash from the flue gases - these technologies are in widespread use;
• **Flue gas desulphurization** reduces the output of sulfur dioxide to the atmosphere by up to 97%, the task depending on the level of sulfur in the coal and the extent of the reduction. It is widely used where needed in developed countries;

• **Low-NOx burners** allow coal-fired plants to reduce nitrogen oxide emissions by up to 40%. Coupled with re-burning techniques NOx can be reduced 70% and selective catalytic reduction can clean up 90% of NOx emissions;

• **Increased efficiency of plant** - up to 45% thermal efficiency now (and 50% expected in future) means that newer plants create less emissions per kWh than older ones;

• **Advanced technologies** such as Integrated Gasification Combined Cycle (IGCC) and Pressurized Fluidized Bed Combustion (PFBC) will enable higher thermal efficiencies still - up to 50% in the future;

• **Ultra-clean coal from new processing technologies** which reduce ash below 0.25% and sulfur to very low levels mean that pulverized coal might be fed directly into gas turbines with combined cycle and burned at high thermal efficiency;

• **Gasification**, including underground gasification in situ, uses steam and oxygen to turn the coal into carbon monoxide and hydrogen;

• **Sequestration** refers to disposal of liquid carbon dioxide, once captured, into deep geological strata.

Some of these impose operating costs without concurrent benefit to the operator. External costs will be increasingly factored in through carbon taxes or similar means that will change the economics of burning coal.

However, waste products can be used productively. In 1999, the EU used half of its coal fly ash and bottom ash in building materials (where fly ash can replace cement), and 87% of the gypsum from flue gas desulphurization.
Introduction to Clean Coal

What is Clean Coal?

Clean coal is the name attributed to coal chemically washed of minerals and impurities, sometimes gasified, burned and the resulting flue gases treated with steam, with the purpose of removing sulfur dioxide, and reburned to make the carbon dioxide in the flue gas economically recoverable. The carbon dioxide can then be captured and stored instead of being released into the atmosphere.

Byproducts of Clean Coal

The byproducts of clean coal are very hazardous to the environment if not properly contained. This is considered technology's largest challenge, both from the practical and public relations perspectives.

While it is possible to remove most of the sulfur dioxide (SO2), nitrogen oxides (NOx) and particulate (PM) emissions from the coal burning process, carbon dioxide (CO2) emissions will be more difficult to address. Technology does exist to capture and store CO2 but they have not been made available on a large-scale commercial basis due to high economic costs.

Uses of Clean Coal

The primary example of clean coal is the proposed U.S. FutureGen plant - a zero-emissions coal-fired power plant.

It is also believed that some process similar to the natural gas fuel cell or microbial fuel cell (charged from biomass or sewage) may be practical using coal as fuel. Those technologies are used mostly for stationary fuel cells, because charging is slow. A large power plant in a coal mine might be the most energy efficient approach and require the least transport of coal to the users, though the return of the coal chute and use in homes may be possible in some places, especially if home sewage or natural gas lines can be tapped as well by an improved fuel reformer technology such as that used already to convert methanol, gasoline to the natural gas form.

FutureGen is a project of the U.S. government to build a "near zero-emissions" coal-fired power plant to produce hydrogen and electricity while using carbon capture and storage. While the plant itself is designed to have reduced emissions levels, the coal mining process will remain the same as other "dirtier" plants.

FutureGen will be a 275-megawatt power plant expected to take ten years to build and whose cost will be shared - $620 million by the Department of Energy and $250 million by a large consortium of coal mining and power industry companies. It will be operated as a research facility.
FutureGen will seek to sequester carbon dioxide emissions at an operating rate of one million metric tons per year in order to adequately stress test a representative portion of a geologic formation (with a capability up to two million tons per year). A field test similar to this was done in Norway.

States have bid to host the demonstration project, and foreign participation has been solicited (since by 2020 more than 60% of man made greenhouse gas emissions are expected to come from developing countries) - as of June, 2006, South Korea and India had joined the U.S. in a partnership.

In May 2006, seven states submitted proposals to host the FutureGen project. These sites are in or near:

- Effingham, Illinois
- Marshall, Illinois
- Mattoon, Illinois
- Tuscola, Illinois
- Henderson County, Kentucky
- Bowman County, North Dakota
- Meigs County, Ohio
- Tuscarawas County, Ohio
- Odessa, Texas
- Jewett, Texas
- Point Pleasant, West Virginia
- Gillette, Wyoming

On July 25, 2006, four finalist sites were announced:

- Mattoon, Illinois
- Tuscola, Illinois
- Odessa, Texas
- Jewett, Texas


**Support and Opposition**

Clean Coal has been mentioned by United States President George W. Bush on several occasions, including his latest State of the Union Address. Bush's position is that clean coal technologies should be encouraged as one means to reduce the country's dependence on foreign oil. Senator Hillary Clinton has also recently said, "We should strive to have new electricity generation come from other sources, such as clean coal and renewables."
Despite the supportive comments from U.S. President Bush regarding clean coal, the White House has only granted $18 million to develop zero-emission coal-fired power plants over the next decade out of a $388 billion omnibus spending bill.

In addition, some prominent environmentalists (such as Dan Becker, director of the Sierra Club's Global Warming and Energy Program) believe that the term clean coal is misleading: "There is no such thing as 'clean coal' and there never will be. It's an oxymoron". Complaints focus on the environmental impacts of coal extraction, the prohibitively high costs to sequester carbon, and uncertainty on how to store end result pollutants.

**Price of Clean Coal**

Many of the ‘clean coal’ technologies that industry is currently touting are still in the development stage and will take hundreds of millions, if not billions, of dollars and many more years before they are commercially available. “Clean coal” technologies are also extremely expensive in terms of day to day running costs. The U.S. Energy Information Administration (EIA) estimates the capital costs of a typical IGCC plant (an experimental low-emission coal power station) to be $1,383/kW, $2,088/kW with carbon sequestration. This compares with $1,015/kW for a typical wind farm.
Examining Clean Coal Technologies

The clean coal technology field is moving very rapidly in the direction of coal gasification with a second stage to produce a concentrated and pressurized carbon dioxide stream followed by its separation and geological storage. This technology has the potential to provide what may be called "zero emissions" - in reality, extremely low emissions of the conventional coal pollutants, and as low-as-engineered carbon dioxide emissions.

This has come about as a result of the realization that efficiency improvements, together with the use of natural gas and renewables such as wind will not provide the deep cuts in greenhouse gas emissions necessary to meet future national targets.

The U.S. DOE sees "zero emissions" coal technology as a core element of its future energy supply in a carbon-constrained world. It has in place an ambitious program to develop and demonstrate the technology and have commercial designs for plants with an electricity cost of only 10% greater than conventional coal plants available by 2012.

Australia is well supplied with carbon dioxide storage sites near major carbon dioxide sources; however, as in other parts of the world, demonstration plants will be needed to gain public acceptance and show that the storage is permanent.

In several countries, "zero emissions" technology seems to have the potential for low avoided cost for greenhouse gas emissions.

In virtually all fields, defining technology is a moving target. Products that were innovative breakthroughs in the past have been refined over time, and are now considered commonplace by today’s standards. For example, cardiac pacemakers – which help stabilize and strengthen the cardiac function of people suffering from heart disease – were rare in the early 1960’s. Today, these tiny implants help heart patients to live longer, more active lives. The first computers cost hundreds of thousands of dollars and filled an entire room. Now, laptop computers are so small that they fit into a backpack and are virtually as common in the American home as a television.

"Clean coal technology" describes a new generation of energy processes that sharply reduce air emissions and other pollutants from coal-burning power plants.

In the late 1980s and early 1990s, the U.S. Department of Energy conducted a joint program with industry and State agencies to demonstrate the best of these new technologies at scales large enough for companies to make commercial decisions. More than 20 of the technologies tested in the original program achieved commercial success.

The early program, however, was focused on the environmental challenges of the time - primarily concerns over the impact of acid rain on forests and watersheds. In the 21st century, additional environmental concerns have emerged - the potential health impacts of trace emissions of mercury, the effects of microscopic particles on people with
respiratory problems, and the potential global climate-altering impact of greenhouse gases.

With coal likely to remain one of the nation's lowest-cost electric power sources for the near future, President Bush has pledged a new commitment to even more advanced clean coal technologies.

As the President said in presenting his National Energy Policy to the American public on May 17, 2001, "More than half of the electricity generated in America today comes from coal. If we were not blessed with this natural resource, we would face even greater [energy] shortages and higher prices today. Yet, coal presents an environmental challenge. So our plan funds research into new, clean coal technologies."

Building on the successes of the original program, the new clean coal initiative encompasses a broad spectrum of research and large-scale projects that target today's most pressing environmental challenges.

The Clean Coal Power Initiative is providing government co-financing for new coal technologies that can help utilities meet the President's Clear Skies Initiative to cut sulfur, nitrogen and mercury pollutants from power plants nearly 70% by the year 2018. In addition, some of the early projects are showing ways to reduce greenhouse emissions by boosting the efficiency at which coal plants convert coal to electricity or other energy forms.

Eight projects were selected under the first round Clean Coal Power Initiative solicitation, of which two were withdrawn. Of the remaining six projects supported by the first round of the CCPI, three projects are currently in the operational phase, two are in the construction phase, and one is still in the pre-award phase.

Four projects were recently selected from the second round CCPI solicitation and are in various stages of development. Of the four projects recently chosen, two will demonstrate advanced IGCC technology; one will demonstrate an innovative multi-pollutant control process for NOx, SOx, and mercury; and one will demonstrate a neural-network control process for advanced multi-pollutant controls by means of plant optimization.

Most advances in clean coal technologies have occurred in two main areas:

- Advanced pollution control systems to reduce sulfur dioxide (SO2) and nitrogen oxide (NOx) emissions; and
- Super-clean, more efficient advanced power generation systems for new coal-based power plants that will power America in the decades to come.
Coal Washing

Coal washing involves grinding the coal into smaller pieces and passing it through a process called gravity separation. One technique involves feeding the coal into barrels containing a fluid that has a density that causes the coal to float, while unwanted material sinks and is removed from the fuel mix. The coal is then pulverized and prepared for burning.

Advanced Pollution Control Systems

These technologies can either be installed on existing power plants or built into new facilities. Practically all of the U.S.’s coal-based power plants have some type of advanced pollution control technology in operation.

The use of these advanced technologies has allowed the coal-based electricity sector to effectively and efficiently reduce emissions of SO2 and NOx.

Reducing SO2

Sulfur dioxide is one of the six “criteria air pollutants” defined by the federal Clean Air Act, and the coal-based electricity sector is the largest emitter of SO2. Because of early concerns about acid rain deposition, developing ways to reduce SO2 emissions became a national priority.

Two basic types of control systems reduce SO2 emissions. One works internally, and the other is an external system. In both cases, these devices remove SO2 from the combustion gases after they exit the boiler.

Some flue gas desulphurization units work inside the existing ductwork of a power plant and are suitable for smaller, older plants with limited space for adding equipment. These emissions control systems reduce SO2 emissions by 50 to 70%, on average.
For larger plants, a technology, known as an advanced flue gas desulphurization unit or “scrubber”, is typically used. These huge devices are typically built as separate units (thus requiring additional space) and are more efficient at removing SO2 than the internal systems. Scrubbers can remove up to 90% of the SO2 emitted at a typical power plant. More recent applications of this technology convert combustion wastes into useful products, such as gypsum for wallboard or ebonite used to make bowling balls.

Reducing NOx

Nitrogen oxide (NOx) is a precursor to the formation of ozone, which is also called urban smog. Cars and other transportation vehicles, as well as coal-based power plants, are significant emitters of NOx. To address public concerns and meet stringent NOx emissions control standards, several advanced control devices are now in use at power plants across the country.

Specially designed combustion units known as low-NOx burners help reduce the formation of nitrogen oxides by carefully controlling the way coal is burned within the boiler. Due to a host of factors, these units achieve varying degrees of success, curbing NOx emissions by 37-68%.

Another process, known as reburning, is used to break down NOx emissions into harmless molecular nitrogen before release into the atmosphere. Reburning can reduce NOx emissions by 50-67%.
In some cases, electricity generators use a combination of low-NOx burners and reburning processes to reach the desired emissions reductions level.

An even more advanced process uses systems that inject ammonia or urea into combustion flue gases to remove nitrogen oxides. These injection systems work similar to an automobile’s catalytic converter, and for power plants, there are two basic systems. Non-catalytic converter devices can reduce NOx by 30-50%, while selective catalytic converters (SCR’s) can eliminate up to 90%.

**Figure 4: Low NOx Burners**

![Low NOx Burners Diagram](source: DTI)

**Advanced Power Generating Systems**

Experts agree that coal will remain an indispensable fuel for meeting America’s electricity demand for decades to come.

As new coal-based power plants are built, electricity generators will use reliable and affordable technologies that also meet superior environmental performance. Two primary designs, Circulating Fluidized Bed Combustion units and Integrated Gasification Combined Cycle systems, hold the most promise. Demonstration projects have proven both of these technologies to be viable technologies for the future.
Circulating Fluidized Bed Combustion

An advanced technology designed for use with new power plants, Circulating Fluidized Bed (CFB) Combustion units remove pollutants inside the boiler – with no scrubber or post-combustion controls needed.

Using this design, pulverized coal is mixed with limestone and fired in a process resembling a boiling fluid. The limestone removes the sulfur and converts it into an environmentally benign powder. The temperature of the combustion process in CFB units is controlled to be lower than that of a traditional boiler, which means less NOx is formed. Fluidized bed systems offer superior environmental performance – reducing SO2 by 90-95% and NOx by 90% or more.

Figure 5: Circulating Fluidized Bed Combustion

Fluidized beds suspend solid fuels on upward-blowing jets of air during the combustion process. The result is a turbulent mixing of gas and solids. The tumbling action, much like a bubbling fluid, provides more effective chemical reactions and heat transfer. Fluidized-bed combustion evolved from efforts to find a combustion process able to control pollutant emissions without external emission controls (such as scrubbers). The technology burns fuel at temperatures of 1,400 to 1,700 degrees F, well below the threshold where nitrogen oxides form (at approximately 2,500 degrees F, the nitrogen and oxygen atoms in the combustion air combine to form nitrogen oxide pollutants).

The mixing action of the fluidized bed results brings the flue gases into contact with a sulfur-absorbing chemical, such as limestone or dolomite. More than 95 percent of the sulfur pollutants in coal can be captured inside the boiler by the sorbent.
Pressurized fluidized-bed combustion (PFBC) builds on earlier work in atmospheric fluidized-bed combustion technology. Atmospheric fluidized bed combustion is crossing over the commercial threshold, with most boiler manufacturers currently offering fluidized bed boilers as a standard package.

The popularity of fluidized bed combustion is due largely to the technology's fuel flexibility - almost any combustible material, from coal to municipal waste, can be burned - and the capability of meeting sulfur dioxide and nitrogen oxide emission standards without the need for expensive add-on controls.

The 1st generation pressurized fluidized bed combustor uses a "bubbling-bed" technology. A relatively stationary fluidized bed is established in the boiler using low air velocities to fluidize the material, and a heat exchanger (boiler tube bundle) immersed in the bed to generate steam. Cyclone separators are used to remove particulate matter from the flue gas prior to entering a gas turbine, which is designed to accept a moderate amount of particulate matter (i.e., "ruggedized").

A 2nd generation pressurized fluidized bed combustor uses "circulating fluidized-bed" technology and a number of efficiency enhancement measures. Circulating fluidized-bed technology has the potential to improve operational characteristics by using higher air flows to entrain and move the bed material, and recirculating nearly all the bed material with adjacent high-volume, hot cyclone separators. The relatively clean flue gas goes on to the heat exchanger. This approach theoretically simplifies feed design, extends the contact between sorbent and flue gas, reduces likelihood of heat exchanger tube erosion, and improves SO2 capture and combustion efficiency.

A major efficiency enhancing measure for 2nd generation pressurized fluidized bed combustor is the integration of a coal gasifier (carbonizer) to produce a fuel gas. This fuel gas is combusted in a topping combustor and adds to the combustor's flue gas energy entering the gas turbine, which is the more efficient portion of the combined cycle. The topping combustor must exhibit flame stability in combusting low-Btu gas and low-NOx emission characteristics. To take maximum advantage of the increasingly efficient commercial gas turbines, the high-energy gas leaving the topping combustor must be nearly free of particulate matter and alkali/sulfur content. Also, releases to the environment from the pressurized fluid bed combustion system must be essentially free of mercury, a soon-to-be regulated hazardous air pollutant.

To reduce cost and carbon dioxide emissions, new sorbents are being evaluated. Sorbent utilization has a major influence on operating costs, and carbon dioxide emissions streams can result in the production and use of alkali-based sorbents.

**Integrated Gasification Combined Cycle Units**

Integrated Gasification Combined Cycle Units (IGCC) are among the cleanest and most efficient power systems in the world. The IGCC system involves two separate processes. The first is a chemical process that converts coal into a synthetic gas. This clean,
synthetic gas is then used as a boiler fuel to generate electricity. The process is extremely efficient because the exhaust from the gas turbine is hot enough to boil water. The steam is then used to drive a turbine that creates a second source of electricity – thus the term “combined cycle”.

IGCC’s offer promise in terms of environmental performance and efficiency. Pilot gasification units operate at efficiency levels 20% above conventional coal-based power plants. As the technology continues to be refined through future applications, IGCC’s will be twice as efficient as today’s typical coal-based units will. On the environmental front, these super-clean units remove as much as 95-99% of the SO2 and NOx emissions and the increased efficiency helps to reduce emissions of carbon dioxide (CO2), a common greenhouse gas.

**Pulverized Coal Combustion (PCC)**

PCC is the most commonly used method in coal-fired power plants, and is based on many decades of experience. Units operate at close to atmospheric pressure, simplifying the passage of materials through the plant.

The principal developments involve:

- Increasing plant thermal efficiencies by raising the steam pressure and temperature used at the boiler outlet/steam turbine inlet;
• Ensuring that units can load follow satisfactorily; and,

• Ensuring that flue gas-cleaning units can meet emissions limits and environmental requirements.

**Characteristics**

The coal is ground (pulverized) to a fine powder, so that less than 2% is +300 µm and 70-75% is below 75 µm, for a bituminous coal. The pulverized coal is blown with part of the combustion air into the boiler plant through a series of burner nozzles. Secondary and tertiary air may also be added.

Combustion takes place at temperatures from 1300-1700°C, depending largely on coal rank. Steam is generated, driving a steam generator and turbine. Particle residence time in the boiler is typically 2-5 seconds, and the particles must be small enough for complete burnout to have taken place during this time.

The technology is well developed, and there are thousands of units around the world, accounting for well over 90% of coal-fired capacity. PCC is used to fire a wide variety of coals, although it is not always appropriate for those with high ash content.

Two broadly different boiler designs are used. One is the traditional two-pass layout where there is a furnace chamber, topped by some heat transfer tubing to reduce the FEGT. The flue gases then turn through 180°C, and pass downwards through the main heat transfer and economizer sections. The other design is to use a tower boiler, where virtually all the heat transfer sections are mounted vertically above each other, over the combustion chamber.

The relative advantages and disadvantages almost balance each other out. Tower designs have been favored recently in Europe. They result in taller structures, and this is one reason why they are not used in Japan, which is in an earthquake zone.

There are variations in the positioning of the burners in the combustion chamber, and designs are offered which use:

• Wall-mounted burners on one side;
• Opposed-fired wall mounted burners; or
• Tangential burners in the corners or on the walls. Some corner burners can be the furnace up or down.

There seem to be few clear-cut advantages or disadvantages with the different arrangements, and the choice is based on cost factors, operating experience, environmental considerations and the experience of the various boiler manufacturers.

Boilers with cyclone burners are discussed separately, as a coarser coal feed is used.
Most PCC boilers operate with what is called a dry bottom. Combustion temperatures (with bituminous coal) are held at 1500-1700°C. With lower rank coals, the range is 1300-1600°C. Most of the ash passes out with the flue gases as fine solid particles to be collected in ESPs or fabric filters before the stack.

Boilers which use anthracite for fuel commonly use the downshot burner arrangement to achieve longer residence times and ensure carbon burn-out. Downshot burners send the coal-air mixture down into the cone at the base of the boiler.

Another arrangement used in some boilers is the cell burner. This involves a wall-fired unit where either two or three circular burners are combined into a single vertically orientated assembly that results in a compact, intense flame. This would generally not be used in new units, as the higher temperature flame results in more NOx formation, which then has to be removed later in the system.

**Unit Size**

PCC boilers have been built to match steam turbines with outputs between 50 and 1300 MWe. In order to take advantage of the economies of scale, most new units are rated at over 300 MWe, but there are few large units with outputs from a single boiler/turbine combination of over 700 MWe. This is because of the substantial effects such units have on the distribution system if they should malfunction, or be unexpectedly shut down.

**Thermal Efficiency**

The driving forces currently encouraging the use of more efficient power plant is the environmental concern in many countries, and the declared goal of most OECD governments to reduce CO2 emissions to 1990 levels. This goal leaves power generators with many unsolved problems, but increasing the thermal efficiency of converting coal to power is one of the less expensive ways of reducing CO2 emissions. However, it does involve the construction of new boilers and turbines, as the costs for retrofitting a supercritical steam system to an existing subcritical boiler would be prohibitive.

Increasing thermal efficiency has the potential for reducing other emissions per MWe generated, such as those of SO2 and NOx. Where the coal cost is high, as where traded coals are used, increasing thermal efficiency can result in reduced overall costs in new plants for power generation, as less fuel is needed.

The overall thermal efficiency of some older, smaller units burning poor quality coals can be as low as 30%. The average efficiency of larger existing plants with subcritical steam burning higher quality coals is in the region of 35-36%. New plants, however, with supercritical steam can now achieve overall thermal efficiencies in the 43-45% range.

Various measures can be used to increase the thermal efficiency relative to current design practice:
• Reducing the excess air ratio from 25% to 15% can bring a small increase;

• Reducing the stack gas exit temperature by 10°C (while recovering the heat involved) can bring about a similar increase;

• Increasing the steam pressure and temperature from 25 MPa/540°C to 30 MPa/600°C can increase efficiency by nearly two percentage points;

• Using a second reheat stage can add another one percentage point;

• Decreasing the condenser pressure from 0.0065 MPa to 0.003 MPa can further increase efficiency.

As with all technical options, there is a trade-off between the costs involved (both capital and operating), the risk element in the decision and the amount of additional energy recovered.

Many of the methods for increasing thermal efficiency have been well known for several decades. In some cases, they were tried back in the 1950s and 60s, but were abandoned due to the lack of suitable construction materials or the low energy prices prevailing. This removed much of the incentive for seeking high thermal efficiencies. Small base-load power plants using steam at 35 MPa and 650°C were built in the 1950s. Regenerative preheating of the feed water was introduced as long ago as the 1920s. Steam reheat was introduced in the 1950s and double reheat in the 60s. The more costly options were often discounted when oil was cheap, and as nuclear energy took over base load power generation in many places.

An increase in the steam pressure and temperature involves the use of austenitic material in various parts of the system. Using thin walled austenitic steels for superheater and reheater tubes means that operational flexibility can be largely maintained. In some older plants, thick walled tubes and junctions have been used which means increased start-up times, and increased start-up losses.

Controlling the excess air is an important function in boiler operation, but requires a careful balance between conflicting requirements. Boilers are normally operated at the minimum practicable excess air amount, but sufficient air is required to burn virtually all the carbon present (99%+), and modern design and practice is to control and stage the addition of air in order to minimize the formation of NOx (air staging).

The maximum efficiencies achievable with lower grade and lower rank coals will be somewhat less in all cases. The maximum efficiencies expected in the brown coal fired plants currently under construction in Germany are around 42% compared with 45% for equivalent new bituminous coal fired units. Net efficiencies of 45-47% are achievable with supercritical steam using bituminous coals and currently developed materials.
New high temperature alloys are under development with the aim of facilitating steam temperatures as high as 700°C. This could make net efficiencies of 50% achievable with PCC. However, a considerable amount of work remains to be done.

**Flue Gas Cleaning/Emissions**

Various technologies are discussed in separate sections, under particulates control, NOx reduction by primary measures or flue gas treatment, and FGD. Emissions from new PCC units with appropriate flue gas cleaning units can meet all current requirements reliably and economically, and using well-proven technology. The necessary emission control measures can be taken with a relatively small effect on overall thermal efficiency, although the capital cost of these measures can represent about one third of the cost of the unit when meeting the most stringent current standards.

**Residues**

The solid residues consist of 80-90% of fine fly ash with a low level of carbon-in-ash, averaging around 0.5%.

**Coal Gasification**

Gasification is a process that converts carbonaceous materials, such as coal, petroleum, petroleum coke or biomass, into carbon monoxide and hydrogen.

In a gasifier, the carbonaceous material undergoes three processes:

1. The pyrolysis (or devolatilization) process occurs as the carbonaceous particle heats up. Volatiles are released and char is produced, resulting in up to 70% weight loss for coal. The process is dependent on the properties of the carbonaceous material and determines the structure and composition of the char, which will then undergo gasification reactions.

2. The combustion process occurs as the volatile products and some of the char reacts with oxygen to form carbon dioxide and carbon monoxide, which provides heat for the subsequent gasification reactions. Pyrolysis and combustion are very rapid processes.

3. The gasification process occurs as the char reacts with carbon dioxide and steam to produce carbon monoxide and hydrogen. The resulting gas is called producer gas or syngas (or wood gas when fueled by wood) and may be more efficiently converted to energy such as electricity than would be possible by direct combustion of the fuel, as the fuel is first combusted in a gas turbine and the heat is used to produce steam to drive a steam turbine. In addition, the gasification process, allowing high temperature combustion of the gas from otherwise problematic fuels, may refine corrosive ash elements such as chloride and potassium out.
The gasification process was originally developed in the 1800s to produce town gas for lighting and cooking. Natural gas and electricity soon replaced town gas for these applications, but the gasification process has been utilized for the production of synthetic chemicals and fuels since the 1920s.

It is now recognized that gasification has wider applications; in particular the production of electricity, ammonia and liquid fuels (oil) using Integrated Gasification Combined Cycles (IGCC), with the possibility of producing methane and hydrogen for fuel cells. IGCC is also a more efficient method of CO2 capture as compared to conventional technologies. IGCC demonstration plants have been operating since the early 1970s and some of the plants constructed in the 1990s are now entering commercial service.

Within the past few years, gasification technologies have been developed that use plastic-rich waste as a feed. A plant in Germany converts plastic waste via producer gas into methanol with such technology, but on a large scale.

Gasification relies on chemical processes at elevated temperatures >700°C, contrary to biological processes such as anaerobic digestion that produce biogas.

Breakdown of hydrocarbons into syngas is done by carefully controlling the amount of oxygen present while heating the hydrocarbons to extreme temperatures.
Four types of gasifier are currently available for commercial use: counter-current fixed bed, co-current fixed bed, fluid bed and entrained flow.

The counter-current fixed bed ("up draft") gasifier consists of a fixed bed of carbonaceous fuel (e.g. coal or biomass) through which the "gasification agent" (steam, oxygen and/or air) flows in counter-current configuration. The ash is either removed dry or as a slag. The slagging gasifiers require a higher ratio of steam and oxygen to carbon in order to reach temperatures higher than the ash fusion temperature. The nature of the gasifier means that the fuel must have high mechanical strength and must be non-caking so that it will form a permeable bed, although recent developments have reduced these restrictions to some extent. The throughput for this type of gasifier is relatively low. Thermal efficiency is high as the gas exit temperatures are relatively low. However, this means that tar and methane production is significant at typical operation temperatures, so product gas must be extensively cleaned before use or recycled to the reactor.

The co-current fixed bed ("down draft") gasifier is similar to the counter-current type, but the gasification agent gas flows in co-current configuration with the fuel (downwards, hence the name "down draft gasifier"). Heat needs to be added to the upper part of the bed, either by combusting small amounts of the fuel or from external heat sources. The produced gas leaves the gasifier at a high temperature, and most of this heat is transferred to the gasification agent added in the top of the bed, resulting in energy efficiency on level with the counter-current type. Since all tars must pass through a hot bed of char in this configuration, tar levels are much lower than the counter-current type.
In the fluid bed gasifier, the fuel is fluidized in oxygen (or air) and steam. The ash is removed dry or as heavy agglomerates that defluidize. The temperatures are relatively low in dry ash gasifiers, so the fuel must be highly reactive; low-grade coals are particularly suitable. The agglomerating gasifiers have slightly higher temperatures, and are suitable for higher rank coals. Fuel throughput is higher than for the fixed bed, but not as high as for the entrained flow gasifier. The conversion efficiency is rather low, so recycle or subsequent combustion of solids is necessary to increase conversion. Fluidized bed gasifiers are most useful for fuels that form highly corrosive ash that would damage the walls of slagging gasifiers. Biomasses generally contain high levels of such ashes.

In the entrained flow gasifier a dry pulverized solid, an atomized liquid fuel or a fuel slurry is gasified with oxygen (much less frequent: air) in co-current flow. The gasification reactions take place in a dense cloud of very fine particles. Most coals are suitable for this type of gasifier because of the high operating temperatures and because the coal particles are well separated from one another. The high temperatures and pressures also mean that a higher throughput can be achieved; however, thermal efficiency is somewhat lower as the gas must be cooled before it can be cleaned with existing technology. The high temperatures also mean that tar and methane are not present in the product gas; however, the oxygen requirement is higher than for the other types of gasifiers. All entrained flow gasifiers remove the major part of the ash as a slag as the operating temperature is well above the ash fusion temperature. A smaller fraction of the ash produced is either a very fine dry fly ash or as black colored fly ash slurry. Some fuels, in particular certain types of biomasses, can form slag that is corrosive for ceramic inner walls that serve to protect the gasifier outer wall. However, some entrained bed type of gasifiers do not possess a ceramic inner wall but have an inner water or steam-cooled wall covered with partially solidified slag. These types of gasifiers do not suffer from corrosive slags. Some fuels have ashes with very high ash fusion temperatures. In this case, a higher quantity of limestone is mixed with the fuel prior to gasification. Addition of a little limestone will usually suffice for the lowering the fusion temperatures. The fuel particles must be much smaller than for other types of gasifiers. This means the fuel must be pulverized, which requires somewhat more energy than for the other types of gasifiers. By far the most energy consumption related to entrained bed gasification is not the milling of the fuel but the production of oxygen used for the gasification.

**Carbon Capture and Storage**

Carbon capture and storage (CCS) is an approach to mitigating climate change by capturing carbon dioxide (CO2) from large point sources such as power plants and subsequently storing it away safely instead of releasing it into the atmosphere. Technology for capturing of CO2 is already commercially available for large CO2 emitters, such as power plants. Storage of CO2, on the other hand, is a relatively untried concept and as yet (2006) no power plant operates with a full carbon capture and storage system. Currently, United States government has approved the construction of world's first CCS power plant, FutureGen, while BP has indicated that it intends to develop a 350
MW carbon capture and storage plant in Scotland, in which the carbon from natural gas will be stripped out and pumped into the Miller field in the North Sea.

CCS applied to a modern conventional power plant could reduce CO2 emissions to the atmosphere by approximately 80-90% compared to a plant without CCS. Capturing and compressing CO2 requires a great deal of energy and would increase the fuel needs of a plant with CCS by 10-40%. These and other system costs are estimated to increase the cost of energy from a power plant with CCS by 30-60% depending on the specific circumstances.

Storage of the CO2 is envisaged either in deep geological formations, deep oceans, or in the form of mineral carbonates. Geological formations are currently considered the most promising, and these are estimated to have a storage capacity of at least 2000 Gt CO2. IPCC estimates that the economic potential of CCS could be between 10% and 55% of the total carbon mitigation effort until year 2100.

Capturing and compressing CO2 requires much energy, significantly raising the costs of operation, apart from the added investment costs. It would increase the energy needs of a plant with CCS by about 10-40%. This, the costs of storage, and other system costs are estimated to increase the costs of energy from a power plant with CCS by 30-60%, depending on the specific circumstances.

The costs of CCS are dominated by costs of capture. The storage is relatively cheap, geological storage in saline formations or depleted oil or gas fields typically cost $0.5-8 per ton of CO2 injected, plus an additional $0.1-0.3 for monitoring costs. However, when storage is combined with Enhanced oil recovery to extract extra oil from an oil field, the storage could yield net benefits of $10-16 per ton of CO2 injected (based on 2003 oil prices).
Capture and Separation of Carbon Dioxide

A number of means exist to capture carbon dioxide from gas streams, but they have not yet been optimized for the scale required in coal-burning power plants. The focus has often been on obtaining pure CO2 for industrial purposes rather than reducing CO2 levels in power plant emissions.

Where there is carbon dioxide mixed with methane from natural gas wells, its separation is well proven. Several processes are used, including hot potassium carbonate that is energy-intensive and requires a large plant, a monoethanolamine process that yields high-purity carbon dioxide, amine scrubbing, and membrane processes.

Capture of carbon dioxide from flue gas streams following combustion in air is expensive as the carbon dioxide concentration is only about 14% at best.

However, today's Integrated Gasification Combined Cycle (IGCC) plant is a means of using coal and steam to produce hydrogen and carbon monoxide, which are burned in a gas turbine with secondary steam turbine (i.e. combined cycle) to produce electricity. If the gasifier is fed with oxygen rather than air, the flue gas contains highly-concentrated CO2 which can readily be captured - at about half the cost of capture from conventional plants. Ten oxygen-fired gasifiers are operational in the USA.

Development of this oxygen-fed IGCC process will add a shift reactor to oxidize the CO with water so that the gas stream is basically just hydrogen and carbon dioxide. These are separated before combustion and the hydrogen alone becomes the fuel for electricity generation (or other uses) while the concentrated pressurized carbon dioxide is readily disposed of.

Currently IGCC plants have a 45% thermal efficiency.

Capture of carbon dioxide from coal gasification is already achieved at low marginal cost in some plants. One (albeit where the high capital cost has been largely written off) is the Great Plains Synfuels Plant in North Dakota, where six million tons of lignite is gasified each year to produce clean synthetic natural gas.

Another technology being developed has potential for retrofit to existing pulverized coal plants, which are the backbone of electricity generation in many countries. This is oxy-fuel combustion, which involves feeding oxygen and recycled flue gases into the boiler to reduce the overall volume of flue gases and increase the CO2 concentration to allow more ready capture of it for sequestration.

Storage and Sequestration of Carbon Dioxide
Captured carbon dioxide gas can be put to good use, even on a commercial basis, for enhanced oil recovery. This is well demonstrated in West Texas, where today over 3000 km of pipelines connect oilfields to a number of carbon dioxide sources in the region.

At the Great Plains Synfuels Plant, North Dakota, some 13,000 tons per day of carbon dioxide gas is captured and 5000 t of this is piped 320 km into Canada for enhanced oil recovery. This Weyburn oilfield sequesters about 85 cubic meters of carbon dioxide per barrel of oil produced, 19 million tons over the project's 20-year life. The first phase of its operation has been judged a success.

Overall, in the U.S., 32 million tons of CO2 are used annually for enhanced oil recovery, 10% from anthropogenic sources.

The world's first industrial-scale CO2 storage was at Norway's Sleipner gas field in the North Sea, where about one million tons per year of compressed liquid CO2 separated from methane is injected into a deep reservoir (saline aquifer) about a kilometer below the seabed and remains safely in place. The $80 million incremental cost of the sequestration project was paid back in 18 months with the carbon tax savings of $50/ton. (The natural gas contains nine percent CO2 that must be reduced before sale or export.) The overall Utica sandstone formation there, about one kilometer below the seabed, is capable of storing 600 billion tons of CO2.

West Australia's proposed Gorgon natural gas project from 2009 will tap natural gas with 14% CO2. Capture and geosequestration of this will reduce the project's emissions from 6.7 to 4.0 million tons of CO2 per year.

Injecting carbon dioxide into deep, unmineable coal seams where it is adsorbed to displace methane (effectively: natural gas) is another potential use or disposal strategy. Currently the economics of enhanced coal bed methane extraction are not as favorable as enhanced oil recovery, but the potential is great.

While the scale of anticipated need for CO2 disposal far exceeds today's uses, they do demonstrate practicality. Safety and permanence of disposition are key considerations in sequestration.

Research on geosequestration is ongoing in several parts of the world. The main potential appears to be deep saline aquifers and depleted oil and gas fields. In both, the CO2 is expected to remain as a supercritical gas for thousands of years, with some dissolving.

Large-scale storage of CO2 from power generation will require an extensive pipeline network in densely populated areas. This has safety implications.

**Economics and Research and Development**

The World Coal Institute notes that at present the high cost of carbon capture and storage ($150-220 per ton of carbon, $40-60/t CO2 - 3.5 to 5.5 c/kWh relative to coal burned at
35% thermal efficiency) renders the option uneconomic. But work is being done to improve economic viability, and the U.S. Dept of Energy (DOE) is funding R&D with a view to reducing the cost of carbon sequestered to $10/tC (equivalent to 0.25 c/kWh) or less by 2008, and by 2012 to reduce the cost of carbon capture and sequestration to a 10% increment on electricity generation costs.

More recently, the DOE has announced the $1.3 billion FutureGen project to design, build and operate a nearly emission-free coal-based electricity and hydrogen production plant. The FutureGen initiative will comprise a coal gasification plant with additional water-shift reactor, to produce hydrogen and carbon dioxide. About one million tons of CO2 (at least 90% of throughput) will then be separated by membrane technology and sequestered geologically. The hydrogen will be burned in a 275 MWe generating plant and in fuel cells.

Construction of FutureGen is due to start in 2009, for operation in 2012. The project is designed to validate the technical feasibility and economic viability of near-zero emission coal-based generation. In particular it aims to produce electricity with only a 10% cost premium and show that hydrogen can be produced at $3.80 per GJ, equivalent to petrol at 12.7 cents per liter.

In Denmark, a pilot project at the 420 MWe Elsa power plant is capturing CO2 from post-combustion flue gases under the auspices of CASTOR (CO2 from Capture to Storage). Flue gases are passed through an absorber, where a solvent captures about 90% of the CO2. The pregnant solution is then heated to 120°C to release pure CO2 at the rate of about one ton per hour for geological sequestration. Cost is expected to be EUR 20-30 per ton.

A 2000 U.S. study put the cost of CO2 capture for IGCC plants at 1.7 c/kWh, with an energy penalty 14.6% and a cost of avoided CO2 of $26/t ($96/t C). By 2010, this is expected to improve to 1.0 c/kWh, 9% energy penalty and avoided CO2 cost of $18/t ($66/t C).

Figures from IPCC Mitigation working group in 2005 for IGCC put capture and sequestration cost at 1.0-3.2 c/kWh, thus increasing electricity cost for IGCC by 21-78% to 5.5 to 9.1 c/kWh. The energy penalty in that was 14-25% and the mitigation cost $14-53/t CO2 ($51-200/tC) avoided. These figures included up to $5 per ton CO2 for transport and up to $8.30/t CO2 for geological sequestration.
Industry Initiatives

Clean Coal Power Initiative

Clean coal technology portrays a new generation of energy processes that drastically lower air emissions and other pollutants as compared to older coal-burning systems. The U.S. government’s Clean Coal Power Initiative (CCPI) is an industry and government partnership to implement the President's National Energy Policy recommendation to increase funding for clean coal technologies. This follows the huge challenge facing the world of ensuring the reliability of electric supply while simultaneously protecting the environment.

The CCPI is a cost-shared partnership between the government and the industry to demonstrate advanced coal-based, power generation technologies. The program’s goal is to speed up commercial deployment of advanced technologies to ensure that the U.S. has clean, reliable, and affordable electricity. This ten-year initiative may be tentatively funded at a total Federal cost share, estimated to be about $2 billion, with a matching cost share of at least 50%.

With coal likely to remain one of the lowest-cost electric power suppliers in the U.S. the near future, President George Bush has pledged a new commitment to even more advanced clean coal technologies.

Building on the successes of the original program, the new CCPI comprises of a broad spectrum of research and large-scale projects that target today's most pressing environmental challenges. Initially, the demonstration portion of the CCPI is providing government co-financing for new coal technologies that can help utilities meet the President's Clear Skies Initiative to lower sulfur, nitrogen and mercury pollutants from power plants by almost 70% by 2018. In addition, some of the early projects are showing ways to reduce greenhouse gases from coal plants by increasing the efficiency at which they convert coal to electricity or other energy forms.

Eight projects were selected under the first round of the CCPI, though later on, two projects - the Colorado Springs circulating fluidized bed combustor and the Airborne Process at LG&E-Energy Corporation - were withdrawn. Of the remaining six projects supported by the first round of the CCPI, three projects are currently in the design phase, two are in the construction phase, and one is still in the pre-award phase.

The program is intended to:

- Create industry/government partnerships that develop promising, initially risky, advanced clean coal technologies;
- Accelerate these new coal energy systems into the market by accomplishing successful full-scale technology demonstrations;
• Generate substantial economic and environmental benefits to ensure a secure energy future as these technologies are commercialized by the industry.

The success of the CCPI program will provide an important part of the technology needed to supply the U.S.’ immediate and long-term energy needs in support of the country’s economic well being, while improving the environment. By demonstrating the latest technology to improve efficiency and low-cost, high-performance emissions controls, CCPI technologies can help in achieving a more secure energy future.

**Table 1: Funding for the CCPI and PPII Programs (Dollars in Thousands)**

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<td>CCPI-1 Projects</td>
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<td>Program Support</td>
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<td>1,701</td>
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<td>SBIR &amp; STTR*</td>
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<td>3,909</td>
<td>4,709</td>
<td>1,367</td>
<td>1,372</td>
<td>15,292</td>
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<tr>
<td>Other Adjustments*</td>
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<td>975</td>
<td>2,119</td>
<td>694</td>
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<td>4,497</td>
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<tr>
<td>Total</td>
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<td>150,000</td>
<td>150,000</td>
<td>172,000</td>
<td>50,000</td>
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</table>

*Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR) Programs. All Fossil Energy programs are required to contribute to these programs on an equal percentage basis.

*Across-the-board general and omnibus reductions required by the annual Appropriations Bills.

Source: DOE

**Clean Coal Technology Program**

Begun in 1986, the Clean Coal Technology Program was the most ambitious government-industry initiative ever undertaken to develop environmental solutions for the Nation’s abundant coal resources.

The program's goal: to demonstrate the best, most innovative technology emerging from the world's engineering laboratories at a scale large enough so that industry could determine whether the new processes had commercial merit.

Originally, the Clean Coal Technology Program was a response to concerns over acid rain, which is formed by sulfur and nitrogen pollutants that can be emitted by coal-burning power plants. Based on recommendations from Special Envoys appointed by the U.S. and Canadian governments, President Reagan commissioned the Clean Coal Technology Program as a cost-shared effort between the U.S. Government, State agencies, and the private sector. Industry-proposed projects were selected through a
series of five national competitions aimed at attracting promising technologies that had not yet been proven commercially. Ultimately, 35 pioneering projects in 18 states became part of the Clean Coal Technology Program.

The federal government's funding share totaled $1.6 billion. The private sector, on the other hand, exceeded expectations, contributing $3.2 billion or nearly two-thirds of total project costs. The program had required only 50% non-federal financing.

The Clean Coal Technology Program led to the initial market entry of 1st generation pressurized fluidized bed technology, with an estimated 1000 megawatts of capacity installed worldwide. These systems pressurize the fluidized bed to generate sufficient flue gas energy to drive a gas turbine and operate it in a combined-cycle.

Table 2: Project Costs and Financial Status of Active CCTDP Projects ((Dollars in Thousands)

<table>
<thead>
<tr>
<th>Project Description</th>
<th>Total Project Costs</th>
<th>DOE Share</th>
<th>DOE Obligated</th>
<th>DOE Cost</th>
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<td>Clean Coal Diesel Demonstration Project (withdrawn, but preparing final reports)</td>
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<td>20,805,979</td>
<td>20,805,979</td>
<td>17,672,062</td>
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<td>Total Active CCTDP</td>
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<td>20,805,979</td>
<td>20,805,979</td>
<td>17,672,062</td>
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</table>

**Coal21**

Initiated by the Australian Coal Industry, COAL21 is a program aimed at fully realizing the potential of advanced technologies to reduce or eliminate greenhouse gas emissions associated with the use of coal.

The program will also explore the role of coal as a primary source of hydrogen to power the hydrogen-based economy of the future. The program is a collaborative partnership between Federal and State governments, the coal and electricity generation industries and the research community.

COAL21 is a partnership between the coal and electricity industries, unions, federal and state governments and the research community. It commenced in March 2003 when the Australian Coal Association issued invitations to participate in a process aimed at first identifying and then realizing the potential for reducing or eliminating greenhouse gas emissions from coal-based electricity generation in Australia.

It is well recognized that fossil fuels will continue to play a strong role in meeting global energy demand, energy security, and, in Australia's case, generating export income, employment and investment. As an energy intensive economy with a strong dependence on coal, reducing emissions that arise from its use is one of a broad suite of responses that will be needed if Australia is to make significant cuts in stationary energy sector
emissions in the near future. Other measures will need to include greater emphasis on end use efficiency, greater use of lower carbon fuels and alternative technologies where they are most practical, greater use of renewables and a strong commitment to research and development in all areas. COAL21 is intended to complement these measures, not replace them.

The objectives of COAL21 recognize the important role that coal plays in sustaining Australia's energy security and economic competitiveness. They also recognize the need to reduce greenhouse gas emissions over time in ways that maintain the advantages of a secure and competitive energy supply.

The formal objectives of COAL21, adopted by the Participants in 2003, are to:

1. Create a national plan to scope, develop, demonstrate and implement near zero emissions coal-based electricity generation that will achieve major reductions in greenhouse gas emissions over time while maintaining Australia's low cost electricity advantage.

2. Use the plan to inform governments and industry as an input to policy development.

3. Facilitate the demonstration, commercialization and early uptake of technologies identified in the plan.

4. Promote relevant Australian RD&D so that it can both build upon and make a unique contribution to international RD&D in the area.

5. Foster greater public awareness of the role of coal and the potential for near zero emissions coal-based electricity generation to significantly reduce or eliminate greenhouse gas emissions and other environmental impacts associated with its use.

6. Provide a mechanism for effective interaction and integration with other international zero emission coal initiatives.

**Program Background**

The first stage of COAL21 was the development of the COAL21 National Action Plan. The process ran from March 2003 to March 2004 and involved input from a wide range of participants and consultation with other key stakeholders.

The second stage of COAL21 commenced in 2004 and is focused on implementing the measures identified in the National Action Plan, including fostering greater community awareness and understanding of the key issues.

**National Action Plan**
Although coal has a number of important uses, the COAL21 National Action Plan focuses exclusively on its use as a fuel in electricity generation, the major source of greenhouse gas emissions arising from the use of coal in Australia.

The National Action Plan covers a range of opportunities for reducing emissions, however the primary focus is on emerging or 'breakthrough' technologies, including those with the potential to deliver major reductions or even eliminate emissions. These are the technologies that will help provide a bridge to a more sustainable energy future, a future based on renewables and fossil fuel-based energy with low or even near zero emissions.

In addition to identifying these technologies, the National Action Plan assesses the potential abatement that could be achieved and describes the actions that need to be taken if they are to be deployed commercially in Australia.

Figure 7: Coal21 Program

Source: Coal21 Website
Outlook

While other technologies (like hydrogen fuel cells and solar panels) may some day play a greater role in meeting America’s energy demand, traditional energy resources (like coal) will be indispensable for the near future. Today, over half of America’s electricity is produced using coal. Electricity from coal is affordable, and America is fortunate to have a 250-year domestic supply of coal available to meet their energy demands.

Using clean coal technologies reduces emissions and improves air quality in our communities. This is true for existing power plants equipped with advanced pollution control devices and that continue to play a role in meeting our daily electricity needs. The same will be true for new power plants built to meet our growing demand for electricity and help further refine advanced generating technologies. Building upon these successes, power plants that our children will depend upon to meet their electricity needs will exceed our current expectations.

Clean Coal Technologies - the products of research and development conducted over the past 20 years - have resulted in more than 20 new, lower-cost, more efficient and environmentally compatible technologies for electric utilities, steel mills, cement plants and other industries.

New programs in clean coal technology, such as the Clean Coal Power Initiative (CCPI), are essential for building on the progress of the original Clean Coal Technology Program, finding solutions for reducing trace emissions of mercury; reducing or eliminating carbon dioxide emissions; and increasing fuel efficiencies. Over the longer term, research in clean coal technology will be directed toward developing coal-based hydrogen fuels. If coupled with sequestration, this will allow greater use of coal with zero emissions. The U.S. Department of Energy has announced a Presidential initiative to build “FutureGen," a $1 billion project that will lead to the world's first emission-free plant to produce electricity and hydrogen from coal while capturing greenhouse gases.

Electricity demand will increase 53.4% over the next 25 years. Meeting this rising growth rate will require the construction of the equivalent of more than 1,200 new power plants of 300 megawatts each; about 65 plants each year.

Coal will remain the largest single source of electricity, accounting for 51% of power generation in 2025. Clean coal technologies will help meet these needs, and continue the decline in SO2 and NOx emissions already underway.

The FutureGen project takes clean coal technology even further. FutureGen, a plant to produce hydrogen from coal and sequester emissions, will be the world’s first zero emission coal-fired plant.
Case Studies

China

Strong demand for Chinese industries to improve energy efficiency and reduce environmental impacts lead the necessity for clean coal technologies in China. However, most of China’s clean coal technologies are small in scale or still in the demonstration stage. They cannot meet the immediate needs of Chinese industry. Under such a circumstance, acquisition of clean coal technologies from industrial countries is an advisable choice for China. By reviewing literatures and comprehensive investigations, this study indicates that in the 1990s, imports of clean coal equipment in China increase rapidly, and license trade is in scale with growth relatively limited. The volume of foreign direct investment in the field of clean coal technology is relatively small and contributes little to China’s clean coal technology acquisition.

The Chinese government has adopted many practical and effective measures such as establishing acid rain control zones, key air pollution control cities, and implementing new Air Pollutant Emission Standard for Power Stations, etc. These efforts certainly promote clean coal technology acquisition. In addition, incentives for acquiring foreign clean coal technology also come from the enhancement of their citizens’ environmental awareness, China’s sufficient reserves of foreign exchange, and the potential for global environmental cooperation under the Framework Convention on Climate Change.

However, there are opposing forces that offset the positive effects of China’s clean coal technology acquisition. First, most of the multinationals prefer to export clean coal equipment only; they are reluctant to transfer advanced technology. Second, there are other forces that do not encourage Chinese enterprises to adopt clean coal technology. These include China’s low energy price, low pollution charge and the inefficient economic system. The high price of foreign technology and low capacity to earn profits by Chinese enterprises constrain clean coal technology acquisition as well.

Despite the affect of these forces, to realize the goal of sustainable development, China should adopt effective methods to integrate acquired technology with independent development to establish its own system of clean coal technology.

Clean coal technology can be developed either by domestic R&D, acquisition from abroad, or both. What is best for China depends on the understanding of the technology gap between China and other foreign countries, the evaluation of the effects of imported technology, and the handling of the relationship between technology transfer and domestic, independent R&D. The objectives of the study are to analyze the current development, utilization and acquisition of clean coal technology in China; to systematically review clean coal technology transfer in China, examining the scale, modes, sector distribution, barriers, and opportunities. Based on analysis and review, the study aims to provide recommendations for the government’s decision-making to expedite clean coal technologies transfer, and to promote sustainable energy use in China.
Several difficulties affect the analysis of international trade in clean coal technology in China. First, the definition for clean coal technology varies in different countries: There are different views on what technology belongs to clean coal technology. Second, statistics are incomplete on clean coal technology transaction in China; yet some data concerning the trade volume have to be obtained through on-the-spot investigation. Clean coal technology involves many sectors. Areas that import clean coal technologies are the machinery sector, the electricity power sector, and the environment protection sector. Areas that apply clean coal technology are coal, electricity power, metallurgical, chemical and building materials, etc. This makes the task to obtain data very difficult. Therefore, how to obtain complete and accurate data concerning this subject becomes the key determinant of the study, because it depends heavily on the data available to the research team.

**Technologies**

**High-efficiency and Low-pollution Pulverized Fuel Combustion**

Most boilers in Chinese power plants apply pulverized fuel combustion technology. Investment for this kind of technology is relatively small, and it is suitable for various kinds of coal in China. Over time, pulverized fuel combustion technology will still be applied for large-scale boilers in power plants. Major boilers, manufactured in China for their power plants and stations, are 300-600MW sub-critical parameters controlled cycle or natural-cycle coal combustion boilers imported from Combustion Engineering, U.S.A. (CE), and its combustion efficiency is 92-93%.

Two sets of 600MW super-critical pressure power equipment (parameters of the equipment are 1900t/h, 25.4Mpa, 541/569°C) imported from abroad by Shanghai Shidongkou No.2 Power Plant have now been in operation, and yielded good results. The preliminary research for super-critical pressure boilers has been completed in China (including water dynamic stability research in near-critical area, heat transfer research, dynamics characteristic research, water-cooling wall and stream-water separator, etc.). Super-critical pressure boilers are being designed by domestic technicians and will be manufactured domestically.

Boilers now used in Chinese power stations are low NOx combustors. They belong to the second generation of air-classified combustors. The focus of Chinese research for new combustor over years is on stable combustion, such as the ship-shaped pulverized fuel combustor that adopts pulverized fuel part-concentration technology in combustion area. This combustor can decrease 30-60% of NOx emission, and it does not increase heat loses as a result of incomplete combustion of flying ash. Additionally, it requires no extra investment.

The goals of China’s development strategy by the year 2000 for the power plant boiler sector are to further integrate 300Mw, 600Mw boilers combustors and combustion technology imported from foreign countries, and to develop combustors and combustion
technology that have high-efficiency, good adaptability for different kinds of coal, low-load combustion stability, good performance of supply and sewerage cinder, and low NOx emission. They should also be convenient to operate as well as economical and practical. Before 2010, all new power stations will have to adopt high-efficiency, stable combustion and low NOx emission pulverized fuel combusts, and boilers of old power stations will be gradually phased out.

Funnel air purification technology is an effective way to reduce pollution emission from existing coal-burning boilers and to improve air quality. Air purification technology in Chinese power plants is now in its early stage. Chinese technicians have independently developed spray rotary dry desulphurization technology, phosphorus-ammonium desulphurization, and spray half-dry desulphurization technology. Spray semi-dry desulphurization technology has been applied in industrial experiment on 200Mw power units with 1/10 air volume. In cooperation with Japan, the industrial test of spray rotary dry desulphurization is being done in Shandong’s Huangdao Power Plant; Tsinghua University has successfully developed GASIN technology. The rotational flow tray absorption funnel gas purification technology, which needs little investment and has high efficiency of desulphurization and dust-removal, is under development.

Cycle Fluidized-Bed Boilers

In the 1990s, fluidized bed combustion - a process that removes pollutants inside the coal boiler - was termed "the commercial success story of the last decade."

In the early 1980s, China began R&D on cycle fluidized-bed boilers. In 1985, the Engineering Thermal Physics Institute of the Chinese Academy of Sciences developed a set of 2.8Mw cycle fluidized-bed combustion experiment equipment, put it into operation, and passed the technical appraisal. In 1988, the institute successfully developed the first set of 10t/h cycle fluidized-bed boiler. The project of a 35t/h cycle fluidized-bed power station boiler, which was undertaken by the institute during the period of the Seventh Five-Year Plan (1986-1990) as one of the national key projects, passed the technical appraisal in 1989. During the period of the Eighth Five-Year Plan (1991-95), research and manufacture of a 75t/h boiler was completed successfully. At present, a 220t/h cycle fluidized-bed boiler is under development.

Apart from the Engineering Thermal Physics Institute, Tsinghua University, Dongnan University and Zhejiang University also lead the research on cycle fluidized-bed boiler combustion. At present, about 300 cycle fluidized-bed boilers of less than 130 ton are manufactured based on domestic technology.

Coal Combustion for Combined Cycle Power Generation

Coal combustion for combined cycle power generation technology includes IGCC, PFBC-CC and AFBC-CC. In the 1980s, China started the research on pressurized fluidized-bed combustion combined cycle technology. Since that time, a great deal of research on combustion, bed dynamics, heat transfer in bed, high temperature aspiration
and wear has been done, and important data applied for the design and operation of pressurized fluidized-bed combustion combined cycle technology has been obtained. In 1991, pressurized fluidized-bed combustion combined cycle power technology was listed in the most important R&D projects of the Eighth Five-Year Plan (1991-1995). In 1995, 15MW pressurized fluidized-bed combustion combined cycle middle-stage experiment power station, which is developed by Dongnan University Thermoenergy Engineering Institute and manufactured by Haerbin Boiler Factory (HBF), was installed and tested in Xuzhou Jiawang Power Plant.

China’s IGCC technology lags far behind that of developed countries. In 1986, a 2.8m Lurgi fixed-bed gas furnace processing 120-ton coal daily and generating gas 1500m3/h was successfully replicated in Taiyuan. A fixed-bed pressurized gas furnace of Czech manufacture and eight sets of Derscu coal gasified furnaces have also been imported. The “three-combined-supply” project under construction in Shanghai Coking Factory is an integral system combining steam-vapor combined cycle equipment and gas, electricity heat and chemical production. It gasifies coal into medium-heat value gas and supplies it to a steam turbine chemical process and municipal gas. In fact, the power is supplied by IGCC equipment. The nation’s high efficiency clean coal combustion lab is constructing 35t/h vapor volume demonstration equipment combined supply by vapor, heat and electricity,

Briquette

Briquette can simply be classified into civil briquette and industrial briquette. China has an advanced position in briquette technology. In 1994, the nation’s total civil consumption of coal was 13047Mt, and the production capacity for civil briquette was 50Mt. At present, 60% of large- and medium-sized cities in China use briquette technology, while in small towns and rural areas, raw coal, straw and timber are used as their main fuels.

Coal Water Mixture Technology

After more than 10 years of effort, China has now entered the commercial demonstration stage for coal water mixture (CMM) technology. At present, there are five CWM plants in China, and the total designed capacity is 850kt/a. For example, the production capacity of Zaozhuang Bayi CWM Plant, which is completely designed and manufactured by domestic institutes and manufacturers, is 250Mt/a. Its first-phase construction of a 50Mt/a production capacity was completed in 1991 and the second-phase construction of a 200Mt/a capacity was completed in 1997. The total investment is about 60 million Yuan.

China has also established two additive plants, with a total production capacity of 1500t/a. The production capacity of Huainan Additive Plant is 55t/a, and the production capacity of Yanqing Additive Plant is 1000t/a. As for the application in combustion, many demonstration projects have been initiated on industry boilers, power station
boilers, industry furnaces, and oil field boilers. These projects have been successful to date, and a great deal of useful experience and data has been obtained.

Coal Gasification

Coal gasification can be classified into complete gasification, mild gasification or underground gasification. These are the basic forms of coal transformation. During the Eighth Five-Year Plan period, Beijing Coal-Chemistry Institute of China Academy of Coal Science initiated a cycle fluidized-bed gasification system that is operated under pressure of 1.0Mpa, Φ300mm. This system has experimented with five kinds of coal and provided industrial gases for combined cycle power research. The institute has also successfully applied advanced technology such as L-valve, air transportation, and flying ash cycle. Shanxi Coal-Chemistry Institute of China Academy of Sciences has developed direct gasification technology of ash melted-accumulated fluidized-bed pulverized fuel and completed its mid-term experiment (the diameter of the gasified stove is 1000mm, and the production capacity is 24t/d). The accumulated operation time of the device is 775h and the total coal consumption is 430t, making the technology mature. This technology has the advantages of good adaptability for various types of coal and large-scale electricity-generating equipment.

Mild gasification of coal can improve the utilization of young coal and produce many value-added products. Underground gasification changes coal into easily transported gas fuel, therefore, it has excellent market potential. In China, the above two technologies are both in the industrialization experimental stage.

Gap Between China and Developed Countries

The gap between China and developed countries in clean coal technology can be viewed from the following two perspectives:

First, China’s technology is relatively immature, and its application scale is rather small. The nation’s clean coal technology, such as PFBC-CC, IGCC, and CFBC, is either in small scale or experimental. For example, the largest production capacity of cycle fluidized-bed boiler in China is 220t/h, while in developed countries, its production capacity can be as high as 700t/h. PFBC technology stands in the 15MW experiment stage in China, while in Sweden, ABB has completed the long run of P200 project (about 75MW), and is now in the 350MW commercial demonstration stage. In the field of IGCC, 250MW demonstration equipment has been put into operation in the Netherlands and the U.S.; while in China, such technology is still in the feasibility/pre-research stage. In the field of non-capital-intensified technology, such as briquette technology, China is in an advanced position in the world.

Second, the application scope of clean coal technology is rather narrow. Obviously, as the nation’s clean coal technology, such as PFBC-CC and IGCC, is still in the stages of experiment or commercial demonstration, the application of such technology remains at a low level. Even though some technology is mature, the application is very limited due to
lack of effective instrumental policy. As a result, the proportion of washed steam coal volume in China is less than 10%; in contrast, the U.S. is at 45%, and European countries at 75%. 
Duke Energy and Vectren Energy

Duke Energy Indiana and Vectren Energy Delivery of Indiana have filed an application with the Indiana Utility Regulatory Commission for “Certificates of Public Convenience and Necessity” (CPCN) to construct an approximately 630-megawatt power plant that will use advanced integrated gasification combined cycle (IGCC) technology. If the project proceeds, it will be one of the first commercial-scale IGCC power plants built in the United States in the last 10 years.

Duke Energy Indiana has selected its existing power plant site in Edwardsport, Ind., as the site for the new IGCC plant. Upon completion of the IGCC project, the existing plant -- with coal and oil units built between 1944 and 1951 – will be retired.

Based on industry data, a 630-megawatt IGCC plant could cost approximately $1.3 to $1.6 billion. The project would use an average of 800 to 900 construction workers over a three-year period, with a peak workforce of 2,000. Ongoing plant operations would employ approximately 100 people.

The IGCC project is located in Knox County and has received support from local and area residents. The Knox County Commission unanimously approved tax incentives for the project. Recent Indiana state legislation to encourage clean coal technology also has made tax incentives available to the project.

Duke Energy Indiana is exploring co-ownership of the plant with Vectren Energy Delivery of Indiana. Both companies are working with GE Energy and Bechtel Corporation on an engineering and design study for the plant, which is expected to be completed by the second quarter of 2007.

Integrated gasification combined cycle technology uses a coal gasification system to convert coal into a synthesis gas (syngas). The syngas is processed to remove sulfur, mercury and ash before being sent to a traditional combined cycle power plant, using two combustion turbines and a steam turbine to efficiently produce electricity.

IGCC technology could also remove the carbon dioxide from coal during the syngas conversion process to enable it to be stored or sequestered in underground geologic formations. This is not in the current scope of the IGCC plant project, but it could be added as carbon dioxide capture and sequestration technology advances and if it is determined that the Edwardsport site has the appropriate geology to sequester carbon dioxide underground.
FutureGen

FutureGen is an initiative to build the world's first integrated sequestration and hydrogen production research power plant. The $1 billion dollar project is intended to create the world's first zero-emissions fossil fuel plant. When operational, the prototype will be the cleanest fossil fuel fired power plant in the world.

The initiative is a response to President Bush's directive to draw upon the best scientific research to address the issue of global climate change. The production of hydrogen will support the President's call to create a hydrogen economy and fuel pollution free vehicles; and the use of coal will help ensure America's energy security by developing technologies that utilize a plentiful domestic resource.

Additionally, other countries will be joining the U.S. to participate in the project. The prototype plant will establish the technical and economic feasibility of producing electricity and hydrogen from coal (the lowest cost and most abundant domestic energy resource), while capturing and sequestering the carbon dioxide generated in the process. The initiative will be a government/industry partnership to pursue an innovative 'showcase' project focused on the design, construction and operation of a technically cutting-edge power plant that is intended to eliminate environmental concerns associated with coal utilization. This will be a 'living prototype' with future technology innovations incorporated into the design as needed.

The project will employ coal gasification technology integrated with combined cycle electricity generation and the sequestration of carbon dioxide emissions. The project will be supported by the ongoing coal research program, which will also be the principal source of technology for the prototype. The project will require 10 years to complete and will be led by the FutureGen Industrial Alliance, Inc., a non-profit industrial consortium representing the coal and power industries, with the project results being shared among all participants, and industry as a whole.
Alaska Industrial Development and Export Authority

Located in Healy, Denali Borough, AK. With a 50 MWe Plant Capacity

Technology used was TRW's Clean Coal Combustion System; Babcock & Wilcox's spray dryer absorber (SDA) with sorbent recycle. Coal used: Usibelli subbituminous 50% run-of-mine (ROM) coal and 50% waste coal. The total cost of the project was $242,058,000

The Project Objective was to demonstrate an innovative new power plant design featuring integration of an advanced combustor coupled with both high- and low-temperature emissions control processes.

Project Description

Emissions are controlled using TRW's clean coal combustion system, an advanced entrained/slagging combustor through staged fuel and air injection for NOx control and limestone injection for SO2 control. Additional SO2 is removed using B&W's activated recycle SDA.

A coal-fired precombustor increases the air inlet temperature for optimum slagging performance. The slagging combustors are bottom mounted, injecting the combustion products into the boiler. The main slagging combustor consists of a water-cooled cylinder that slopes toward a slag opening. The precombustor burns 25%-40% of the total coal input. The remaining coal is injected axially into the combustor, rapidly entrained by the swirling precombustor gases and additional air flow, and burned under substoichiometric conditions for NOx control. The ash forms molten slag, which flows along the water-
cooled walls and is driven by aerodynamic and gravitational forces through a slot into the slag recovery section.

About 70%-80% of the ash is removed as molten slag. The hot gas is then ducted to the furnace where, to ensure complete combustion, additional air is supplied from a tertiary air windbox to NOx ports and to final overfire air ports. Pulverized limestone (CaCO3) for SO2 control is fed into the combustor where it is flash calcined (converting CaCO3 to lime [CaO]). The mixture of this CaO and ash that was not removed in the combustor, called flash-calcined material, is removed in the fabric filter system. Most of the flash-calcined material is used to form a 45% solids slurry, which is injected into the spray dryer. The SO2 in the flue gas reacts with the slurry droplets as water is simultaneously evaporated. The SO2 is further removed from the flue gas by reacting with the dry flash-calcined-material on the baghouse filter bags.

Results

Environmental
- NOx emissions ranged from 0.208–0.278 lb/106 Btu, with typical emissions of 0.245 lb/106 Btu on a 30-day rolling average, which is well below the permit limit of 0.350 lb/106 Btu on a rolling day average.
- SO2 emissions were consistently less than 0.09 lb/106 Btu, with typical emissions of 0.038 lb/106 Btu, which are below the permit limit of 0.10 lb/106 Btu (3-hour average).
- High SO2 removal efficiencies in excess of 90% were achieved with low-sulfur coal and Ca/S molar ratios of 1.4–1.8.
- Particulate matter (PM) emissions were 0.0047 lb/106 Btu, which is well below the permit limit of 0.02 lb/106 Btu.
- CO emissions were less than 130 ppm at 3.0% O2, with typical emissions of 20–50 ppm at 3.0% O2, which is well below the permit limit of 202 ppm at 3.0% O2.
- Tests showed that the SDA system SO2 emissions, PM emissions, and opacity were well within guarantees of the technology supplier.

Operational
- Carbon burnout goals for the technology supplier were achieved—greater than 99% carbon burnout at 100% maximum continuous rating (MCR) for the ROM, 50/50 blend of ROM/waste coal, and 55/45 blend. The carbon burnout was typically 99.7%.
- The contract goal of the technology supplier for slag recovery greater than 70% at 100% MCR for all coals was also achieved. Slag recovery ranged from 78–87%, with a typical recovery of 83%.
- During a 90-day test in the second half of 1999, the plant availability was 97% at a capacity factor of 95%.
- The SDA pressure drops and power consumption were well below guarantee levels of the technology supplier.
- The system required less limestone and produced less solid waste by-product than anticipated.
- Economic
• The capital costs of a 50-MWe and 300-MWe plant using this system are $90.6 million ($1,812/kW) and $450.7 million ($1,502/kW) (1993$), respectively.
• The variable operating costs for the 300-MWe system are $7.2 million/yr (1993$) for the fixed cost and $28.4 million/yr (1993$) for the variable costs (based on 90% capacity factor).
• The levelized cost of power is 36.5 mills/kWh (constant 1993$) for the 300-MWe plant (based on 90% capacity factor).
• The levelized cost per ton of SO2/NOx removed is $6,499/ton (constant 1993$) for the 300 MWe plant (based on 90% capacity factor).

Project Summary
The Healy Clean Coal Project is the first utility-scale demonstration of the TRW clean coal combustion system. The project site is adjacent to the existing Healy Unit No. 1 near Healy, Alaska and the Usibelli coal mine. Power is supplied to the Golden Valley Electric Association (GVEA).

Environmental Performance
The entrained/slagging combustor is designed to minimize NOx emissions, achieve high carbon burnout, and remove the majority of fly ash from the flue gas prior to the boiler. The slagging combustor is also the first step of a three-step process for controlling SO2 by first converting limestone to flash-calcined lime. Second, the flash calcined-lime absorbs SO2 within the boiler. Third, the majority of the SO2 is removed with B&W's SDA system, which uses the flash-calcined lime and fly ash captured in the baghouse. Because most of the coal ash is removed by the slagging combustors, the recycled material is rich enough in calcium content that the SDA can be operated solely on the recycled solids, eliminating the need to purchase or manufacture lime for the back end scrubbing system.

Operational Performance
The slagging stage of the combustor performed extremely well and continuously demonstrated the capability to burn both ROM and ROM/waste coal blends over a broad range of operating conditions. The precombustor performed very well with ROM coal, but exhibited more variable performance, in terms of slagging behavior, during the initial tests with ROM/waste coal blends.

Localized slag freezing was observed in the precombustor during early testing. A combination of hardware configuration and operational configuration changes were made that minimized slag freezing. These changes included relocating the secondary air from the precombustor mix annulus to the head end of the slagging stage and completely transferring the precombustor mill air to the boiler NOx ports following boiler warmup. These changes eliminated the mixing of excess air downstream of the precombustor chamber to minimize local slag freezing and increased the precombustor operating temperature to provide additional temperature margin. The mill air change had the added benefit of simplifying combustor operation by eliminating the need to monitor and control coal-laden mill air flow to the precombustor mill air ports during steady-state operation.
Testing of the slagging combustor also showed that the contract goals were achieved, which included greater than 99% carbon burnout at 100% MCR for the performance, ROM, 50/50 blend of ROM/waste coal, and 55/45 blend; and greater than 98% carbon burnout at 100% MCR for waste coal. The carbon burnout was typically 99.7%. Slag recovery ranged from 78–87%, with a typical reading of 83%, easily meeting the contract goal for slag recovery of greater than 70% at 100% MCR for all coals.

The SDA system also performed well. During performance testing in June 1999, system pressure drops were well below the 13 inches water gage (in. w.g.) guarantee. The range was 9.6–10.0 in. w.g. as can be seen in Exhibit 5-48. Power consumption was approximately 38–41% less than the guaranteed level. Based on these results, Stone & Webster concluded that the SDA system met all performance guarantees.

**Economic Performance**

Capital and operating cost estimates were prepared by an independent consultant to the participant for new plants in the “lower 48” that incorporate the technology demonstrated at Healy. The capital costs for a 50-MWe and 300-MWe plant are $90.6 million (1,812 $/kW) and $450.7 million (1,502 $/kW) (1993$), respectively. The variable operating cost for the 300-MWe plant is estimated at $7.2 million per year and the fixed operating costs are estimated at $28.4 million per year based on a 90 percent capacity factor (1993$). The levelized cost of power would then be 36.5 mills/kWh (constant 1993$). The levelized cost per ton of SO2 and NOx removed is $6,499/ton (constant 1993$) for the 300-MWe plant.

**Commercial Applications**

This technology is appropriate for any size utility or industrial boiler in new or retrofit uses. It can be used in coal-fired boilers as well as in oil- and gas-fired boilers because of its high ash-removal capability. However, cyclone boilers may be the most amenable type to retrofit with the entrained/slagging combustor because of the limited supply of high-Btu, low-sulfur, low-ash-fusion-temperature coal that cyclone boilers require. The commercial availability of cost-effective and reliable systems for SO2, NOx, and particulate control is important to potential users planning new capacity, repowering, or retrofits to existing capacity in order to comply with CAAA requirements.

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The Ohio Power Company

Located in Brilliant, Jefferson County, OH (Ohio Power Company's Tidd Plant, Unit No. 1). Plant Capacity is 70 MWe (net). Coal used was Ohio bituminous, 2-4% sulfur. Technology used was The Babcock & Wilcox Company's pressurized fluidized-bed combustion (PFBC) system (under license from ABB Carbon). Total Cost is $189,886,339

Project Objective
To verify expectations of PFBC economic, environmental, and technical performance in a combined-cycle repowering application at utility scale; and to accomplish greater than 90% SO2 removal and NOx emission level of 0.2 lb/106 Btu at full load.

Project Description
Tidd was the first large-scale operational demonstration of PFBC in the United States. The project represented a 13:1 scaleup from the pilot facility.

The boiler, cyclones, bed reinjection vessels, and associated hardware were encapsulated in a pressure vessel 45 feet in diameter and 70 feet high. The facility was designed so that one-seventh of the hot gases produced could be routed to an advanced particulate filter (APF).

The Tidd facility used a bubbling fluidized-bed combustion process operating at 12 atm (175 psi). Pressurized combustion air is supplied by the turbine compressor to fluidize the bed material, which consists of a coal-water fuel paste, coal ash, and a dolomite or limestone sorbent. Dolomite or limestone in the bed reacts with sulfur to form calcium sulfate, a dry, granular bed-ash material, which is easily disposed of or is usable as a by-product. A low bed-temperature of about 1,600 °F limits NOx formation.

The hot combustion gases exit the bed vessel with entrained ash particles, 98% of which are removed when the gases pass through cyclones. The cleaned gases are then expanded through a 15-MWe gas turbine. Heat from the gases exiting the turbine, combined with heat from a tube bundle in the fluid bed, generates steam to drive an existing 55-MWe steam turbine.

Results
Environmental
- Sorbent size had the greatest effect on SO2 removal efficiency as well as stabilization and heat transfer characteristics of the fluidized-bed.
- SO2 removal efficiency of 90% was achieved at full load with a calcium-to-sulfur (Ca/S) molar ratio of 1.14 and temperature of 1,580 °F.
- SO2 removal efficiency of 95% was achieved at full load with a Ca/S molar ratio of 1.5 and temperature of 1,580 °F.
- NOx emissions were 0.15-0.33 lb/106 Btu.
- CO emissions were less than 0.01 lb/106 Btu.
- Particulate emissions were less than 0.02 lb/106 Btu.
Operational
- Combustion efficiency ranged from an average 99.3% at low bed levels to an average 99.5% at moderate to full bed levels.
- Heat rate was 10,280 Btu/kWh (HHV, grass output) (33.2% efficiency) because the unit was small and no attempt was made to optimize heat recovery.
- An advanced particulate filter (APF), using a silicon carbide candle filter array, achieved 99.99% filtration efficiency on a mass basis.
- PFBC boiler demonstrated commercial readiness.
- ASEA Stal GT-35P gas turbine proved capable of operating commercially in a PFBC flue gas environment.

Economic
- The Tidd plant was a relatively small-scale facility, and as such, detailed economics were not prepared as part of this project.
- A recent cost estimate performed on Japan's 360-MWe PFBC Karita Plant projected a capital cost of $1,263/kW (1997$).

Project Summary
The Tidd PFBC technology is a bubbling fluidized-bed combustion process operating at 12 atmospheres (175 psi). Fluidized-bed combustion is inherently efficient because the pressurized environment enhances combustion efficiency, allows very low temperatures that mitigate thermal NOx generation, promotes flue gas/sorbent reactions that increase sorbent utilization, and produces flue gas energy that is used to drive a gas turbine. The latter contributed significantly to system efficiency because of the high efficiency of gas turbines and the availability of gas turbine exhaust heat that can be applied to the steam cycle. A bed design temperature of 1,580 °F was established because it was the maximum allowable temperature at the gas turbine inlet and was well below temperatures for coal ash fusion, thermal NOx formation, and alkali vaporization.

Coal crushed to one-quarter inch or less was injected into the combustor as a coal/water paste containing 25% water by weight. Crushed sorbent, either dolomite or limestone, was injected into the fluidized bed via two pneumatic feed lines, supplied from two lock hoppers. The sorbent feed system initially used two injector nozzles but was modified to add two more nozzles to enhance distribution.

In 1992, a 10-MWe equivalent APF was installed and commissioned as part of a research and development program and not part of the CCT Program demonstration. This system used ceramic candle filters to clean one-seventh of the exhaust gases from the PFBC system. The hot gas cleanup system unit replaced one of the seven secondary cyclones.

The Tidd PFBC demonstration plant accumulated 11,444 hours of coal-fired operations during its 54 months of operation. The unit completed 95 parametric tests, including continuous coal-fired runs of 28, 29, 30, 31, and 45 days. Ohio bituminous coals having sulfur contents of 2 - 4% were used in the demonstration.
Environmental Performance
Testing showed that 90% SO2 capture was achievable with a Ca/S molar ratio of 1.14 and that 95% SO2 capture was possible with a Ca/S molar ratio of 1.5, provided the size gradation of the sorbent being utilized was optimized. This sulfur retention was achieved at a bed temperature of 1,580 °F and full bed height. Limestone induced deterioration of the fluidized-bed, and as a result, testing focused on dolomite. The testing showed that sulfur capture as well as sintering was sensitive to the fineness of the dolomite sorbent (Plum Run Greenfield dolomite was the design sorbent). Sintering of fluidized-bed materials, a fusing of the materials rather than effective reaction, had become a serious problem that required operation at bed temperatures below the optimum for effective boiler operation. Tests were conducted with sorbent size reduced from minus 6 mesh to a minus 12 mesh. The result with the finer material was a major positive impact on process performance without the expected excessive elutriation of sorbent. The finer material increased the fluidization activity as evidenced by a 10% improvement in heat transfer rate and an approximately 30% increase in sorbent utilization. In addition, the process was much more stable as indicated by reductions in temperature variations in both the bed and the evaporator tubes. Furthermore, sintering was effectively eliminated.

NOx emissions ranged from 0.15-0.33 lb/106 Btu, but were typically 0.2 lb/106 Btu during the demonstration. These emissions were inherent in the process, which was operating at approximately 1,580 °F. No NOx control enhancements, such as ammonia injection, were required. Emissions of carbon monoxide and particulates were less than 0.01 lb/106 Btu and 0.02 lb/106 Btu, respectively.

Operational Performance
Except for localized erosion of the in-bed tube bundle and the more general erosion of the water walls, the Tidd boiler performed extremely well and was considered a commercially viable design. The in-bed tube bundle experienced no widespread erosion that would require significant maintenance. While the tube bundle experienced little wear, a significant amount of erosion on each of the four water walls was observed. This erosion posed no problem, however, because the area affected is not critical to heat transfer and could be protected by refractory.

The prototype gas turbine experienced structural problems and was the leading cause of unit unavailability during the first three years of operation. However, design changes instituted over the course of the demonstration proved effective in addressing the problem. The Tidd demonstration showed that a gas turbine could operate in a PFBC flue gas environment.

Efficiency of the PFBC combustion process was calculated during testing from the amount of unburned carbon in cyclone and bed ash, together with measurements of the amount of carbon monoxide in the flue gas. Combustion efficiencies averaged 99.5% at moderate to full bed heights, surpassing the design efficiency of 99.0%.
Using data for typical full-load operation, a heat rate of 10,280 Btu/kWh (HHV) was calculated. This corresponds to a cycle thermodynamic efficiency of 33.2% at a point where the cycle produced 70 MWe of gross electrical power while burning Pittsburgh No. 8 coal. Because the Tidd plant was a repowering application at a comparatively small scale, the measured efficiency does not represent what would be expected for a larger utility-scale plant using Tidd technology. Studies conducted under the PFBC Utility Demonstration Project showed that efficiencies of over 40% are likely for a larger, utility-scale PFBC plant.

In summary, the Tidd project showed that the PFBC system could be applied to electric power generation. Further, the demonstration project led to significant refinements and understanding of the technology in the areas of turbine design, sorbent utilization, sintering, post-bed combustion, ash removal, and boiler materials.

Testing of the APF for over 5,800 hours of coal-fired operation showed that the APF vessel was structurally adequate; the clay-bonded silicon carbide candle filters were structurally adequate unless subjected to side loads from ash bridging or buildup in the vessel; bridging was precluded with larger particulates included in the particulate matter; and filtration efficiency (mass basis) was 99.99%.

**Economic Performance**

The Tidd plant was a relatively small-scale demonstration facility, so detailed economics were not prepared as part of this project. However, a recent cost estimate performed on Japan's 360-MWe PFBC Karita Plant projected a capital cost of $1,263/kW (1997$).

**Commercial Applications**

Combined-cycle PFBC permits use of a wide range of coals, including high-sulfur coals. The compactness of bubbling-bed PFBC equipment allows utilities to significantly increase capacity at existing sites. Compactness due to pressurized operation reduces space requirements per unit of energy generated. PFBC technology appears to be best suited for applications of 50 MWe or larger. Capable of being constructed modularly, PFBC generating plants permit utilities to add increments of capacity economically to match load growth. Plant life can be extended by repowering with PFBC using the existing plant area, coal- and waste-handling equipment, and steam turbine equipment.

The Tidd project received Power magazine's 1991 Powerplant Award. In 1992, the project received the National Energy Resource Organization award for demonstrating energy-efficient technology.

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**SaskPower**

SaskPower's innovative Clean Coal Project is examining the feasibility of designs that will see the capture of over 90% of a major contributor to global warming: carbon dioxide (CO2).

A new clean coal power plant will produce 300 megawatts (MW) of electricity - more than enough to supply a city of 200,000. It will also create enough liquefied CO2 to extract millions of new barrels of oil from Saskatchewan oilfields through enhanced oil recovery.

Additional emissions-control technologies will also be incorporated, bringing the Clean Coal Project to near zero emission status. They'll also take our world closer to a more environmentally and economically sustainable future for electricity generated from coal.

SaskPower will focus further engineering efforts for its Clean Coal Project on expansion of the Shand Power Station near Estevan. Should the project proceed, Shand will be the location for the first clean coal unit.

As part of its Clean Coal Project, SaskPower was exploring two regions for development of potential clean coal units - the Estevan area and the Coronach/Willow Bunch area.

When the impacts of local coal characteristics, mining costs, carbon dioxide (CO2) transportation, transmission system interconnection, cooling water, and provision for existing coal supply agreements are considered, initial deployment at the Shand site presents a number of advantages - which include both capital and lifecycle cost savings - over initiating the technology at the Poplar River site near Coronach.

Plans to proceed at the Shand site are pending successful negotiations with key stakeholders in the Estevan area. The Poplar River Power Station near Coronach will be reconsidered if problems occur with development of the Estevan site.

In 2005-06, SaskPower invested $130 million to rebuild Poplar River Power Station Unit 2. SaskPower also plans to rebuild Unit 1 in the coming years.

If successful, the advanced clean coal unit will be the first of its kind in a utility scale application in the world. A decision on whether to proceed with the project will be made in mid-2007, with an in service date of 2011.

SaskPower, Babcock & Wilcox Canada (B&W) and Air Liquide have come to an agreement to jointly develop carbon dioxide (CO2) separation technology as the core process for SaskPower's Clean Coal Project.

The technology, called Oxyfuel, nearly eliminates emissions of combustion by-products, including greenhouse gas emissions.
Neill and Gunter, a leading North American provider of engineering design and consulting services, has been selected as the primary project consultant for SaskPower's Clean Coal Project.

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JEA Large-Scale CFB Combustion Demonstration Project

The Northside Repowering Project received the 2002 Powerplant Award from Power magazine. In September 1997, the U.S. DOE and JEA entered into an agreement to repower JEA’s Northside Generating Station Unit 2 with CFB boiler technology from FW. The purpose of this agreement was to demonstrate CFB technology for coal firing in large-scale applications while providing increased plant electric output, reduced emissions and broad fuel flexibility.

CFB technology is an advanced method for utilizing coal and other solid fuels in an environmentally acceptable manner. The low combustion temperature allows sulfur dioxide (SO2) capture via limestone injection while minimizing oxides of nitrogen (NOx) emissions. The technology is flexible enough to handle a wide range of coals as well as petroleum coke and blends of coal and coke. CFB boilers have been installed in smaller, industrial-size plants but have only recently been considered for larger utility power plants. The DOE helped test a 110 MW CFB boiler at a power station in Colorado in one of its earliest and most successful Clean Coal Technology projects. At nearly 300 MW each, the JEA CFB boilers more than double the size of the Colorado unit and are among the world’s largest.

The JEA Large-Scale CFB Demonstration Project involved repowering Northside (NS) Unit 2, an existing 275 MW oil/gas fired boiler which had been out of service since the early 80’s, with a 297.5 MW CFB boiler. The DOE contributed approximately $73 million from the Clean Coal Technology Program, and JEA provided the remainder of the total budget. The DOE cost sharing included two years of demonstration test runs, during which both coal and coal/petroleum coke blends were fired. JEA also repowered Northside Unit 1 with an identical CFB boiler. The DOE did not cost share in the Unit 1 repowering.

The project involved the construction and operation of two CFB boilers fueled by coal and petroleum coke to repower two existing steam turbines, each generating nearly 300 MW. CFB boilers are generally capable of removing over 98% of SO2. However, to improve the overall economics and environmental performance, a polishing scrubber was included to minimize reagent consumption while firing petroleum coke containing up to 8.0% sulfur. The relatively low furnace operating temperature of about 1600°F inherently results in appreciably lower NOx emissions compared to conventional coal-fired power plants.

However, the project also included a new selective non-catalytic reduction (SNCR) system to further reduce emissions of NOx. Over 99.8% of particulate emissions are removed by a baghouse. In addition to the CFB combustor and the air pollution control systems, new equipment for the project included a chimney as well as fuel, limestone, and ash handling systems. The project also required overhaul and/or upgrades of existing systems such as the steam turbines, condensate and feedwater systems, circulating water systems, water treatment systems, plant electrical distribution systems, the switchyard, and the plant control systems.
New construction associated with the Repowering Project occupies approximately seventy-five acres of land at the Northside Generating Station. Solid fuel delivery to the site required new receiving, handling, and storage facilities. Limestone and ash storage and handling facilities were also required. Wherever possible, existing facilities and infrastructure were used for the project. These include the intake and discharge system for cooling water, the wastewater treatment system, and the electric transmission lines and towers.

Project activities included engineering and design, permitting, equipment procurement, construction, start-up, and demonstration of the commercial feasibility of the technology. During the demonstration period, Unit 2 was operated under normal dispatch conditions and also tested on several different types of coal and coal/petroleum coke blends to demonstrate the viability of the technology. Units 1 and 2 continue to operate successfully to provide a significant portion of JEA’s power generation.

The CFB boiler technology selected by JEA for the Demonstration Project is an advanced method for utilizing coal and other solid fuels in an environmentally acceptable manner. The low combustion temperature allows SO2 capture via limestone injection, while minimizing NOx emissions. The technology provides the capability to burn a wide range of fuels including coal, petroleum coke, and blends of the two.

Although CFB boilers are generally capable of removing over 98% of SO2, a polishing scrubber was included to minimize reagent consumption and improve environmental performance while firing petroleum coke containing up to 8.0% sulfur. Based on the incremental amount of SO2 removal required, dry scrubber technology, followed by a baghouse for particulate removal, was selected for the AQCS.

Firing of solid fuels on the Northside site required the design and installation of a completely new system for receiving, handling, and storing coal and petroleum coke. The same system is used for receiving and handling limestone for CFB boiler reagent. Firing of solid fuels results in the production of ash byproducts, so new provisions had to be designed and installed for handling and processing these materials. Facilities were also included for storing the byproducts pending development of useful markets for these materials.

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Appendix

Figure 8: Market for New Coal Power Plant Technology

Source: DOE

Figure 9: Efficiency of Hard Coal Power Stations

Source: DOE
### Table 3: Primary Characteristics of Different Gasifiers

<table>
<thead>
<tr>
<th>Flow Regime</th>
<th>Moving (or “Fixed” Bed)</th>
<th>Fluidized Bed</th>
<th>Entrained Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion Analogy</td>
<td>Grate fired combustors</td>
<td>Fluidized bed combustors</td>
<td>Pulverized coal combustors</td>
</tr>
<tr>
<td>Fuel Type</td>
<td>Solids only</td>
<td>Solids only</td>
<td>Solids or liquids</td>
</tr>
<tr>
<td>Fuel Size</td>
<td>5-500 mm</td>
<td>0.5-5 mm</td>
<td>&lt; 500 microns</td>
</tr>
<tr>
<td>Residence Time</td>
<td>15-30 minutes</td>
<td>5-50 seconds</td>
<td>1-10 seconds</td>
</tr>
<tr>
<td>Oxidant</td>
<td>Air or oxygen-blown</td>
<td>Air or oxygen blown</td>
<td>Almost always oxygen-blown</td>
</tr>
<tr>
<td>Gas Outlet Temperature</td>
<td>400-500°C</td>
<td>700-900°C</td>
<td>900-1400°C</td>
</tr>
<tr>
<td>Ash Handling</td>
<td>Slagging and non-slagging</td>
<td>Non-slagging</td>
<td>Always slagging</td>
</tr>
<tr>
<td>Commercial Examples</td>
<td>Lurgi dry ash (non-slagging)</td>
<td>GTI U-Gas, HT Winkler, KRW</td>
<td>GE Energy, Shell, Prenflo, ConocoPhillips, Noell</td>
</tr>
<tr>
<td>Comments</td>
<td>Moving beds are mechanically stirred, fixed beds are not</td>
<td>Bed temperature below ash fusion point to prevent agglomeration</td>
<td>Not preferred for high-ash fuels due to energy penalty of ash-melting</td>
</tr>
<tr>
<td></td>
<td>Gas and solid flows are always countercurrent in moving bed gasifiers</td>
<td>Preferred for high-ash feedstocks &amp; waste fuels</td>
<td>Unsuitable for fuels that are hard to atomize or pulverize</td>
</tr>
</tbody>
</table>

Source: EIA

### Figure 10: Global Distribution of Gasification Capacity

Source: U.S. Department of Energy
Glossary

**Acid Rain:** Fossil biomass (coal) contains sulfur, carbon and nitrogen, which convert to gas upon burning. When the gas combines with atmospheric water, it forms carbonic acid, nitric acid and sulfuric acid/sulfate. Carbonic and nitric acids along with sulfates act as nutrients to plants and trees.

**Aggregate Flotation:** A clean coal technology that involves floating finely ground coal in water. The coal has been chemically conditioned to stick to rising air bubbles. Through this method, nearly all of the inorganic sulfur sinks to the bottom of the mixing tank. The result is a cleaner burning coal that emits less sulfur dioxide.

**Anthracite:** A hard coal, almost pure carbon, used mainly for heating homes.

**Ash:** Non-organic, non-flammable substance left over after combustible material has been completely burned.

**Atmospheric Fluidized Bed Combustion:** A clean coal technology that uses pulverized coal mixed with limestone. The limestone effectively absorbs sulfur from the gases resulting from the combustion of the coal. The process reduces approximately 90% of sulfur dioxide emissions and causes a moderate reduction of nitrogen oxide emissions.

**Bacterial Cleaning (Microbial):** Any pre-combustion cleaning technique that uses biological reactions allowing easier removal of organic sulfur from coal.

**Bituminous Coal:** A soft coal, the most common in the United States, used to generate electricity and to make coke for the steel industry.

**BTU:** British thermal unit. A measure of the energy required to raise the temperature of one pound of water by one degree Fahrenheit.

**CCT By-Products:** Useful substances that are created from gases and liquids because of removing sulfur and nitrogen from coal. These by-products are being researched for use in the pavement of roads, building materials and other applications.

**Calcium-Based Sorbents:** Calcium-based or hydrated lime additives that are mixed with coal to absorb sulfur from coal combustion gases.

**Carbonic Acid/Carbon Dioxide:** Coal contains carbon, which converts to a gas upon burning. When carbon dioxide combines with atmospheric water, it forms carbonic acid, which is absorbed as a nutrient by plants and trees.

**Circulating Fluidized Bed Combustion (CFBC):** Circulating fluidized bed combustion is a clean coal technology process that produces a mixture of coal and limestone in a
liquid state by vertically moving air. The process effectively removes sulfur and nitrogen from coal, thus reducing sulfur dioxide and nitrogen oxide from coal-burning emissions.

Chemical Cleaning: Any pre-combustion cleaning technique that creates a chemical reaction, which changes the molecular form of organic sulfur in order for the sulfur to be easily separated and removed.

Chiyoda Thoroughbred Scrubber: A flue gas desulphurization device that removes sulfur dioxide from the gas generated by coal combustion. The process combines this gas with a limestone, which reacts chemically with sulfur dioxide to absorb the gas.

Clean Coal Technologies (CCTs): Technologies developed to clean the coal burning emissions of sulfur dioxide, nitrogen oxide, carbon dioxide, air toxins and particulates, while enabling coal-burning facilities to meet or exceed emission standards.

Coal Resources: Total coal deposits, regardless of whether they can be mined or recovered. The United States may have as much as four trillion tons of coal resources, according to the U.S. Geological Survey.

Coal Seam: A deposit of coal.

Coal Washing (Physical): Removal of pyritic sulfur from coal through traditional coal pre-separation procedures of float/sink separation -- cleaning the coal with substances that enhance combustion efficiency and reduce potential pollutants. Because pyrite is much heavier than coal, washing coal enables coal particles to float in the pre-separation fluid, while pyritic sulfur particles sink to the bottom of the preparation container.

Demonstrated Reserves: Coal deposits that are potentially mineable on an economic basis with existing technology. The U.S. Department of Energy estimates that there are about 500 billion tons of demonstrated reserves in the United States.

Electrostatic Precipitator (ESP): An electrical device for removing small particles such as fly ash from combustion gases before release from a power plant’s stack.

EXILL: An export trading company that is a not-for-profit division of the Illinois World Trade Center. EXILL seeks foreign buyers for Illinois coal.

Flue Gas Desulphurization: A clean coal technology consisting of a device fitted between a power plant’s boiler and its smokestack. The device removes sulfur dioxide from flue gases flowing up the stack during the post-combustion stage of coal churning.

Fluidized Bed Combustion: A clean coal technology process that removes sulfur from coal during combustion. In a fluidized bed boiler, crushed coal and limestone are suspended in the boiler by an upward stream of hot air. The coal is burned in this ebullient, liquid-like mixture, hence the name "fluidized." As the coal burns, sulfur gases from coal combine with limestone to form a solid compound that is recovered with ash.
**Fly Ash:** The finely divided, inert particles of ash in flue gases arising from the combustion of fuel.

**Gas Reburning-Sorbent Injection (GR-SI):** A coal-fired boiler can burn coal with a gas reburning-sorbent injection clean coal technology to remove 60% of nitrogen oxide and 50% of sulfur dioxide from emissions. The process uses a hydrated lime sorbent to absorb noxious sulfur dioxide. Natural gas is mixed with recirculated flue gas to reduce nitrogen oxide emissions.

**High Sulfur:** Coal that naturally contains a large amount of sulfur that converts into sulfur dioxide upon burning.

**In-Duct Injection:** In clean coal technology known as flue gas desulphurization, in-duct injection is the introduction of a calcium-based sorbent into the flue stream between a boiler unit’s air preheater and its electrostatic precipitator, thereby removing sulfur dioxide and producing a dry, environmentally safe solid waste.

**Lignite:** The softest coal with the highest moisture content. It is being used more and more for generating electricity in certain areas of the country and for conversion to synthetic gas.

**Liquefaction:** Converting coal into synthetic liquid fuel similar in nature to crude oil and/or refined products such as gasoline.

**Micronized Coal:** Coal can be micronized by pulverizing it to the consistency of talcum powder. Micronized coal can be combined with micronized limestone to capture sulfur dioxide emissions when coal is burned. Nitrogen oxide emissions can also be reduced through this clean coal technology process.

**National Acid Precipitation Assessment Program (NAPAP):** A 10-year, $570 million federal effort that investigated and assessed the acid rain phenomenon from 1980 to 1990.

**Nitrogen Oxide Emissions/Nitric Acid:** As coal is burned, nitrogen oxide is released. The nitrogen oxide combines with atmospheric water and forms nitric acid. Nitric acid is a natural fertilizer for plants and trees.

**Partial Oxidation:** Fuel reforming reaction where the fuel is partially oxidized to carbon monoxide and hydrogen rather than fully oxidized to carbon dioxide and water. This is accomplished by injecting air with the fuel stream prior to the reformer. The advantage of partial oxidation over steam reforming of the fuel is that it is an exothermic reaction rather than an endothermic reaction and, therefore, generates its own heat.

**Physical Cleaning:** Any pre-combustion coal cleaning method involving the grinding of coal into powder particles to remove pyritic sulfur.
Pre-Combustion Cleaning: Coal is cleaned by removing sulfur and mineral matter before combustion to reduce the emission of sulfur dioxide from combustion gases.

Post-Combustion Cleaning: Cleaning coal emissions after combustion between the boiler and the smokestack.

Preparation Plant: A facility for crushing, sizing and washing coal to prepare it for use by a particular customer.

Pressurized Fluidized Bed Combustion: A clean coal technology that is similar to atmospheric fluidized bed combustion (AFBC), except the boiler is pressurized up to 16 times the atmospheric pressure. Sulfur dioxide emissions are reduced 95% and nitrogen oxide is reduced moderately.

Ranks of Coal: Classification of coal by degree of hardness, moisture and heat content. Ranks of coal include anthracite, bituminous coal, sub-bituminous coal and lignite.

RDF: Refuse derived fuel

Renewable Energy: Renewable energy includes solar power, wind, wave and tide, and hydroelectricity. Solid renewable energy sources consist of energy crops, other biomass, wood, straw and waste, whereas gaseous renewables consist of landfill gas and sewage waste.

Scrubber: Any of several forms of chemical/physical devices that operate to remove sulfur compounds formed during coal combustion. These devices combine the sulfur in gaseous emissions with another chemical medium to form inert "sludge," which is removed for disposal or sold as a by-product.

Slagging Combustors: A form of furnace sorbent injection that involves a slagging combustor chamber operating at a very high temperature, which causes the mineral matter in coal to melt into “slag” form.

Sorbent: A sulfur-absorbing substance or material.

Steam Coal: Coal used in power plant and industrial steam boilers to produce electricity; generally lower in Btu content than metallurgical coal.

Sub-Bituminous Coal: A coal with a heating value between bituminous and lignite with low-fixed carbon and high percentages of volatile matter and moisture. Anthracite has the highest Btu content followed by bituminous coal, sub-bituminous coal and lignite.

Sulfur Dioxide Emission/Sulfuric Acid-Sulfate: Coal contains sulfur, which converts to gas upon burning. The sulfur dioxide gas combines with atmospheric water to form sulfuric acid/sulfate. Sulfate is a nutrient for trees and plants; however, in remote areas more sulfur is emitted than is needed by plants.
**Synfuel:** Synthetic gas or synthetic oil. Fuel that is artificially made as contrasted to that which is found in nature. Synthetic gas made from coal is considered to be more economical and easier to produce than synthetic oil. When natural gas supplies in the earth are being depleted, it is expected that synthetic gas will be able to be used widely as a substitute fuel.

**Syngas:** Synthetic gas made from coal.

**Town Gas:** Town gas, also known as coal gas, is the gaseous by-product of the partial combustion of coal to make coke. The semi-liquid by-product produced process is known as coal tar. The gas is a mixture of hydrogen and methane, with small amounts of carbon monoxide and carbon dioxide.

**Turbine:** A device used in the generation of electricity. It has a shaft with blades at one end and electromagnets at the other. Water, steam, or some other energy source pushes the blades, which make the shaft and the magnets spin very fast. The magnet end is surrounded by heavy coils of copper wire, and the spinning magnets cause electrons in the wire to begin to move, creating electricity.

**Turbine Generator:** The combination of a turbine and a generator working together to produce power.

**Watt:** A unit of measure of electric power at a point in time, as capacity or demand.