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CLEAN COAL TECHNOLOGY

The New Coal Era

U.S. DEPARTMENT OF ENERGY
ASSISTANT SECRETARY FOR FOSSIL ENERGY
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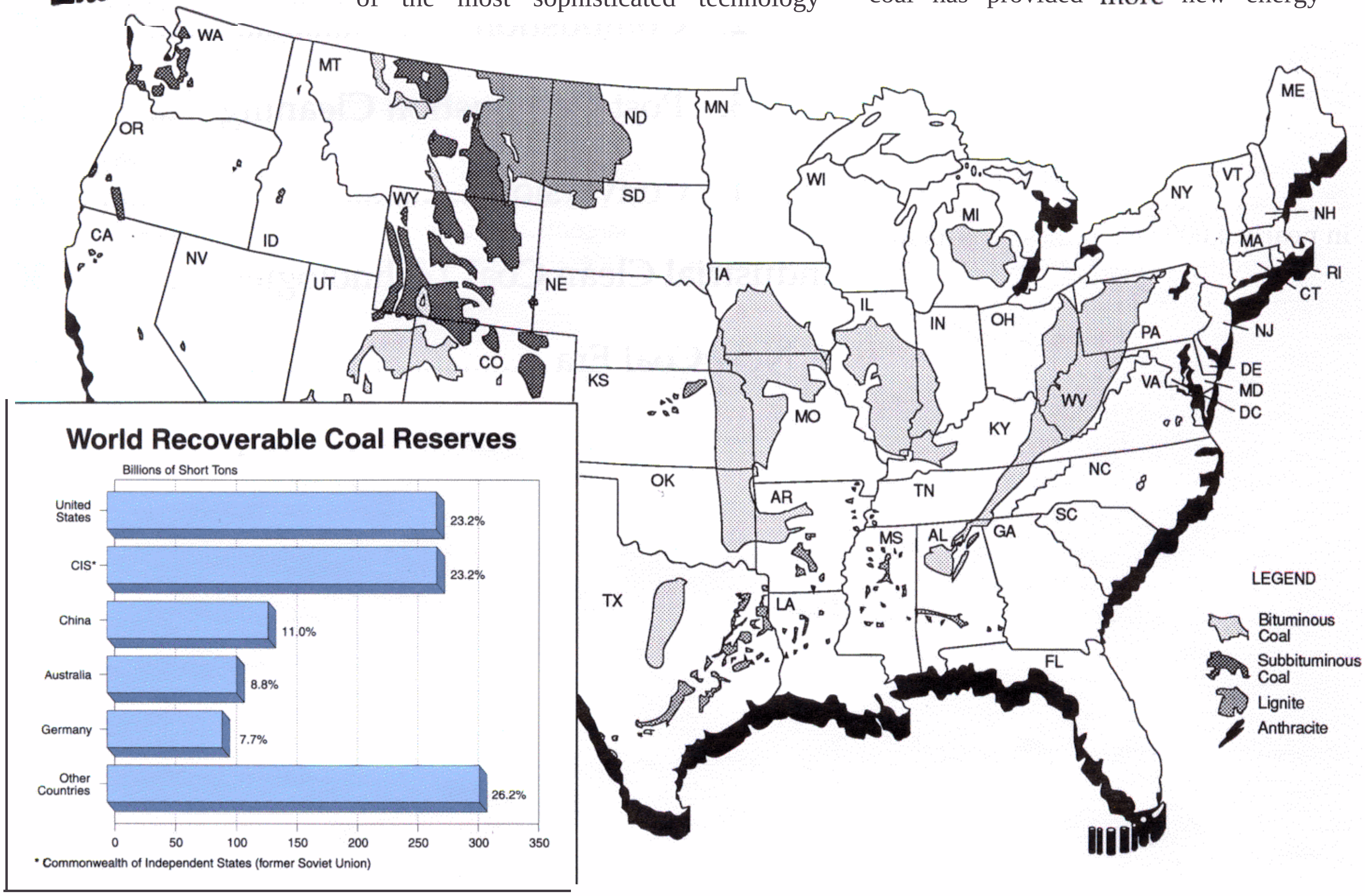
Introduction

The term "clean coal technology" entered the energy vocabulary in the 1980s. It describes a new generation of advanced coal technology, environmentally cleaner and in many cases more efficient and less costly than conventional coal-burning processes. These new power generating and pollution control concepts are the products of years of research and development in hundreds of government and private laboratories throughout the world. Their emergence in the 1980s is bringing about a new coal age-one that not only responds to past problems with some of the most sophisticated technology available in the world today but offers a bright future for coal as well.

Coal is the nation's most plentiful fossil fuel. One quarter of all the world's known coal lies within U.S. borders. Coal deposits can be found beneath 38 of the 50 states. More than 50 billion tons of coal have been produced in the U.S. since the first commercial mine was opened more than 200 years ago. Even so, at present rates of consumption, remaining reserves could power the U.S. well into the 22nd century.

Coal is used in all 50 states and the District of Columbia. Since 1973, coal has provided more new energy



tor the U.S. than any other fuel. A fourth of all primary energy consumed by the U.S. comes from coal. More than half of the electricity used by American consumers is produced trom coal-burning power plants. Per capita, Americans use 19 pound:, ot coal per day, primarily in the form ot electricity. Greater coal use by U.S. electric power plants has saved the equivalent of nearly 3.2 million barrels of oil daily since 1973.

Coal also is an energy bargain. Even with the sharp decline in world oil and gas prices in the mid-1980s, coal has remained the least expensive fossil fuel in the U.S. This is one reason why utilities expect to continue using coal to generate half or more of the U.S.'s electricity through at least 2030.

To meet the current demand for coal, more than 100,000 persons work in nearly 4,000 U.S. mines, producing a commodity valued at more than $20 billion per year. Most of the coal is used domestically, but part of it is exported. Coal exports, valued at about $4 billion per year, help the nation's balance of payments.

In the future, coal can help the economies of this country and our trading partners grow, creating new jobs and economic opportunities-if if can be used without endangering the Earth's fragile ecology.

The new suite of advanced, clean coal technologies will help achieve that objective. They will ensure that the U.S. can continue using its most abundant energy resource while maintaining a commitment to a clean, healthy environment.

How Coal was Formed

Coal haditsoriginsasancientplants that grew in swamps millions of years ago. Geological processes working over vast spans of time compressed and altered the decaying plants, increasing the percentage of carbon present and thus producing different ranks of coal: lignite (the softest of coals), subbituminous, bituminous, and anthracite (the hardest).

Coal in the eastern U.S. was formed mainly during the Carboniferous period of the Earth's history, 280 million to 320 million years ago. Coal in the western U.S. is almost all of Cretaceous and Tertiary ages, less than 140 million years old.

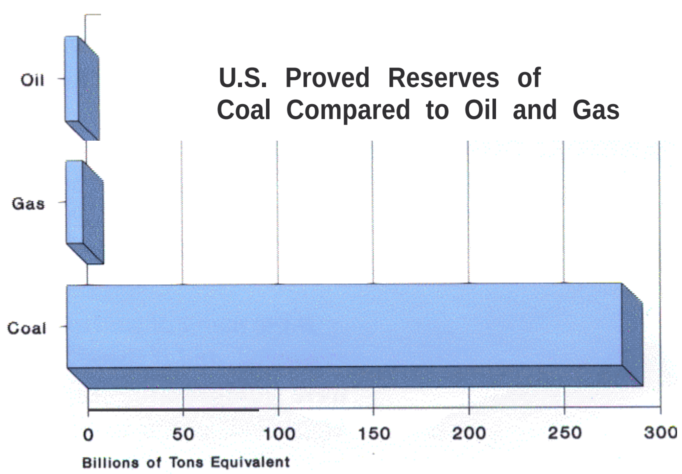
Along with carbon, scattered atoms of hydrogen, oxygen, nitrogen, and sulfur also are present in coal. In fact, coal contains traces of virtually every mineral that exists on Earth today.

Coal-bearing rocks underlie 458,600 square miles of the U.S., about 13% of the total land area.

Coal seams in the U.S. range in thickness from less than an inch to more than 100 feet. Geologists estimate that 3 to 10 feet of compacted plant matter accumulated to form each foot of coal. The average thickness is a little more than 4 feet in the Appalachian region, about 6 feet in the midwestern coal fields, and more than 30 feet in the West.

The energy in coal ranges from an average of 6,500 British thermal units (Btu) per pound for lignite to about 15,000 Btu per pound for some bituminous coals.

Using an average of 11,000 Btu per pound, a ton of coal contains the same energy as 22,000 cubic feet of natural gas, 158 gallons of distillate fuel oil, or one cord of seasoned hardwood.



The Clean Coal Technology Program

The Clean Coal Technology Program is a government and industry cofunded effort to demonstrate a new generation of innovative coal processes in a series of full-scale "showcase" facilities built across the country.

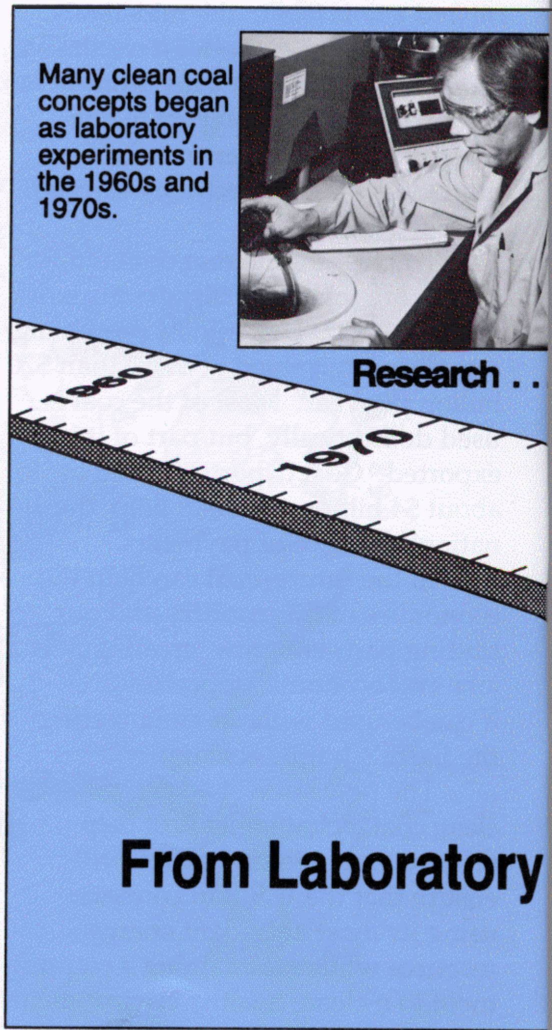
Begun in 1986 and expanded in 1987, the program is expected to finance more than $6.8 billion of projects. Nearly two-thirds of the funding will come from the private sector, well above the 50 percent industry co-funding expected when the program began.

The original recommendation for a multi-billion dollar clean coal demonstration program came from the U.S. and Canadian Special Envoys on Acid Rain. Envoys Drew Lewis of the U.S. and William Davis of Canada were appointed in 1985 by their respective governments to study ways of resolving concern:, between the two nations over the transboundary problem of acid rain.

In January 1986, Special Envoys Lewis and Davis presented their recommendations. Included was the call for a 5-year, $5-billion program in the U.S. to demonstrate, at commercial scale, innovative clean coal technologies that were beginning to emerge from research programs both in the U.S. and elsewhere in the world. As the Envoys said:

> *If the menu of control options was expanded, and if the new options were significantly cheaper, yet highly efficient, it would be easier to formulate an acid rain control plan that would have broader public appeal.*

Moreover, the Envoys said, demonstration of innovative control technologies should lead to some near-term reductions in the emissions associated with acid rain, namely sulfur dioxide (SO,) and nitrogen oxides (NO_x) (see page 6). Because the technology demonstration program would be part of a long-term response to the transboundary acid rain problem, the Envoys recommended that prospective projects be evaluated according to several criteria:



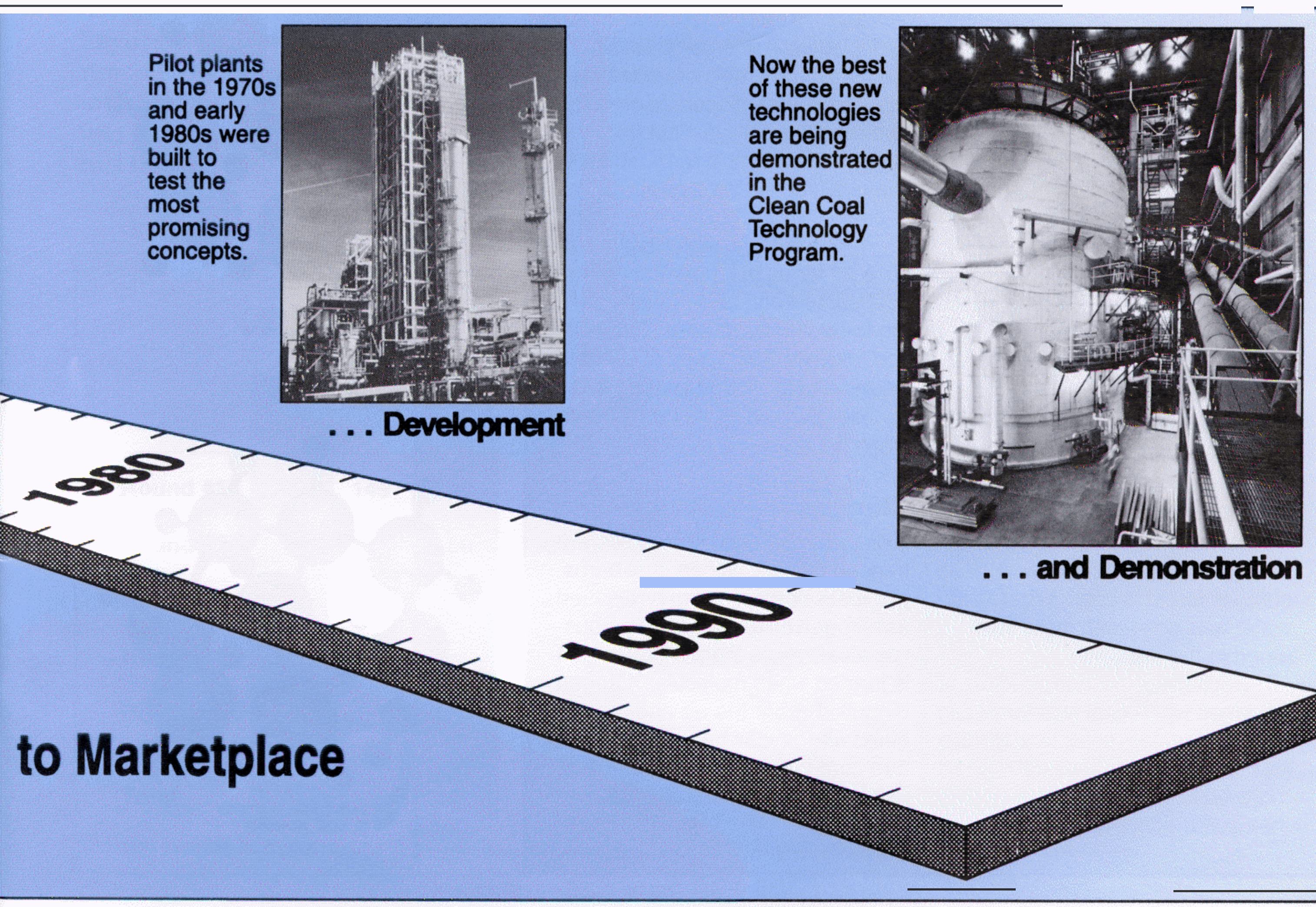
- *The federal government should cofund projects that have the potential for the largest emission reductions, measured as a percentage of SO_2 or NO_x removed;*

- *Among projects with similar potential, government funding should go to those that reduce emissions at the cheapest cost per ton;*

- *More consideration should be given to projects that demonstrate retrofit technologies applicable to the largest number of existing sources, especially sources that, because of their size and location, contribute to transboundary air pollution.*

- *Special consideration should be given to technologies that can be applied to facilities currently dependent on the use of high-sulfur coal.*

Clean coal technologies are today becoming commercially ready after as much as 20 years of laboratory research and smaller scale engineering development.



While the Special Envoys were carrying out their year-long study, the U.S. Congress also was examining the potential for clean coal technologies. On December 19, 1985, Congress set aside nearly $400 million for the government's share of funds for "constructing and operating facilities to demonstrate the feasibility of their future clean coal commercial application" (Public Law No. 99-190). Congress directed the Department of Energy (DOE) to run a competition to select suitable projects to meet this objective. The competition was to be open to all coals in all market applications. DOE carried out the competition in 1986.

SO_x and NO,-The Bane of Coal

Coal, once America's preeminent energy source, was deposed in the mid 20th century by cleaner, more manageable fuels.

Clean coal technologies offer a way to remove the environmental objections to coal use. They reduce two main pollutants released when coal burns-sulfur and nitrogen.

Sulfur

The sulfur in coal is the legacy of mineral deposits in seawater. Trapped inland by the upheaval of land masses, the seawater formed vegetation-rich, primordial bogs that eventually evaporated, leaving behind coal deposits.

Wherefresh waterwaspresent during the "coalification" period, less sulfur is found in coal. Where saltwater was dominant, more sulfur is found in the deposits.

Because of the land structure at the times when coal was formed in the U.S., western coals tend to have less sulfur and midwestern coals more sulfur; eastern coals vary in their sulfur contents.

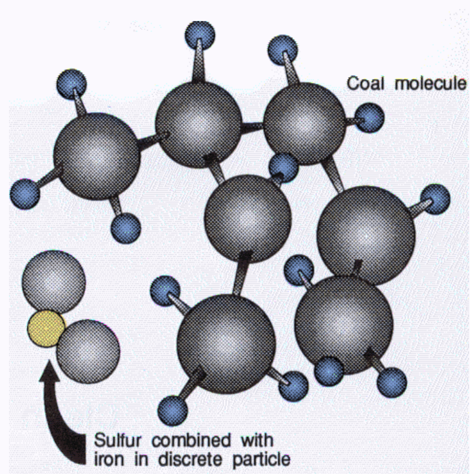
Sulfurexistsincoalintwoforms: *pyritic sulfur* and *organic sulfur.* In the pyritic form, sulfur is combined with iron in finely dispersed particles that are physically distinct from the coal. In the organic form, sulfur is chemicallyboundtothecarbonatoms of coal.

In some coals, pyriticsulfurcan account for as much as 70% of the total sulfur content; in other coals, organicsulfurdominates. Combustion releases both types of sulfur in a reaction with air that creates sulfur dioxide (SO,), or as it is sometimes known, SO_x.

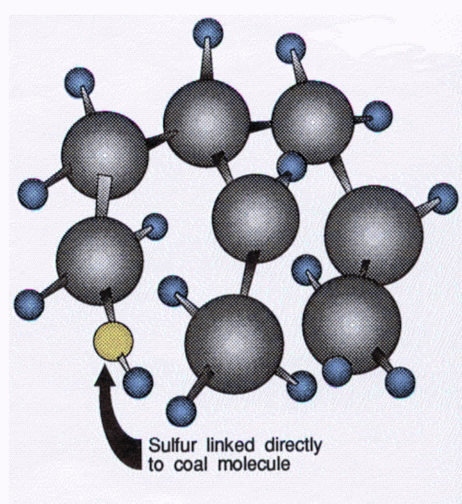
Nitrogen

Like sulfur, nitrogen molecules are trapped in coal. When coal burns, this *fuel-boundnitrogen* is released as nitrogen oxides (NO_x). Combustion also creates *thermal* NO_x which is formed when molecular nitrogen is "pulled" from the air and recombined with oxygen by high-temperature combustion, typically 3,000 °F or more. Most NO, is produced thermally.

Pyritic Sulfur



Organic Sulfur



The $400-million competition conducted under congressional direction became Round #1 of the Clean Coal Technology Program.

On March 18, 1987, President Reagan issued a directive to expand the program to a much larger effort one that ultimately would encompass five rounds of competition and reflect an expanding set of national environmental priorities.

Round #2, run in 1988, was the first competition to be carried out specifically under the Special Envoys' guidelines. Round #3, run in 1989, expanded eligibility to projects that could process coal into new, environmentally cleaner fuel forms.

Rounds #4 and #5 broadened the program even more. Greater emphasis was placed on even cleaner and more efficient technologies. DOE encouraged industrial sponsors to demonstrate very highly advanced systems that would be able to comply with the more stringent air quality standards to take effect in the 21st century (see pages 9-10). Not only will these new systems virtually eliminate acid rain pollutants, their high efficiencies will reduce the release of carbon dioxide (a "greenhouse gas," see page 34).

Round #4 was run in 1991. Round #5 was completed in 1993

"We are setting the course for coal's future. We are moving forward into the 21st century realizing that coal will continue to play a pivotal role in meeting the demand for electricity in the U.S. and abroad."
-Hazel O'Leary
Secretary of Energy

Clean Coal Technology Program Funding

Fiscal Years ($ Million)

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	Totals
Round #1	99	149	149									397
Round #2			50	190	133	197						570
Round #3					414	154						566
Round #4						35	315	0	100	100	50	600
Round #5							100	0'	150	250	100	600
Total	99	149	199	190	547	386	415	0	250	350	150	2.735

'Funds available from prior year

Special Envoys' Program (1988–1996)

The New Technology of Coal

Most advances in technology used today to produce energy from coal were made in the 1950s and 1960s. This technology is approaching the limits of its effectiveness.

Until recently coal-burning processes evolved principally to boost efficiency and increase capacity.

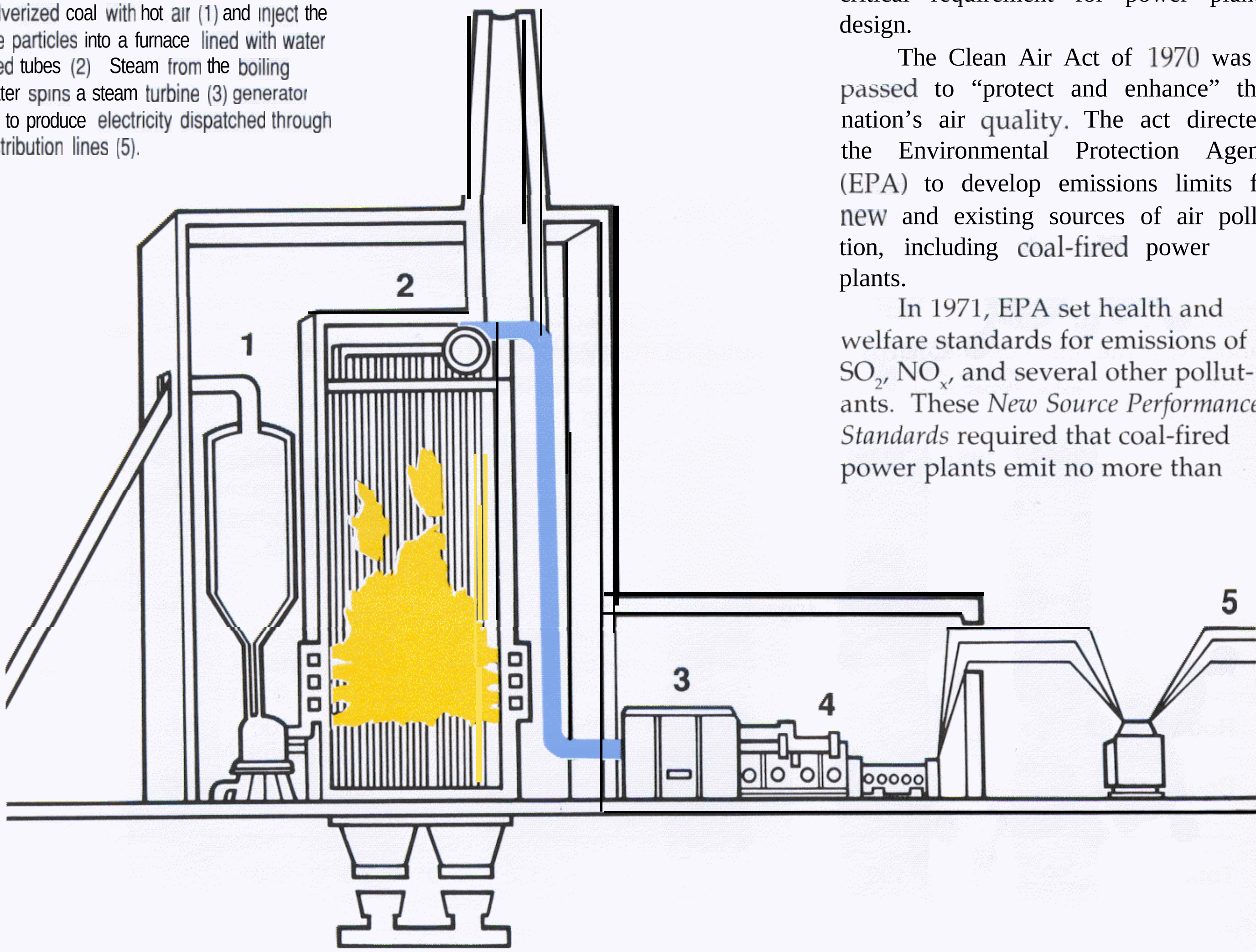
The first coal-fired power plants in the late 1800s tapped only 5% or less of the energy in coal. By the late 1960s, coal-burning power plants were attaining efficiencies approaching 35%. At the same time, boiler sizes increased from SO kilowatts (a kilowatt is 1,000 watts of electricity) to 1,200 megawatts (a megawatt is one million watts of electricity).

Today coal-burning technology of the 1950s and 1960s is approaching its practical limits of efficiency and costs. At the same time, environmental performance has become a critical requirement for power plant design.

The Clean Air Act of 1970 was passed to "protect and enhance" the nation's air quality. The act directed the Environmental Protection Agency (EPA) to develop emissions limits for new and existing sources of air pollution, including coal-fired power plants.

In 1971, EPA set health and welfare standards for emissions of SO_2, NO_x, and several other pollutants. These *New Source Performance Standards* required that coal-fired power plants emit no more than

To generate electricity most coal plants mix pulverized coal with hot air (1) and inject the fine particles into a furnace lined with water filled tubes (2) Steam from the boiling water spins a steam turbine (3) generator (4) to produce electricity dispatched through distribution lines (5).



1.2 pounds of SO_2 per million Btu of coal consumed. Many utilities were able to meet the standard by burning low-sulfur coal.

In 1977, Congress amended the act, retaining the original emissions cap on SO, but adding a further requirement that all plants built or altered after September 18, 1978, reduce SO_2 emissions by 70% to 90% from the levels that would be emitted had no sulfur controls been installed.

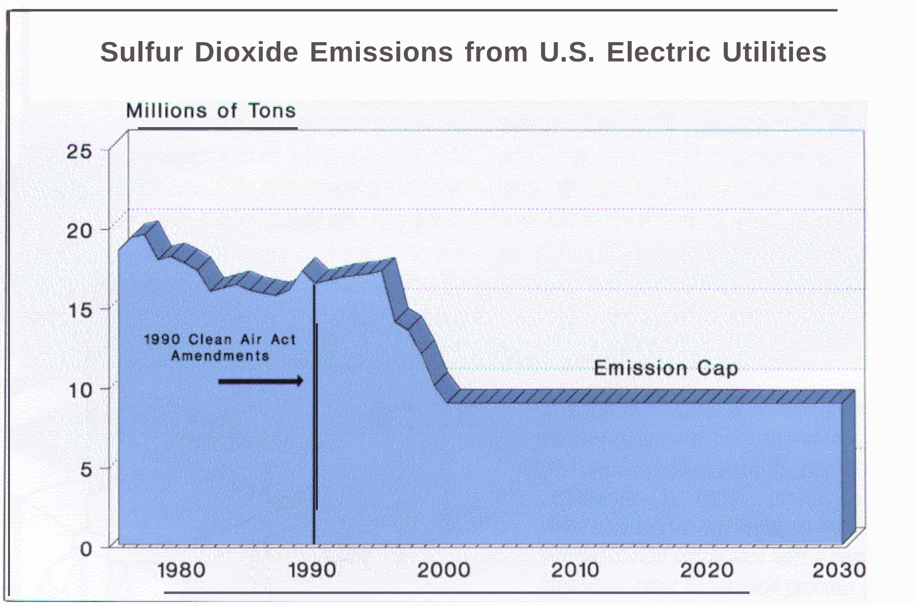
The Clean Air Act and its 1977 amendments created, in effect, two major categories of coal-burning power plants in the U.S.: (1) those built before 1978 which typically have little, if any, pollution control equipment (except, in some cases, devices that capture small particles of ash called *particulates*) and (2) those built after 1978 which are equipped with *flue gas scrubbers* (until recently the scrubber was the only commercial technology capable of achieving the 70% to 90% SO, reduction standard).

The nation's clean air laws were tightened substantially in 1990 when Congress again amended the 1970 Clean Air Act. The amendments constituted the most sweeping changes in environmental legislation since the original Act, with provisions to reduce releases of virtually every airborne pollutant from smog-causing automobile emissions to toxic pollutants from factories and chemical plants. The acid rain provisions of the new legislation were among the most stringent. They affect almost every existing power generator in the U.S. and will influence the choice of fuel and technology for every new power plant to be built in this country in the forseeable future.

Under the new legislation, signed by President Bush on November 15, 1990, utilities will have to cut their sulfur dioxide emissions by 10 million tons from 1980 levels by the year 2000 (with a 4-year time extension if certain clean coal technologies are used). After that time, a nationwide utility SO_2 emission cap of 8.9 million tons per year will go into effect. All new power generators that burn fossil fuels after 2000 will have to stay within the SO, cap, either offsetting sulfur releases from new plants by cutting emissions at existing plants or by purchasing emission "credits" from utilities that have made greater-than-required SO, reductions.

The tightened emission standards will make ultra-clean technologies increasingly necessary. Particularly attractive will be those

The 1990 Clean Air Act Amendments imposed a permanent cap of 8.9 million tons per year on sulfur emissions from U.S electric utilities alter the year 2000.



The “Box on the Back End”

Until clean coal technologies emerged, the flue gas scrubber, developed in the 1960s, was the only commercial technology capable of achieving the 70% to 90% SO_2 reduction required under the 1977 Clean Air Act amendments.

Scrubbersareactuallycomplex chemical plants--separate gas processing facilities installed at the “back end” of a power plant leading to its smokestack.

As of 1988, 146 scrubbers have been installed at 82 of the 370 currentlyoperable U.S. coal-fired power plants. Installation and operational costs for these scrubbers currently exceed more than $17 billion.

There are two categories of conventional scrubbers-wet and dry. Both remove only SO_2; neither reduces NO_x emissions.

Wet Scrubber

Flue gases from the combustion of coal are sprayed with a slurry made up of water and an alkaline reagent, usually limestone. The SO_2 in the flue gas reacts chemically with the reagent to form calcium sulfite and calcium sulfate in the form of a wet sludge (having the consistency of toothpaste). Over its lifetime, a 500-megawatt coal-fired power plant will produce enough sludge to fill a 500-acre disposal pond to a depth of 40 feet (often creating a waste disposal problem).

Wet scrubbers are effective—removing 90% or more of the SO_2-but they are expensive to install, costing as much as $300 per kilowatt of capacity (or $150 million for atypical 500-megawatt plant). They consume 5% to 8% of a power plant’sthermal energytorunpumps, fans, and a flue gas reheat system, thereby reducing electricity output by 1% to 2% (a significant reduction for a utility). They require large amounts of water, typically 500 to 2,500 gallons per minute for a unit of 500 megawatts.

Dry Scrubber

In a dry scrubber, the reagent slurry (usually lime) is injected in a finely atomized form, which is why these devices are also known as spray dryers. The droplets evaporate in the hot gas, leaving only dry particles for collection as waste. Although simpler in concept than the wet scrubber, the dry scrubber has not been as successful on high-sulfurcoalduetotheincreasedamounts of expensive reagents required to reduce SO_2 by 90%

technologies that achieve extremely low pollution levels inherently as part of the power generating process rather than requiring expensive add-on cleanup equipment. Today, building a new, large coal-fired power plant will cost about $1.5 billion. Environmental controls account for more than 30% of the cost. Many of these controls must be added as separate facilities, raising the cost and complexity of the power plant and reducing its efficiency (because some of the plant’s power must be used to operate the controls).

Clean coal technology represents a fundamental change in coal-fired

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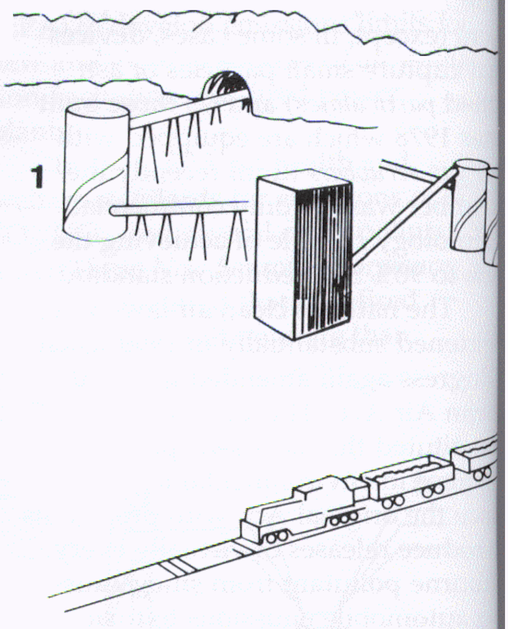


power plant technology. In many cases, emissions reductions and cost improvements are achieved concurrently, rather than being pitted against each other.

In terms of sulfur and nitrogen emissions, clean coal technologies have the potential to make a coal-fired plant as clean as an oil-fired plant and, in some cases, as clean as a plant that burns natural gas-the cleanest of all fossil fuels.

Moreover, unlike scrubbers, the new clean coal technologies do not achieve this high environmental performance at the expense of efficiency-in many cases, they actually boost a plant's performance at the same time they reduce pollution.

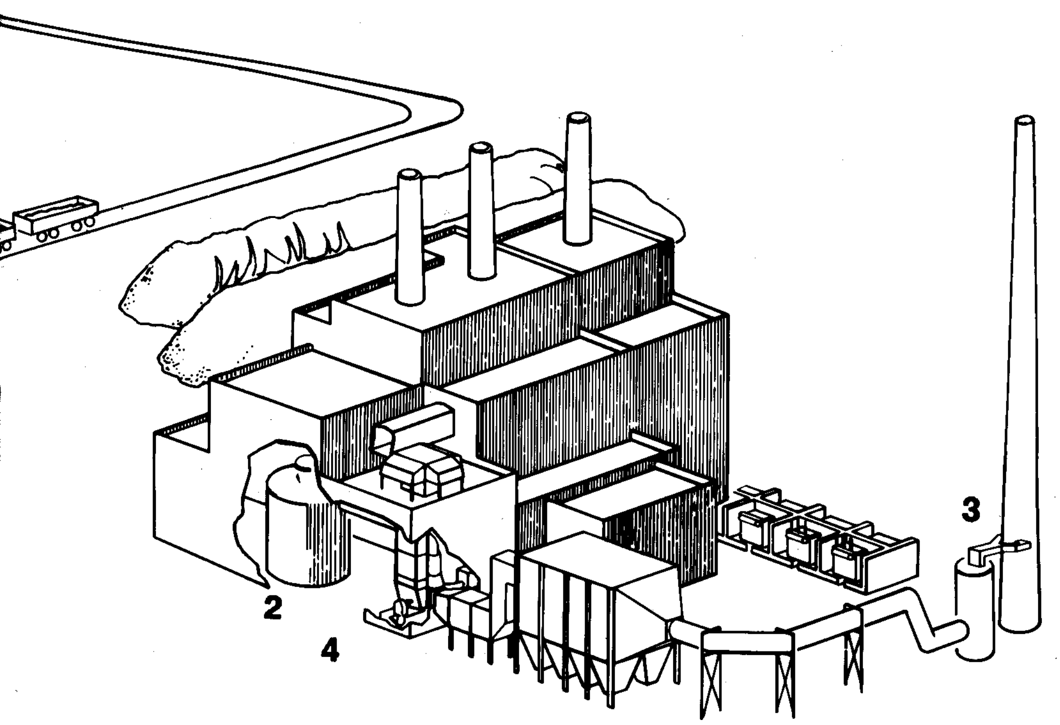
Clean coal technologies can be installed at any of three stages in the "fuel chain,"-the path coal follows from a mine to a power plant or factory-or in a fourth manner that departs from the traditional method of coal burning:

1. Precombustion. Sulfur and other impurities in coal are removed before it reaches the boiler.

2. Combustion. Pollutants inside the combustor or boiler are removed while the coal burns.

3. Post-combustion. Flue gases released from coal boilers are cleaned in the ductwork leading to the smokestack or in advanced versions of today's scrubbers.

4. Conversion. The combustion process is bypassed altogether; coal is changed into a gas or liquid that can be cleaned and used as a fuel.



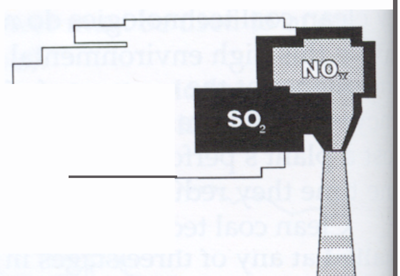
Coal can be cleaned at several points in its "fuel chain"-at the preparation plant (l), inside the combustor (2), or at the smokestack (3). Another category of clean coal technology replaces the traditional coal combustor with a coal gasifier or other conversion process (4).

1 Precombustion Cleaning

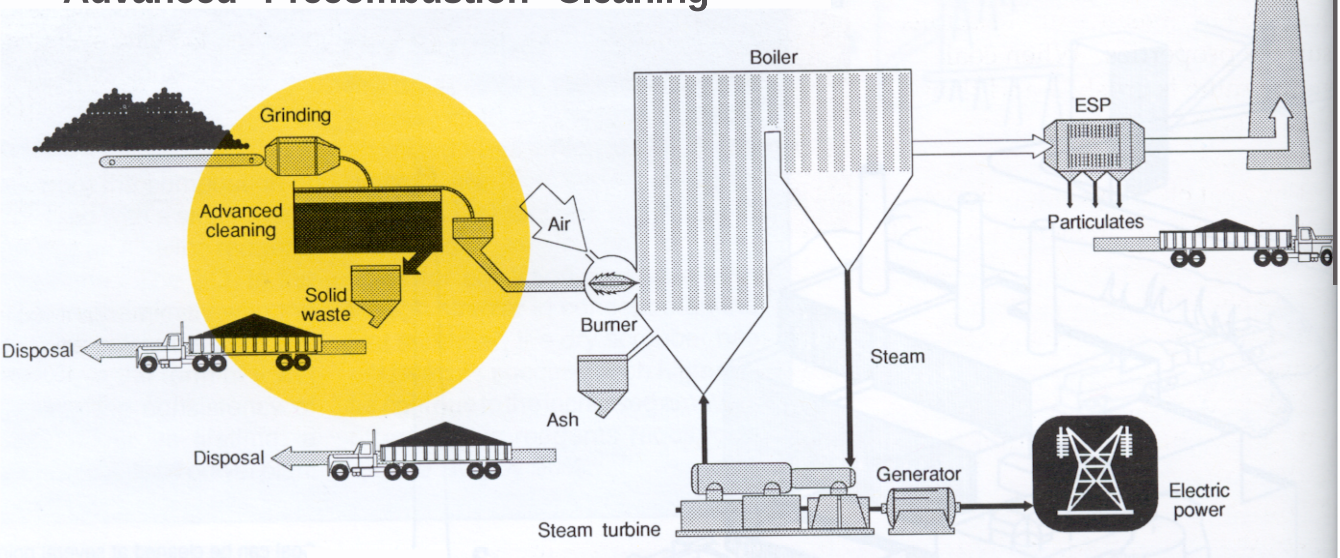
Years ago when coal was mined by pick and shovel, quality was maintained simply by hand-loading only the visibly clean coal. But productivity was low. Advances in technology retired the pickax, and hand loading gave way to mechanical loading. Productivity improved, but the amount of impurities in the mined coal increased. Also, many of the richest seams became depleted, especially in the eastern U.S., leaving deposits with higher levels of undesirable minerals. Some form of precombustion coal cleaning became necessary.

Today about 40% of the coal bound for U.S. utility boilers receives some cleaning before it is burned. Most commercial coal cleaning (sometimes called *coal beneficiation*) is done on eastern an midwestern bituminous coals at m than 500 preparation plants.

Most coal cleaning plants are operated by coal companies at the mine mouth The Electric Power Research Institute has estimated t wider use of coal cleaning process could reduce total SO, emissions b 10% nationwide. To achieve great



Advanced Precombustion Cleaning



SO_2 EMISSION	NO_x REDUCTION	COMPARED WITH CONVENTIONAL TECHNOLOGY* PLANT EFFICIENCY	POWER OUTPUT	PLANT LIFE	INCREMENTAL ELECTRICITY COST	CAPITAL COST
30-90%	No Change	Small Increase	No Change	Slight Extension	6-21 MILLS/KWH	Additional Fuel cost Only

* CONVENTIONAL COAL-FIRED ELECTRIC POWER PLANT

reductions, however, significant improvements will have to be made to coal cleaning technology.

Traditionally research to improve precombustion cleaning has concentrated on two major categories of cleaning technology: *physical cleaning* and *chemical cleaning*. Recently a new category, *biological cleaning*, has attracted interest as advances have been made in microbial and enzymatic techniques for removing sulfur from coal.

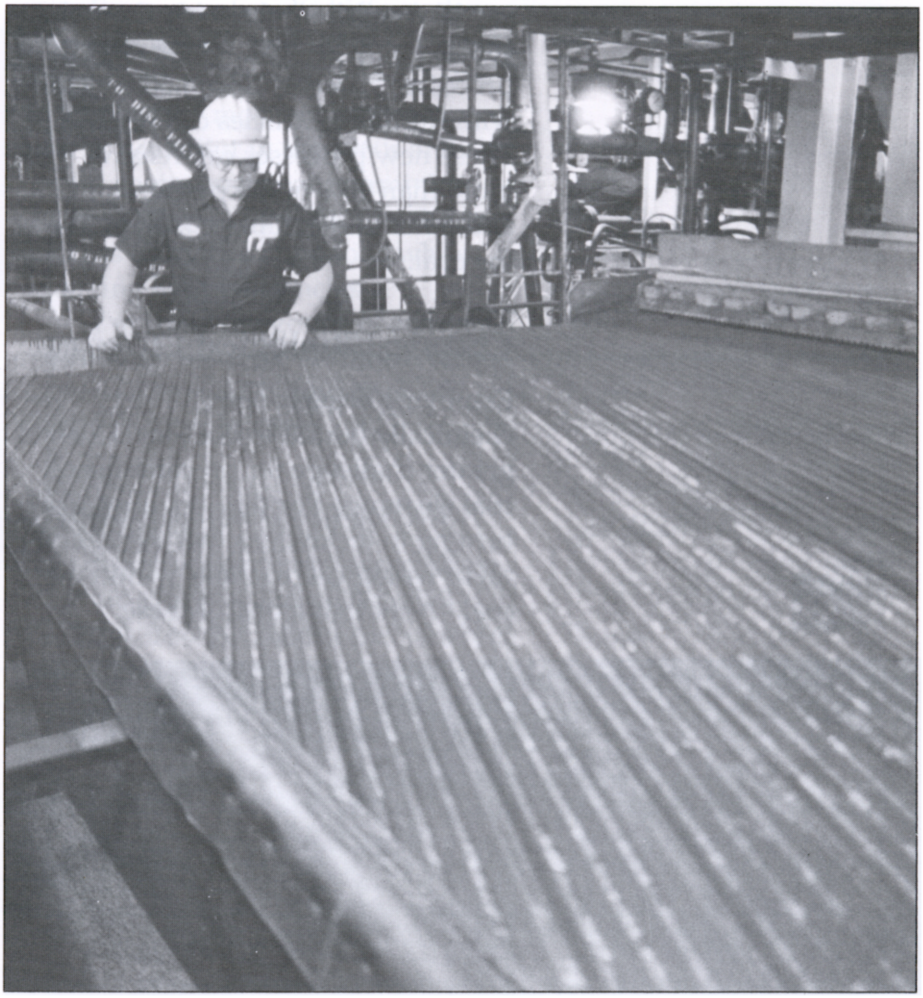
Physical Cleaning

Virtually all coal cleaning today is done with physical techniques, some of which have been used for more than a century. Physical cleaning typically separates undesirable matter from coal by relying on differences in densities or variations in surface properties. When coal from the mine is crushed and then washed, the heavier impurities are separated.

Physical cleaning can remove only matter that is physically distinct from the coal, such as small dirt particles, rocks, and *pyritic sulfur* (sulfur that is combined with iron particles; see page 6).

Physical cleaning cannot remove sulfur that is chemically combined with the coal (called *organic sulfur*). It also cannot remove nitrogen from the coal, another source of pollution.

Physical cleaning commercially in use today can remove 30% to 50% of the pyritic sulfur (or 10% to 30% of the total sulfur) in coal and about 60% of the ash-forming minerals.



About two-thirds of the coal mined in the eastern U.S. is washed to remove some of the impurities. For every 100 tons of raw coal cleaned. about 30 tons of refuse are removed

Advanced physical cleaning techniques, several of which are expected to be demonstrated in the Clean Coal Technology Program, boost the cleaning effectiveness significantly.

In most cases, the new physical cleaning techniques achieve their increased effectiveness by first grinding the coal into much smaller sizes than is done commercially today. At fine sizes, coal takes on the consistency of talcum powder and more impurities can be freed from the coal. Once the coal is finely ground, a host of new processes specially designed to work with ultrafine particles can be used. These new processes can remove more than 90% of the pyritic sulfur and other undesirable minerals from the coal.

Chemical/Biological Cleaning

Removing organic sulfur that is chemically bound to the coal is a far greater challenge for precombustion coal cleaning. For this, scientists are turning to techniques that use chemical or biological reactions within the coal. Although many of these processes are still experimental, some could be ready for larger-scale demonstration by the late 1990s.

One chemical technique that has shown promise is *molten-caustic leaching*. In this method, coal is exposed to a hot, sodium- or potassium-based chemical. The chemical leaches sulfur and mineral matter from the coal.

Other advanced methods being studied modify the chemical characteristics of coal or coal char (char is a partially burned form of coal) in a way that makes the coal more receptive to cleaning techniques.

A new family of coal cleaning, *biological cleaning*, is being tested in the laboratory. Biological cleaning represents some of the most exotic, yet potentially rewarding efforts currently envisioned.

Researchers have identified naturally occurring bacteria that can desulfurize coal. Scientists are improving the sulfur-removing characteristics of these microbes, particularly their speed in "eating" organic sulfur. Other researchers are working with approaches that use fungi rather than bacteria. Still others are examining ways in which the sulfur-digesting enzyme is extracted from a bacterial organism and injected directly into the coal processing system to speed the biological reaction.

Chemical or biological coal cleaning appears to be capable of removing as much as 90% of the total sulfur (both pyritic and organic) in coal. Some chemical techniques also may remove 99% of the ash.

A Clean Coal Computer "Expert"

One of the Department of Energy's Clean Coal Technology projects will not develop new pollution control hardware. Instead it will produce software-a computerized "Coal Quality Expert" that will mimic human reasoning and problem solving.

Expert computer programs are relatively new, especially for desktop or personal computers. Such programs attempt to capture the knowledge of a human expert, such as an engineer, and make it available through a series of logic questions that can be programmed to draw a conclusion.

The Coal Quality Expert could help a utility choose the right precleaned coal for its boilers. The variety of new precombustion cleaning techniques being developed is likely to make it increasingly difficult for plant operators to choose among the various combinations of coal quality and costs. If they pick a low-cost, minimally cleaned coal, the plant could be plagued by higher pollution levels and frequent outages. If they pick a cleaner, more expensive coal, the consumer could face needlessly high electric bills. The Coal Quality Expert could help utilities make the optimum choice.

The software will be developed using data from a series of test burns of coals cleaned by different means and extensively analyzed. The software will be tested at 10 utility sites across the country to ensure its accuracy. If all goes as planned, the Coal Quality Expert could be ready for testing by 1992.

2 Combustion

Coal can also be cleaned while it burns-an advantage because no additional sulfur or nitrogen removal equipment is required.

In most of conventional coal combustion plants, raw coal is pulverized into particles small enough to form a combustible cloud and injected with hot air into burners along the lower portion of a hollow rectangular box called a steam boiler.

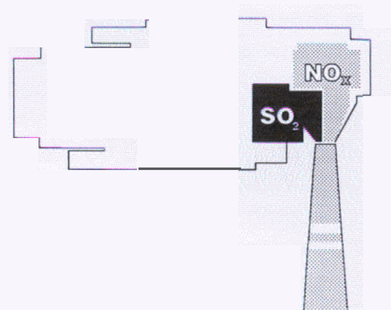
Coal burns in a long, luminous flame in the huge furnace cavity at temperatures of at least 2,700 “F. The heat is transferred to water-filled tubes typically welded into the sides of the boiler. Boiling water in the tubes creates steam that spins a turbine generator which produces electricity.

For must of coal’s history, the principal design goal for coal-burning boilers was higher efficiency, that is, extracting the most energy from a unit of coal. But in the 1960s and 19705, engineers began examining ways to alter the coal combustion process to reduce emissions while retaining high efficiencies.

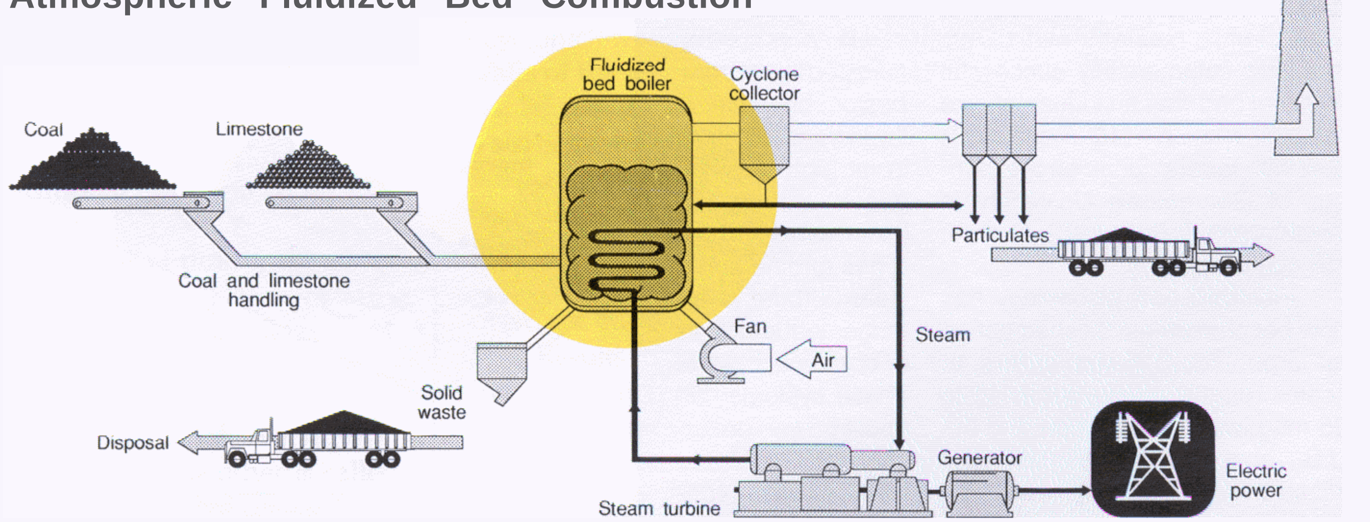
Two new categories of advanced technology resulted: (1) fluidized bed combustors and (2) advanced (slagging) combustors.

Fluidized Bed Combustors

In a fluidized bed combustor, rather than blowing a cloud of tiny coal particles into the combustor, crushed coal mixed with limestone is



Atmospheric Fluidized Bed Combustion



SO_2 REDUCTION	NO_x REDUCTION	EFFICIENCY	NEW PLANT CAPITAL COST	NEW PLANT ELECTRICITY COST	REPOWERED PLANT CAPITAL COST	REPOWERED PLANT INCREMENTAL ELECTRICITY COST	REPOWERED PLANT POWER OUTPUT	REPOWERED PLANT LIFE EXTENSION
90%	70%	35-36%	$1,200-1,400 PER KW	50-60 MILLS/KWH	$700-900 PER KW	12-17 MILLS/KWH	0-15% INCREASE	25-30 YEARS

Fluidized Bed Combustion

The fluidized bed was invented in the 1920s in Germany as a chemical processing technique. The turbulent mixing and close contact of materials within a fluidized bed were found to accelerate chemical reactions. Early systems were used for breaking down the dense components of crude oil (U.S. production of high-octane gasoline was aided by this technology during World War II). Later the concept was applied to roasting ore and incinerating industrial sludge.

A 500-kilowatt fluidized bed test plant built in Alexandria, Virginia, in 1965 probably could be called the "grandfather" of U.S. fluidized bed coal combustors. It provided much of the design data for a 30-megawatt prototype unit at the Monongahela Power Company in Rivesville, West Virginia, built in the mid-1970s. The first commercially successful fluidized bed was an industrial-size atmospheric unit (IO megawatts) built with federal funds on the campus of Georgetown University in Washington, D.C., in 1979. The unit still operates today.

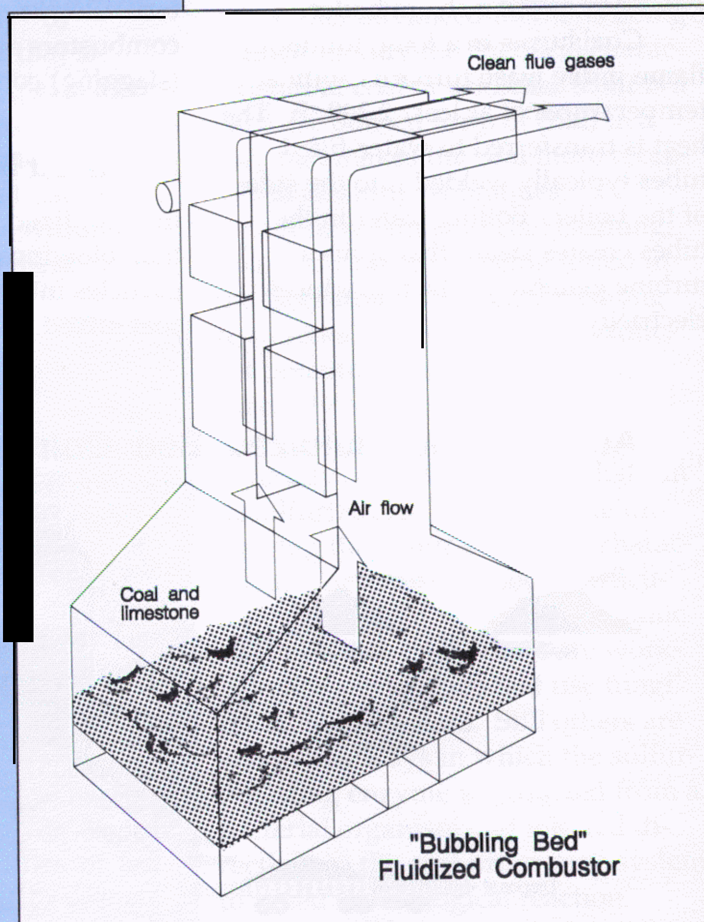
Fluidized bed technology has now become an established option for large, industrial size boilers, at scales roughly equivalent to 10 to 25 megawatts. In Europe and the U.S., about 300 atmospheric fluidized bed units supply heat to industrial processes, municipalities, oil producers for thermal recovery processes, and farms for hay drying.

Through private efforts and the Clean Coal Technology Program, fluidized bed technology is moving into the much larger 75- to 350-megawatt scales necessary for utility plants. Utility-scale fluidized bed plants are now in operation in Colorado, Minnesota, and Tennessee.

An *atmospheric fluidized bed combustor* performs roughly the same functions as a conventional boiler in driving a steam turbine, except with far fewer emissions. Two types are being developed: the *bubbling bed* and the *circulating bed.*

A pressurized fluidized bed combustor, because of the increased energy in its high-pressure gases exiting the boiler, can drive both a gas turbine and a steam turbine, an arrangement known as a *combined cycle.* These systems can boost power generating efficiencies to well above 40% (much greater man the 30% to 35% efficiencies of conventional coal-fired technology).

A "bubbling" fluidized bed is one category of this new clean-burning coal technology. In this combustor, coal particles tumble in a turbulent fashion, taking on some of the characteristics of a boiling, bubbling liquid.



suspended on jets of air. This "bed" of coal and limestone actually floats inside the boiler, tumbling in a manner that resembles a boiling liquid, hence the name "fluidized." As the coal burns, sulfur is released. The limestone acts like a chemical "sponge" to capture the sulfur before it can escape the boiler. More than 90% of the sulfur released from coal can be caught in this manner.

The sulfur-laden limestone forms a dry waste product. Some of the solid waste is removed with the bed ash through the bottom of the boiler. Smaller ash particles, or "fly ash," are carried out of the boiler and captured with dust collectors.

Also, because the tumbling motion of the coal enhances the burning process, combustion temperatures can be held to around 1,400 to 1,600 °F, or almost half the temperature of a conventional boiler. This is below the threshold where nitrogen pollutants form (see page 6). Thus, fluidized bed combustors can meet both SO, and NO_x standards without any additional pollution control equipment.

Two types of fluidized bed combustion are being demonstrated in the Clean Coal Technology Program. One is called atmospheric *fluidized* bed *combustion* because the process operates at normal atmospheric pressures; the other is called *pressurized fluidized bed combustion* because pressures inside the boiler are elevated 6 to 16 times higher than normal atmospheric pressure (see page 16).

Advanced Combustors

Advances have also been made in other types of combustors, again combining high combustion efficiency with pollutant removal.

Most of these new coal-burning technologies are based on the *"cyclone"* combustor concept. In a cyclone combustor, coal is burned in a separate chamber outside the furnace cavity. The hot combustion gases then pass into the boiler where the actual heat exchange takes place.

The advantage of a cyclone combustor is that the ash is kept out of the furnace cavity where it could collect on boiler tubes and lower heat transfer efficiency. To keep ash from being blown into the furnace, the combustion temperature is kept so hot that mineral impurities melt and form slag, hence the name *"slagging combustor."* A vortex of air (the "cyclone") forces the slag to the outer walls of the combustor where waste can be removed.

because of their high combustion temperatures, many older cyclone combustors produce high levels of NO_x. The Clean Coal Technology Program is demonstrating advanced combustors that overcome this drawback.

Results to date show that positioning air injection ports so that coal is burned in stages can reduce NO_x emissions by as much as 80%. Also, sulfur emissions can be lowered by injecting limestone into the combustor or boiler. To increase sulfur capture, this limestone--converted to SO_2-absorbing lime by the combustion heat-can be captured in a baghouse, reactivated, and injected with water into flue gases downstream of the boiler in a "spray dryer absorber."

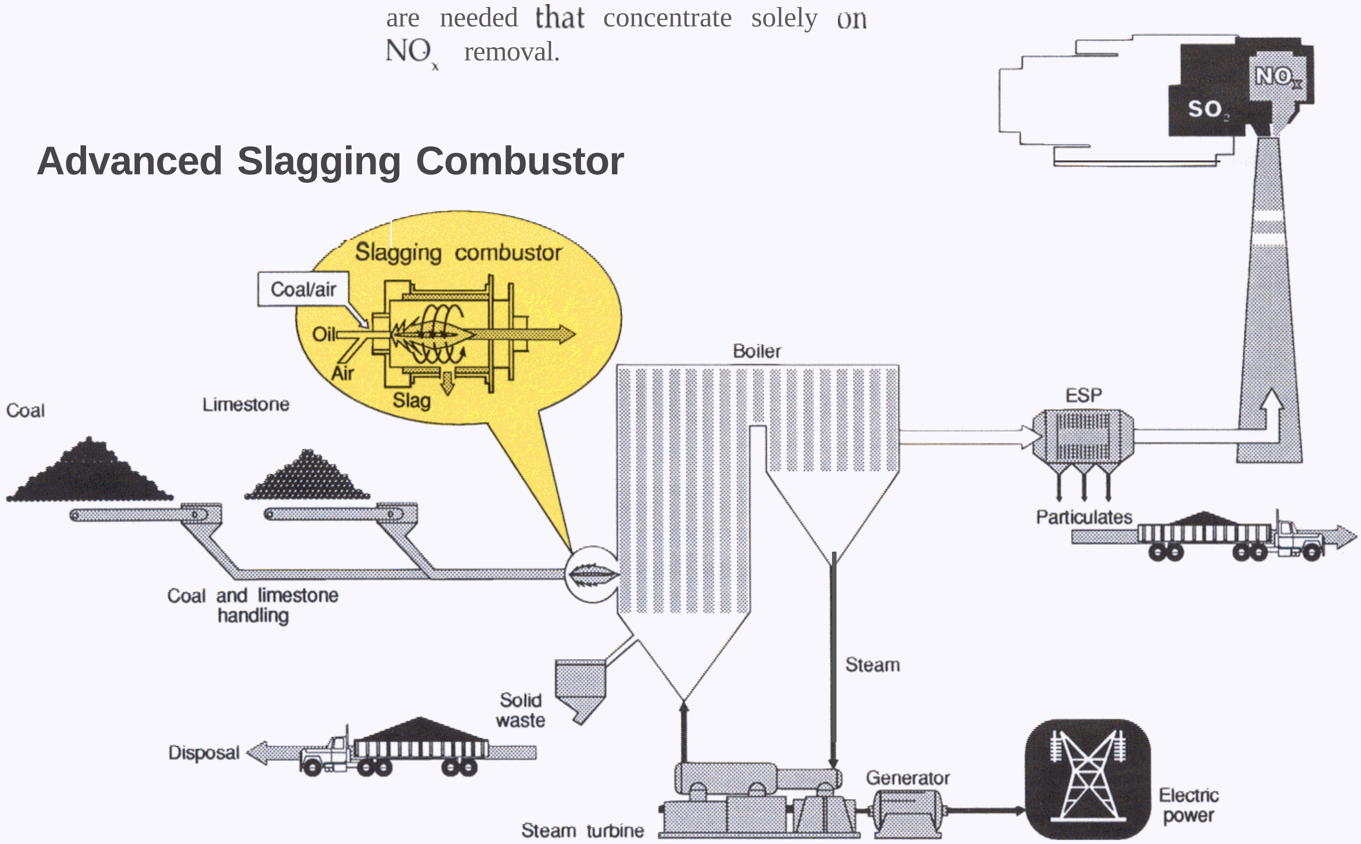
Advanced combustors being tested in the Clean Coal Technology Program could replace oil-fired units in both utility and industrial applications.

Nitrogen Oxide Controls

Some plants in the U.S. already have sulfur controls installed but may be faced with tightening NO_x standards. For these plants, new technologies are needed that concentrate solely on NO_x removal.

Lowering NO_x emissions has gained attention in recent years because nitrogen-based pollutants also have been implicated as a cause of acid rain and smog (when combined with other hydrocarbons and exposed to sunlight). Unlike sulfur emissions, which have declined substantially in the last 15 years, NO_x emissions have risen slightly. About half of all NO_x pollution comes from automobiles and other vehicles, but coal-burning power plants also add

Advanced Slagging Combustor



SO_2 EMISSION	NO_x REDUCTION	COMPARED WITH CONVENTIONAL TECHNOLOGY[1] PLANT EFFICIENCY	POWER OUTPUT	PLANT LIFE	INCREMENTAL ELECTRICITY COST	CAPITAL COST
50-90%	70-80%	Small increase	Small Increase	Slight Extension	1-2 MILLS/KWH	$50-60 PER KW

[1] CONVENTIONAL COAL-FIRED ELECTRIC POWER PLANT

to the problem. Power plants release about 25% of the total manmade NO_x emitted nationwide.

Most NO_x controls work by preventing formation of the pollutant inside the furnace (although post-combustion NO_x scrubbers have been tested more recently, see page 22).

To control NO_x, plant engineers can modify the combustion process to permit a more gradual mixing of fuel and air. This lowers flame temperature, reducing NO_x. They also can adjust the fuel mix so that only enough oxygen is present to support combustion and not enough to combine with nitrogen to form NO_x. Low-NO_x burners, for example, retard the conversion of nitrogen to NO_x by delaying the mixing of fuel and air in the burner zone. By keeping the primary combustion zone deficient in oxygen, NO_x formation can be cut by about 50%.

In other techniques, air ports are added in the furnace wall above the top row of burners to create a fuel-rich, low-NO_x combustion zone. While these techniques require less hardware changes than low-NO_x burners, they only reduce NO_x formation by 15% to 30%.

A variation of NO_x control also being tested in the Clean Coal Technology Program is *natural* gas *reburning*. A small amount of natural gas (10% to 20% of total fuel input) is injected above the normal combustion zone to form an oxygen-deficient zone (see box). Other reburning concepts use coal instead of natural gas.

Natural Gas as a Pollution Control

In the 1970s burning natural gas in a utility boiler was considered irresponsible-almost the same as burning imported oil. Gas supplies appeared to be diminishing rapidly, and the government passed laws restricting the use of gas in utility boilers. Buttoday, theattitudeabout natural gas has changed. As federal price controls were removed from gas, new supplies became available, and a gas surplus developed. Concerns over acid rain prompted new attention to gas, which burns cleanly and emits virtually no SO_2.

Two methods using natural gas to control pollutants have received the most attention-co-firing and *reburning.*

Co-firing, a commercially available technique, burns gas and coal simultaneously in the same boiler.

Typically the two fuels are not physically mixed. Different burners are used and often positioned at different heights within the boiler. The amount of SO_2 reduction is directly proportional to the amount of gas fired in place of coal; that is, if 10% of the fuel is natural gas, sulfur emissions will be roughly 10% less than if only coal were burned. Gas co-firing also reduces NO_x emissionsandcanmitigateashfoulingin the boiler.

Gas *reburning* is principally an NO_x control technique. C in the lower regions of a boiler to provide 80% to 90% of the total heat released. Natural gas is fired in the "reburn" region above the main combustion zone. Within the fuel-rich reburn region, hydrocarbon fragments from the gas will react with the nitric oxide produced in the main flame to form molecular nitrogen— the same form of nitrogen that exists naturally in the air. Secondary airisaddedabovetherebumregion to finish the combustion at a lower temperature, preventing NO_x from forming.

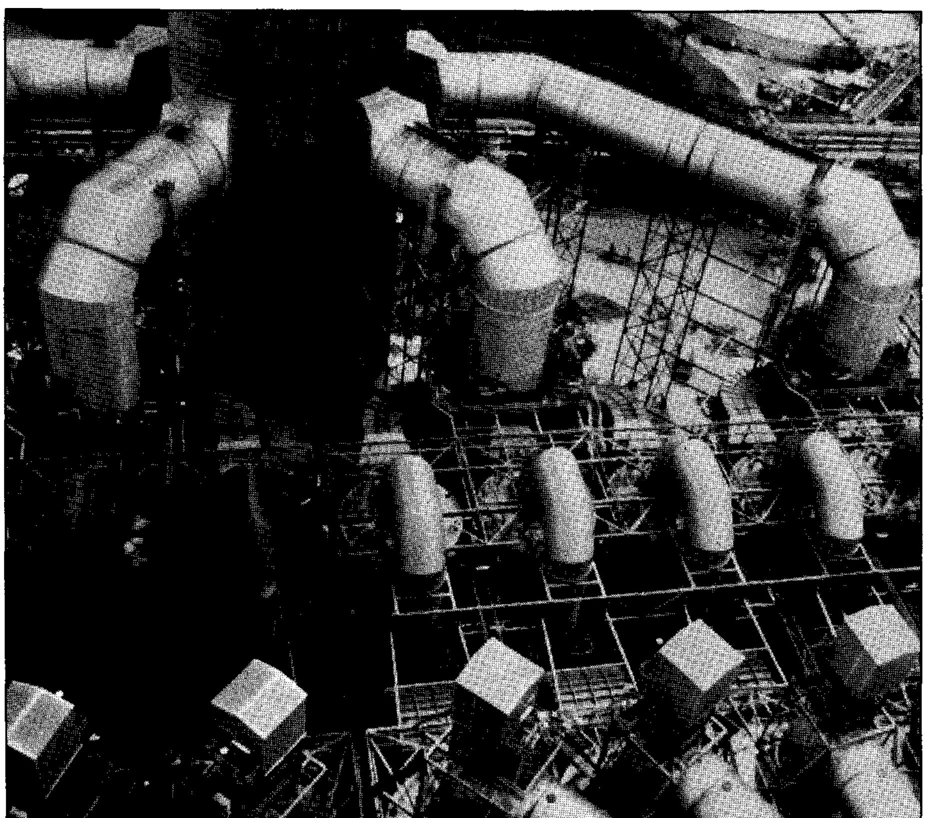
NO_x emissions from a gas reburning system are expected to be about 40% less than those from a unit firing solely coal.

The capital cost of retrofitting a natural gas reburn system on a 500-megawatt boiler is estimated to be around $12 per kilowatt, competitive with low-NO_x burners. Depending upon the boiler configuration and design requirements, costs could range from about $5 per kilowatt to $30 per kilowatt.

Because it works independently of the main combustion zone, gas reburning can be used with any boiler type, including cyclone, tangentially-fired orwall-fired. Tests in the Clean Coal Technology Program are showing that NO_x emissions can be reduced by more than 60%.

3 Post-Combustion Cleaning

Today's scrubbers are really complex chemical plants. They must handle huge volumes of sulfur-laden flue gas. For a 300-megawatt plant, a typical scrubber will process as much as one million cubic feet of flue gas per minute.



Until the emergence of clean coal technologies, post-combustion cleaning has been the principal method of meeting modern-day air quality standards. Although techniques are available today that remove as much as 90% of sulfur pollutants from the flue gases of burning coal, new methods for post-combustion cleaning offer significant improvements.

When the Clean Air Act was passed in 1970, methods for cleaning combustion gases were still in their infancy. Although the basic process for "scrubbing" flue gases was developed shortly after the turn of the century, the first scrubbers were not built until the 1930s—and these were in Great Britain. It was not until 1967 that a full-scale scrubber began operating in the U.S., in a coal-fired power plant owned by Union Electric Company of Missouri.

Early "wet" scrubbers were plagued by corrosion and plugging. As the technology matured, operational problems lessened. Yet, for nearly 90% of the scrubbers in the U.S. today, handling and disposing of the waste product-a wet, pasty sludge-remain expensive and complex problems. "Spray dryer" scrubbers that produce a dry product have been developed, but these have been most effective on plants burning lower sulfur coal.

Neither today's "wet" nor "dry" scrubber is capable of removing NO_x from the flue gas.

Innovations in post-combustion cleaning are being demonstrated in the Clean Coal Technology Program. Virtually all of these advanced techniques produce a less onerous waste product than conventional scrubbers. In most, the product is a dry powder which may have commercial value. Several new concepts capture only sulfur emissions; some, however, also remove NO_x and particulates.

Sulfur Dioxide Control

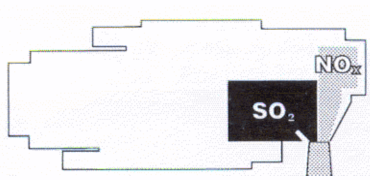
Advanced post-combustion SO, controls can be grouped according to where in the physical layout of the power plant each performs its sulfur-removing functions.

In-duct sorbent injection works inside the ductwork leading from the boiler to the smokestack. Sulfur absorbers (such as lime) are sprayed into the center of the duct. By carefully controlling the humidity of the flue gas and the spray pattern of the sorbent, 50% to 70% of the SO_2 can be removed. The reaction produces dry particles that can be collected downstream. Because a plant's existing ductwork is used, extensive new construction is not needed. In-duct injection could be attractive for retrofitting smaller, older plants that may not have enough space to install new scrubber systems.

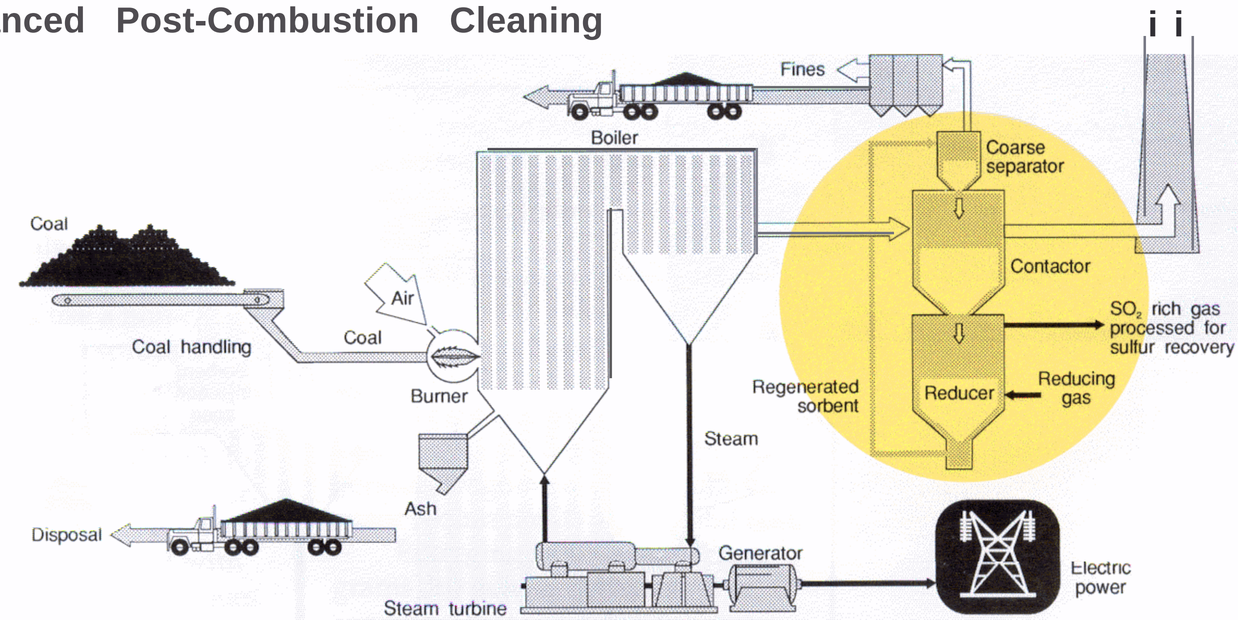
Advanced scrubbers, like their predecessors, place the flue gas processing facilities outside the main power plant. These innovative devices offer advantages such as (1) regenerating the sulfur-absorbing chemical, making the system more economical; (2) removing both SO_2 and NO_x; (3) producing an environmentally benign, dry waste product; or (4) streamlining operations by reducing or eliminating the need for reheating or backup modules.

Some improvements may use an addititve to boost sulfur capture. For example, adding adipic acid to the scrubbing solution may permit as much as 97% SO_2 removal, rather than the current 90% standard.

Other scrubber advancements a-e more elaborate. The Chiyoda Thoroughbred 121 (CT-1211 process is



Advanced Post-Combustion Cleaning



SO_2	NO_x	COMPARED WITH CONVENTIONAL TECHNOLOGY*			INCREMENTAL	CAPITAL
EMISSION REDUCTION		PLANT EFFICIENCY	POWER OUTPUT	PLANT LIFE	ELECTRICITY COST	COST
90%	High	Decrease	Small Decrease	NO Change	10-12 MILLS/KWH	$175-300 PER KW

* CONVENTIONAL COAL-FIRED ELECTRIC POWER PLANT

an example of a second-generation scrubber technology. It incorporates all of the necessary steps for SO_2 control-absorption, oxidation, neutralization, and crystalization-into a single vessel, a "jet bubbling reactor." The process reverses conventional scrubbing methods. Rather than spraying a sulfur-absorbing slurry into the flue gas, the flue gas is bubbled through the slurry. Using this technique, high levels of SO_2 can be removed without the scaling, plugging, and corrosion that often occurs with today's wet scrubbers.

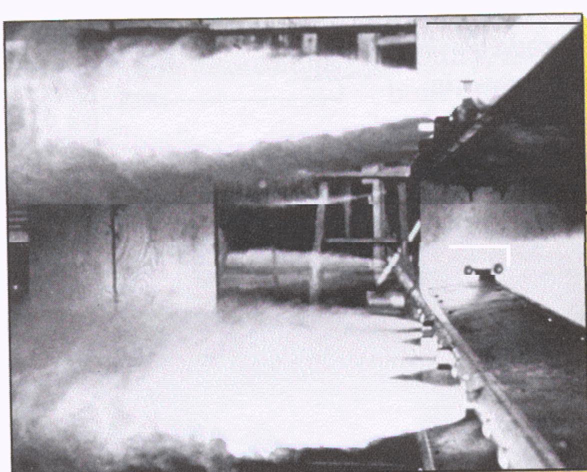
Other advanced concepts might include new chemical absorbers. One such device, developed by DOE, uses copper oxide which changes SO_2 into copper sulfate which in turn converts NO_x into nitrogen when combined which ammonia.

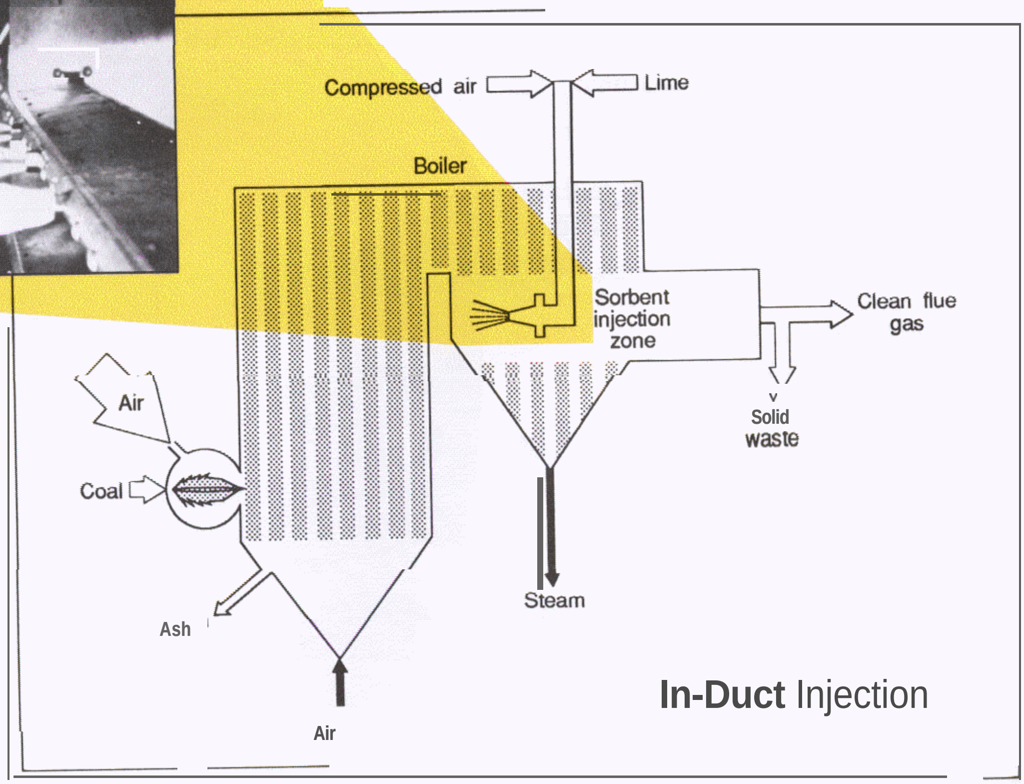
Nitrogen Oxide Controls

Recent innovations in treating flue gases make it possible to reduce NO_x in flue gases leaving the coal boiler (instead of modifying the combustor).

The most extensively developed concept is *selective catalytic reduction* (SCR). This technique is now being applied commercially in Japan and tested in the Federal Republic of Germany. Small-scale tests have

An alternative to a scrubber especially for some older plants, may be to install injection ports into the existing ductwork that carries flue gas from the boiler Sulfur absorbing limestone would be injected into the ductwork to clean the flue gases.





been conducted in the U.S., and the technology may be demonstrated in the Clean Coal Technology Program.

In an SCR system, ammonia is first mixed with flue gas and passed through a reaction chamber separate from the scrubber vessel. In the presence of a catalyst, NO_x is converted by the ammonia to molecular nitrogen and water. SCR systems are projected to reduce nitrogen emissions by 50% to 80%.

Unique problems arise when the technology is used with high-sulfur coal, however. The same catalysts that help break down NO_x also encourage sulfur dioxide to change into sulfur *trioxide*. Sulfur trioxide, in turn, combines with ammonia to form solid and liquid sulfates which can cause corrosion and plugging of downstream components. The Clean Coal Technology Program plans to test techniques to overcome the high-sulfur coal problem and provide better data on catalyst life.

Other post-combustion controls for NO_x emissions use a non-catalytic process. One method sprays a urea solution into the boiler's convective zones at carefully controlled temperatures. Urea combines with NO_x to form harmless nitrogen and water. Such systems can reduce NO_x by up to 30% and can be combined with other low-NO_x combustion techniques.

Other Clean Coal Technology projects remove more than one pollutant. In one system, both SO_2 and NO_x are captured and saleable sulfuric acid is produced as a byproduct. The system recycles heat from the process to reduce the drain on power plant efficiency. Another project captures SO_2, NO_x, and particulates in a single device: a high-temperature baghouse. This minimizes space requirements and capital costs.

Emerging from research programs are new ways to improve scrubbers that use more expensive scrubbing solutions such as sodium-based liquid sprays. One technique recovers SO_2 from the flue gas with an organic solvent, then regenerates the scrubbing solution

Improving Today's "Scrubbers"

Although most scrubbers in use today are based on concepts developed in the 1960s, significant opportunities exist to improve scrubbing technology.

Ideally, better scrubbers would be more reliable, cost less, perhaps employ a recoverable absorbent that can be reused or marketed for other purposes, require less water, consume less of the plant's total energy output, produce a salable dry waste product, and in the best of cases, reduce both sulfur and nitrogen pollutants in a single system.

New scrubbers that offer one or more of these advantages are joining the Clean Coal Technology Program.

In one new configuration, flue gas is bubbled through a scrubbing slurry (rather than the conventional approach of spraying the slurry into the flue gas stream). The scrubber consumes less energy because the slurry need not be pumped through spray nozzles. Also the waste product is a relatively dry gypsum that is potentially marketable.

Other scrubber concepts in the Clean Coal Technology Program use a normally discarded waste product such as cement dust or biomass ash as the scrubbing agent and produce both potassium-based fertilizer and distilled water for commercial sale. Another innovation uses a "single loop" technique which eliminates the need for an external oxidation unit and handles flue gas from several boilers.

Also emerging from the research laboratory is also an advanced technique that uses electron beams to "excite" sulfur and nitrogen molecules, causing both to react with absorbing chemicals and separate from the flue gas.

4 Conversion

Techniques that convert coal into another fuel form bypass the conventional combustion process altogether. In the most commonly envisioned systems, coal is first converted into a gaseous fuel; in other techniques, a liquid form of coal is made, while in still others, a combination of a gases, liquids, and solids is produced.

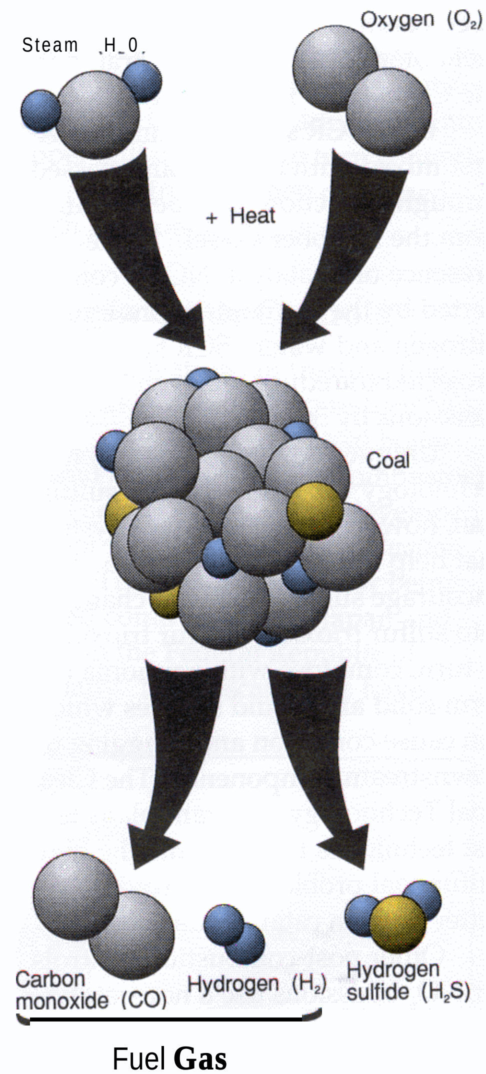
Gasification Combined Cycle

Over the last decade, the gasification combined cycle method for generating electricity from coal has progressed from the research laboratory to the threshold of commercial application.

The process basically has four steps: (1) coal is broken into gaseous molecules by bringing it into contact with high-temperature steam and oxygen (or air); (2) the gases are purified; (3) the very clean gases are burned and the very hot exhaust is routed through a gas turbine to generate electricity; and (4) the residual heat in the exhaust is used to boil water for a conventional steam turbine-generator to produce more electricity.

This combination of gas and steam turbines accounts for the name *"combined cycle."* (Combined cycle systems can also be powered by a pressurized fluidired bed combustor; see page 16.)

Gasification combined cycle systems are among the cleanest of the emerging clean coal technologies. Sulfur, nitrogen compounds, and particulates are removed before the



In the gasification process. coal IS broken apart by a reaction with steam (water) and oxygen (or air) A mixture of carbon monoxide and hydrogen IS produced Sulfur IS released as hydrogen sulfide a gas that can be almost totally removed furl is burned in the gas turbine, before combustion air is added. For this reason, there is a much lower volume of gas to be treated than in a post-combustion scrubber.

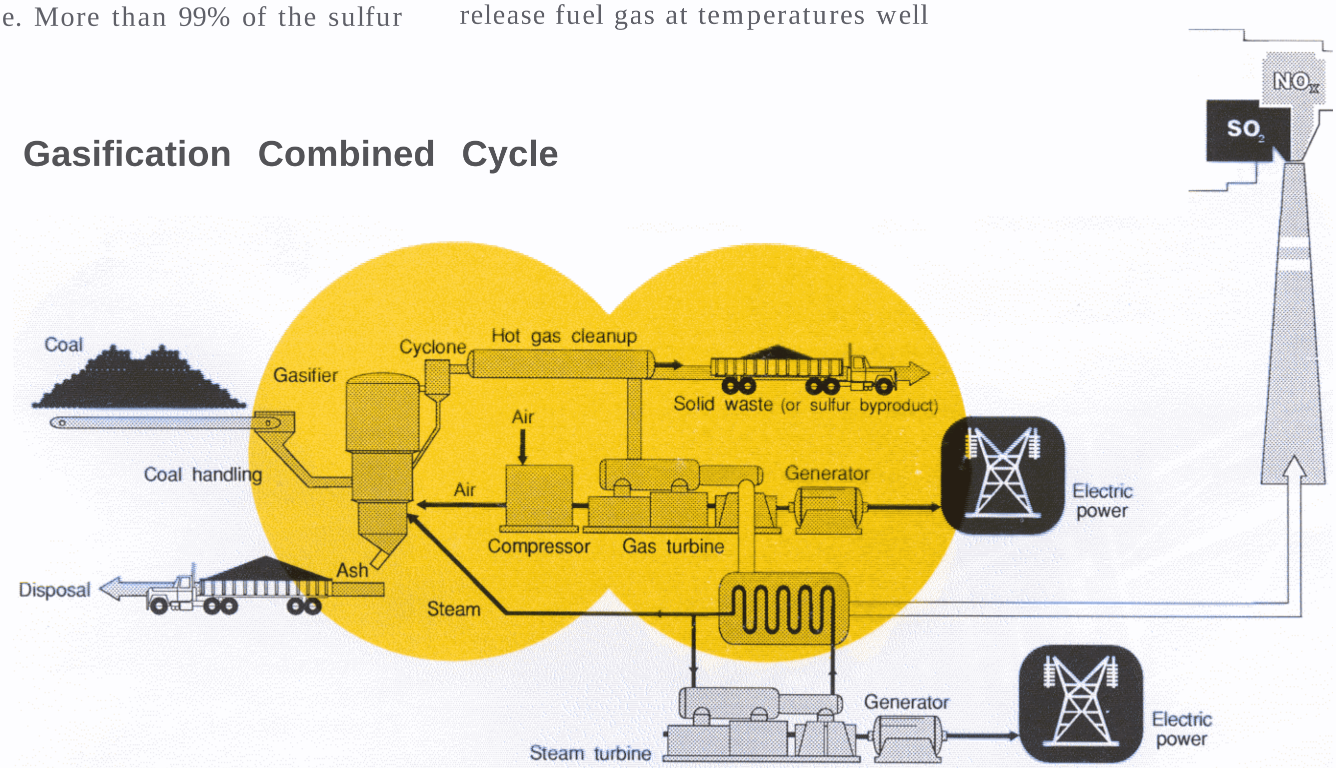
The gas stream must have extremely low levels of impurities not only to avoid pollution but to protect turbine components from chipping or corroding.

In a coal gasifier, unlike coal combustion processes, the sulfur in coal is released in the form of hydrogen sulfide rather than sulfur dioxide. Several commercial processes are capable of removing hydrogen sulfide. More than 99% of the sulfur can be removed from the gas, making it as clean as natural gas.

The first commercial-scale gasification combined cycle demonstration plants are now being built in the U.S. (see page 26). Several electric utilities are evaluating the concept as part of a modular approach to adding new generating capacity (see page 33). The distinction between these first demonstration plants and those to be tested in the Clean Coal Technology Program lies principally in the methods for cleaning the hot gases exiting the gasifier.

Some modern-day coal gasifiers release fuel gas at temperatures well

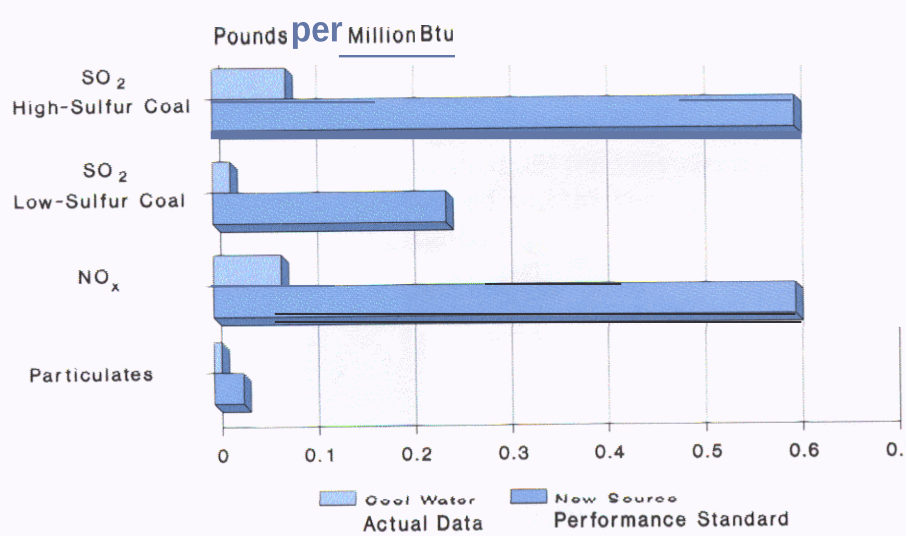
Gasification Combined Cycle



SO_2 REDUCTION	NO_x REDUCTION	EFFICIENCY	NEW PLANT CAPITAL COST	NEW PLANT ELECTRICITY COST	REPOWERED PLANT CAPITAL COST	REPOWERED PLANT INCREMENTAL ELECTRICITY COST	REPOWERED PLANT POWER OUTPUT	REPOWERED PLANT LIFE EXTENSION
95-99%	>90%	40-42%	$1,100-1,400 PER KW	45-50 MILLS/KWH	$950.1,200 PER KW	o-4 MILLS/KWH	1 oo-200% INCREASE	25-30 YEARS

While conventional methods for generating electricity from coal struggle to meet federal air quality standards. the Cool Water gasification combined cycle process easily surpassed them The unit demonstrated that 95% to 99% sulfur removal was possible and that NO_x emissions could be held to less than 25 parts per million

Environmental Performance at Cool Water



Coal Gasification— From London Bridge to the Mojave Desert

Few technologies offer more potential than coal gasification—and even fewer can trace their roots farther back in time.

Gas made from coal was used to light street lamps along London Bridge in 1813. In the late 19th and early 20th centuries before the advent of interstate natural gas pipelines, "town gas" from coal provided both heat and light to many American homes.

Commercialusesdiedoutwhen cheaper fuels became plentiful in the 1950s, but research continued and coal gasification technologies were vastly improved.

The 1970s brought renewed interest in gas from coal as a substitute for natural gas or petroleum. A $2-billion commercial coal gasification plant was built in North Dakota in the early 1980s to produce substitute natural gas. But interest again waned as oil prices declined and more natural gas suppliescame into the market.

The appeal of coal gasification today is driven not so much by a need to produce a substitute for oil or gas, but by its potential as the first step in an extremely clean, efficient process to generate electricity. The technique is called *integrated gasification combined cycle*. Two differem technologies-coal gasification and gas turbines-are joined to create a new way to generate power from coal.

The U.S. facility that pioneered gasificationcombinedcyclewasthe Cool Water Gasification Plant located in the Mojave Desert near Barstow, California. This $263-million, 120-megawatt demonstration unit ran from 1984 to 1989.

The Clean Coal Technology Program ispreparingtodemonstrate the next generation of gasification combined cycle technology. These newer techniques typically employ hot gas cleanup, which eliminates the more costly, less efficient method of cooling the gas to remove impurities, as was used at Cool Water.

in excess of 2,000 °F. However, current commercial gas cleaning technology operates at much lower temperature-typically as low as 100 to 200 “F. Consequently, the coal gas first must be cooled, then cleaned, then reheated to between 1,850 and 2,500 “F, the inlet temperatures of gas turbines. The cooling/reheating step requires expensive equipment, increases plant complexity, and lowers overall efficiency-all make the electricity produced more expensive.

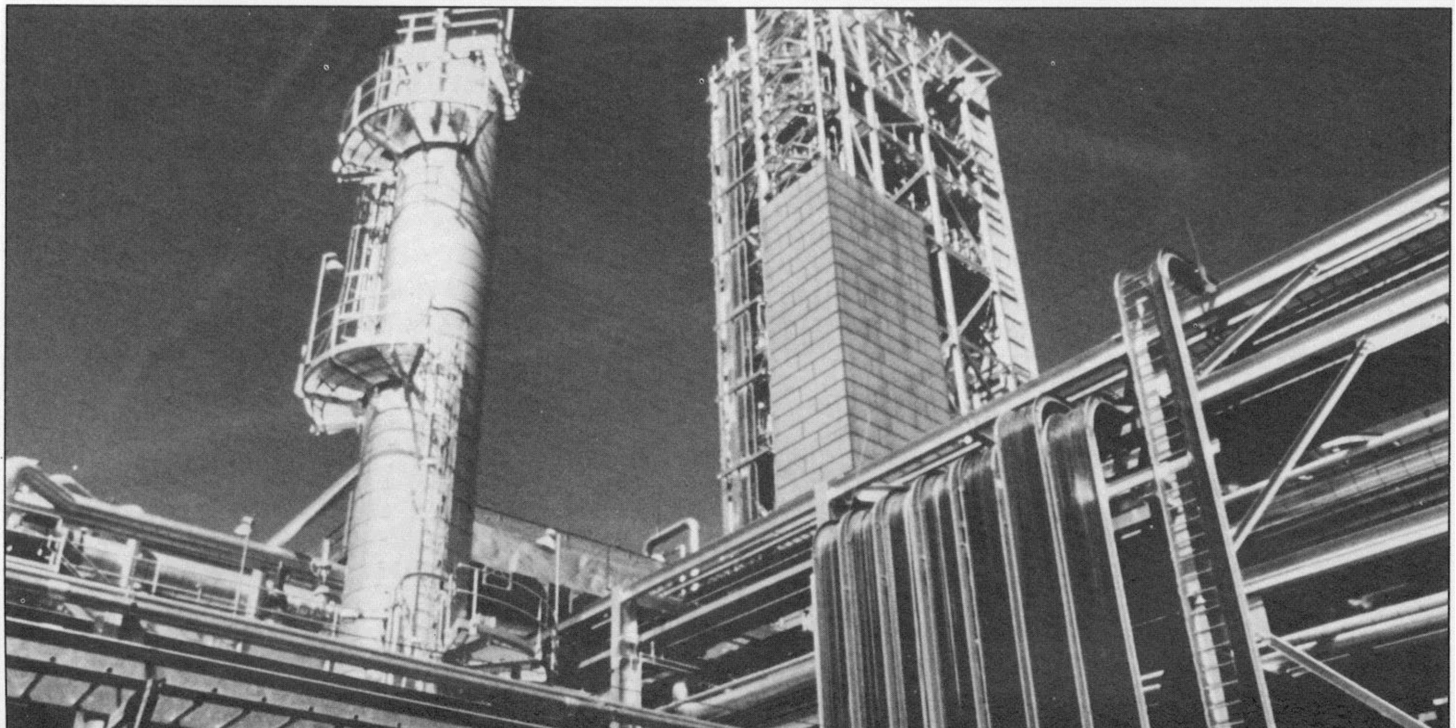
The next generation of gasification combined cycle power plants will likely employ hot gas cleanup techniques, many of which were developed in the Energy Department’s research program.

These techniques remove sulfur and other impurities in the fuel gas stream at much higher temperatures than today’s technology, eliminating or minimizing the efficiency-robbing cooling step.

One such technology sends the hot coal gas through a bed of zinc ferrite particles. Zinc ferrite can absorb sulfur contaminants at temperatures in excess of 1,000 °F, and the compound can be regenerated and reused with little loss in effectiveness. During the regeneration stage, salable sulfur is produced. The technique is capable of removing more than 99.9% of the sulfur in coal.

High levels of nitrogen removal are also possible. Some of coal’s

From 1984 to 1989, the Cool Water Demonstration Plant in California converted 1,000 tons of coal per day to 120 megawatts of electricity. The plant was built by a consortium that included the Electric Power Research Institute (the technology arm of the electric utility industry.)



A Coal Refinery?

Nearly 85% of all coal consumed in the U.S. today is burned in electric power plants. But coal is also a rich source of potentially valuable liquid, gaseous, and solid fuels as well as chemicals. Historically these products have been too expensive to compete with cheaper oil and natural gas; however, recent advances in clean coal technology may offer more economical products.

The secret may be this: rather than designing a coal processing facility to produce a single product, the facility might be configured to convert coal into a family of products, each with value in a specific market-essentially the way an oil refinery works.

One approach, for example, would be to design a process that converts coal into a char for use as a smokeless fuel or for steelmaking or as a source of chemical carbon. The co-products of this process would be an oil-like liquid and a fuel-grade gas. Together, these products might be sufficiently valuable to make the coal facility profitable.

Producing new fuel forms was made a key objective in the Clean Coal Technology Program beginning in Round #3. Not only can they be produced cleanly, but if they can be made economically, a variety of coal-based products manufactured at a "coal refinery" might substitute one day for imported oil.

nitrogen is converted to ammonia which can be almost totally removed by straight forward chemical processes. NO_x formed from the combustion air can be held to well within allowable levels by staging the combustion process at the turbine or by adding moisture to hold down flame temperature.

Underground Gasification

Coal gasification can also take place underground-or *in situ* (the Latin word for "in place").

In underground gasification, steam and oxygen are injected into a coal seam through wells drilled from the surface. The coal seam is ignited and partially burned. Heat generated by the combustion gasifies additional coal to produce fuel-grade gases. The gases are piped to the surface where they are cleaned and processed using the same techniques applied in surface gasification.

Underground gasification may be particulary useful in extracting energy from coal seams that are unmineable. Seams that slope steeply from the surface or are too deep or of marginal quality may be future candidates for *in-situ* gasification.

Coal-Oil Coprocessing

In the late 1970s and early 1980s, when energy prices were skyrocketing, many companies began synthetic fuel projects to turn coal into a liquid substitute for crude oil. When energy prices subsequently declined, these ventures were abandoned.

Today, a variation of these synthetic fuel technologies could offer better economics. Rather than liquefying only coal in a complex and expensive process, coal-oil *coprocessing* mixes coal with the heavy residual oil that is the waste product of refineries.

The slurry is then processed in an advanced refining concept called a *cracking* unit. The residual oil provides all or most of the hydrogen needed for the coal conversion process. This eliminates or reduces the need for hydrogen production, a step that added considerably to the cost of the earlier synthetic fuel processes.

Once produced by the coprocessing plant, the coal-based liquid can be cleaned of its sulfur and ash before being used.

On the Horizon...Fuel Cells and MHD

Two of the most advanced methods for extracting energy from coal are fuel cells and MHD, which isshortfor magnetohydrodynamics.

Fuel Ceils

Unlike other coal systems, fuel cells do not rely on combustion. Instead, an electrochemical reaction generates electricity. Electrochemical reactions release the chemical energy that bonds atoms together-in this case, theatomsof hydrogenand oxygen. The concept is much like a battery, except the fuel cell will produce electricity (and usable heat) as long as hydrogen and oxygen are fed to it.

The fuel cell is extremely clean and highly efficient. In a clean coal technology configuration, the fuel cell is fueled by hydrogen extracted from coal gas made by a coal gasifier. Techniques exist to clean and purify the coal gases (see page 25), and the principal waste product from the fuel cell is water.

Fuel cells are often categorized by the substance used to separate the electrodes, termed the "electrolyte." The most mature fuel cell concept is the *phosphoric acid* fuel cell. These cells have been used in hospitals, apartment buildings, and shopping centers and are now being developed for utility use. Other concepts are being developed. One is the *molten carbonate* fuel cell which uses a hot mixture of lithium and potassium carbonate as the electrolyte. The newest type is the *solid oxide* fuel cell which uses a hard ceramic material instead of a liquid electrolyte.

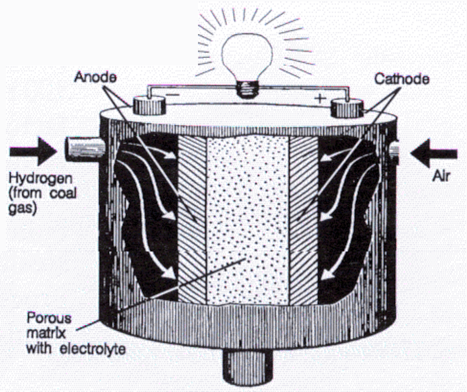
MHD

The MHD concept has been likened to a "coal-fired rocket blast" through a magnetic field. Coal is burned at extremely high temperatures (close to 5,000 °F). At these temperatures, thecombustiongases are released as a hot stream of highly charged particles called plasma. Theelectricalconductivity of the gases is enhanced by "seeding" them with special salts, and the plasma is channeled through an intense magnetic field at close to the speed of sound.

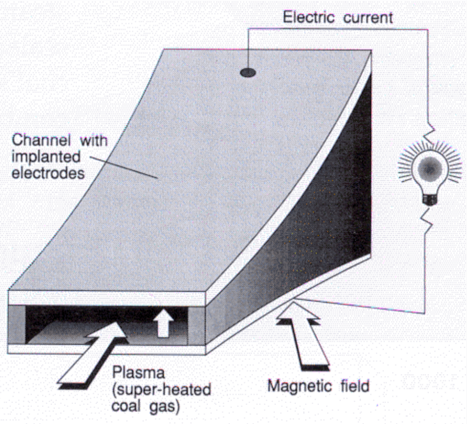
An electrically conductive substance moving through a magneticfieldgenerateselectricity. The electricity generated in the MHD process is tapped from the plasma by electrodes imbedded in the channel walls. The exhaust gases leaving the channel are hot enough to boil water for a conventional steam-turbine, resulting in a coal-fired system that can achieve efficiencies of 50% or more.

The salts added to increase electrical conductivity also chemically react with sulfur released from coal, removing in excess of 99% of the impurities from the exhaust gases. NO_x is minimized by burning the coal in stages with a fuel-oxygen mixture that retards the formation of nitrogen pollutants (see page 19).

Fuel Cell



Magnetohydrodynamics (MHD)



Industrial Clean Coal Technologies

Coal consumption in non-utility markets has declined since 1950, even as the total "se of coal expanded. Clean coal technologies could improve coal's environmental acceptability in the industrial and commercial sectors and perhaps increase its use.

Co&burning electric power plants are not the only users of coal nor are they the only sources of pollutants from coal. Each year about 100 million tons of coal are used by factories and other industrial manufacturing facilities.

More than 9,000 industrial boilers today burn coal to produce steam for various manufacturing processes. Coal is also used to produce steel and cement, and it can be a valuable raw material for such products as perfume, dyes, insecticides, andmedicines.

Clean coal technologies are being developed for these applications. In some cases-industrial steam production, for example-scaled-down versions of utility clean coal systems, such as fluidized bed combustors, offer attractive options.

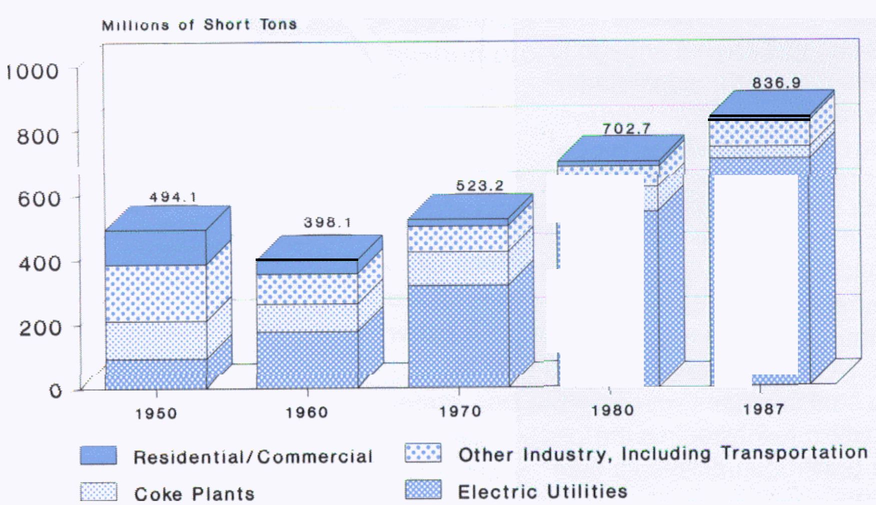
In fact, more than IUU process steam and small-power fluidized bed combustors are already operating in the U.S.; at least half of these units were added since 1983. Industrial-size fluidized bed combustors can be found today in paper mills, food processing plants, tire manufacturing factories, hospitals, and district heating systems.

Research is under way to further improve these systems, making them more practical and economic for smaller businesses and perhaps someday even for apartment buildings and homes.

But burning coal is not the only way to use this abundant resource.

Steelmaking and cement production are two other applications that are being outfitted with special types of clean coal technologies.

U.S. Coal Consumption by Sector 1950-l 987



Steelmaking

An important use of coal in the industrial sector is to produce coke, which is used in smelting iron ore to make steel. Coke is made by a process called "carbonization" in which a blend of two or more bituminous coals is baked in the absence of air. The coke is then combined with iron ore and limestone in a blast furnace. The resulting carbon monoxide and heat reduce the ore to produce molten pig iron, essential to steel production.

The existing 30 coke oven plants in the US. emit about 300,000 tons of sulfur pollutants each year, along with airborne toxic chemicals such as benzene and other hydrocarbons.

Many coke ovens have no desulfurization equipment, while others use gas treatment processes that are more than 30 years old and rely on a cumbersome series of steps.

Modern-day clean coal technology can make coke plants both cleaner and simpler. In one clean coal technology project, ammonia will be captured from coke oven gas and used to scrub hydrogen sulfide from the gas. Then, using special catalysts, the ammonia is chemically changed into nitrogen and water vapor, and the hydrogen sulfide decomposed into elemental sulfur, a salable byproduct. More than 80% of the hydrogen sulfide and 98% of the ammonia can be removed, along with benzene and other pollutants.

Fill 'er Up. . . with Coal?

America's transportation sector is the most vulnerable part of its energy economy. Nearly two-thirds of the oil consumed in the U.S. is burned in cars, trucks, trains, and other vehicles. Alternatives such as compressed natural gas and electric vehicles are being tested in some urban areas, but a major shift from liquid transportation fuels will likely be slow.

Could coal be used instead of oil? Prospects for changing coal into a substitute for petroleum have long intrigued coal chemists and engineers. The technology to accomplish this chemical transformation exists, but the drawback has been economics. Coal liquids historically have been too expensive to compete with natural crude oil.

Now that may be changing. During the 1980s, major advances were achieved in coal *liquefaction.* Scientists learned that by separating the coal-to-oil process into multiple stages, they could squeeze 30% more liquids from the same amount of coal. They learned how to reduce construction and operation costs, how to operate at lower temperatures and pressures, and how to improve the performance of catalysts that accelerate the chemical reactions. They learned how to produce a higher quality liquid product that would be more valuable than a comparable quantity of raw crude oil.

The result? Today liquids can be produced from coal for as low as $35 per barrel-almost half the cost of 15 years ago. In the future, new coal pretreatment steps, better solvents and improved process designs could lower costs to $25 per barrel. At these costs, the prospects for fueling tomorrow's vehicles with clean burning coal liquids could become much brighter, and America would have another option for reducing its need for imported oil.

Cement Making

Cement is made by heating a mixture of limestone, clay, sand, and other minerals in a kiln until they fuse. More than 250 cement kilns have been built in the U.S. and along the St. Lawrence River in Canada. Because most of these kilns burn coal, they emit about 230,000 tons per year of SO_2.

One innovative clean coal technology uses the waste products from a cement kiln to reduce air pollutants. When the minerals in a cement kiln are heated, they release vapors containing sodium and potassium salts. These vapors later condense as a fine dust. Usually this dust had to be disposed of, but the clean coal technology can use it to absorb sulfur from the kiln's exhaust gases.

Sulfur-laden kiln gases are bubbled through a slurry made of the dust and water. Chemical reactions in the slurry remove at least 90% of the sulfur pollutants, producing potassium sulfate which can be used as a fertilizer. Additional process steps recover solid calcium products that can be reused in the kiln.

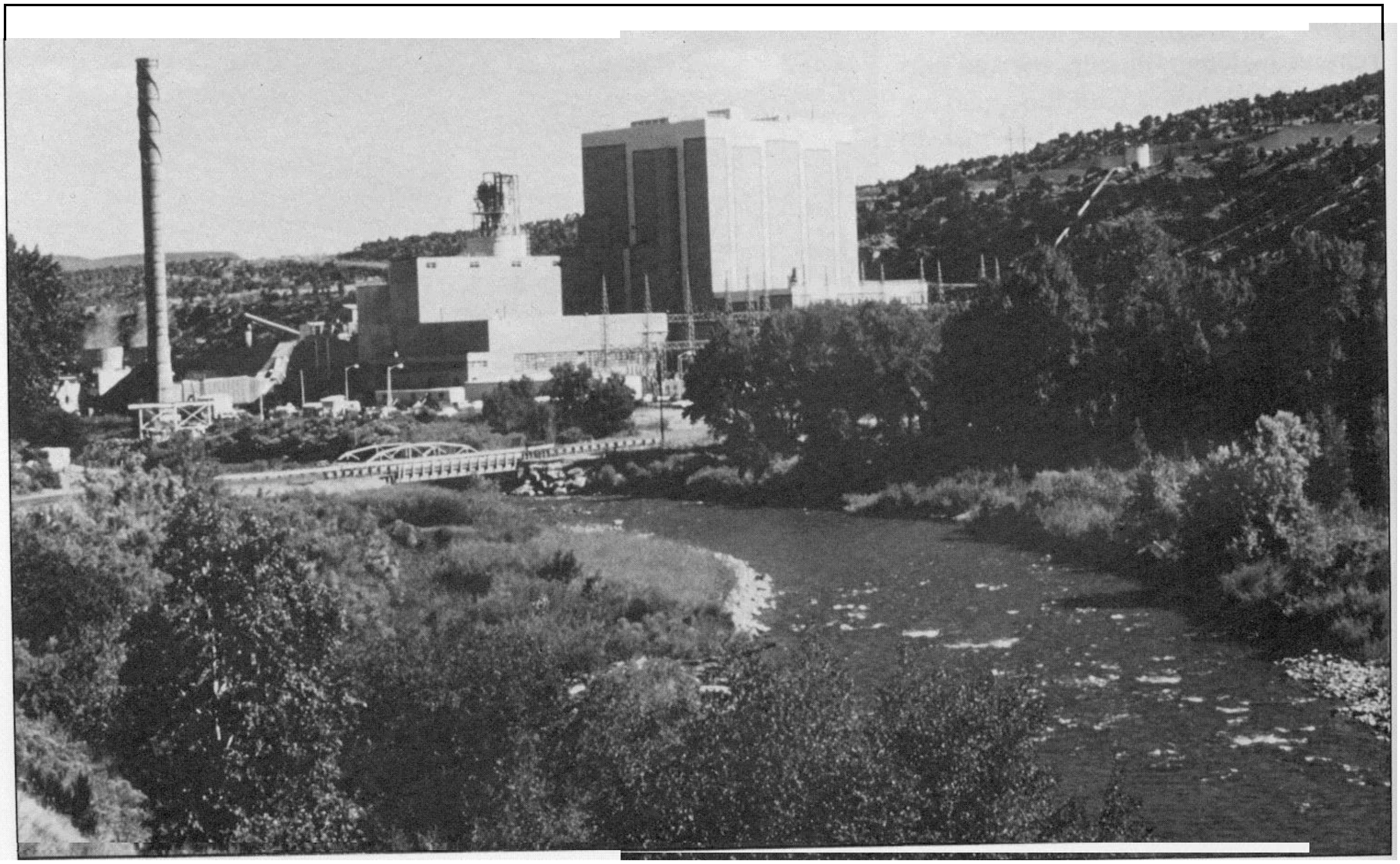
The result is a cement kiln that emits virtually no waste products other than distilled water.

A New Coal Era

The 1990s are a period of transition for the nation's energy industry, especially the electric utilities. Coal today supplies 57% of the nation's electricity, and the U.S. is richly endowed with coal reserves. But U.S. utilities must be able to meet a growing demand for electricity while responding to new environmental concerns.

Clean coal technologies offer a solution. These advanced concepts offer options for retrofitting older U.S. power plants, controlling pollution at lower costs and with less space requirements than current technology.

In 1993, the nation's investment in clean coal technology demonstrations began to pay off. The first market sales of technologies tested in the Clean Coal Technology Program began occurring. A Pennsylvania power plant became the first commercial customer for an advanced low-NO_x burner system demonstrated in the program. An Ohio utility made an advanced Clean Coal Technology catalytic flue gas cleanup system a permanent part of its Clean Air Act compliance strategy. Circulating fluidized bed combustors, with design improvements based largely



Air Quality-The Nation's Track Record

Passage of the Clean Air Act and its subsequent amendments set the U.S. on a course that has committed billions of dollars to protecting the environment. The Environmental Protection Agency estimates that U.S. industry has expended well over $250 billion to control air emissions since enactment of air quality legislation in 1970.

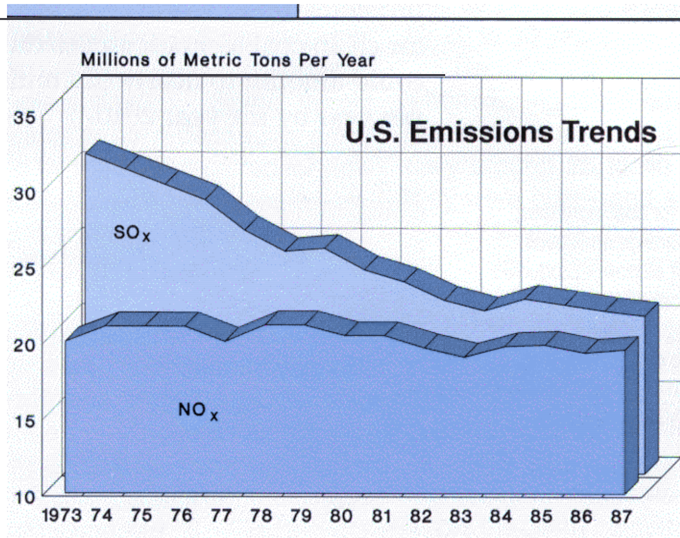
Much of this has been spent by electric utilities, particularly those that use coal to generate power. Since 1975 the nation's utilities have spent more than $100 billion for SO, capture alone (either in building and operating flue gas scrubbers, or by incurring coal washing costs; or by purchasing higherpriced, lowersulfur coal). An average of nearly $8 billion a year is spent by coal-burning utilities to comply with current air quality standards.

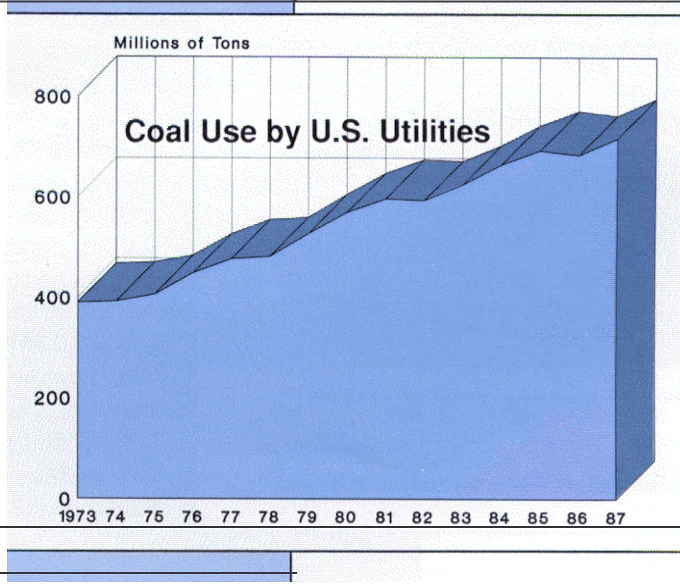
As a result of these air quality expenditures, SO, emissions have declined dramatically. Since the 1970 Clean Air Act, nationwide SO, emissions from all sources have dropped more than 25% from their peak in 1973. Coal-fired power plants nationwide have reduced their SO, emissions by nearly 12% from their peak in 1977. This has occurred even as coal use was soaring. While SO, emissions were falling, U.S. electric utilitieswere increasing their coal consumption by nearly 80%.

If the SO, released per ton of coal burned in 1987 had been the same as in 1975, with the increased coal use by utilities, SO, emissions from coal-fired utilities would have topped 30 million tons.

U.S. NO_x emissions generally held constant from 1975 to 1987 at about 20 million tons per year.

In terms of acid rain causing emissions, the nation's air is becoming cleaner even as coal use has steadily increased. Clean coal technologies can help maintain these trends





on lessons learned from a Clean Coal Technology project, began entering the market.

These environmentally improved technologies may also find large markets overseas, particularely in newly industrialized nations seeking economic growth while cleaning up old environmental problems. The worldwide market for clean coal technology purchases could amount to nearly $24 billion per year by the year 2010.

In the long run, the more lasting impact of clean coal technologies may extend well beyond simply reducing pollution from older U.S. plants or modernizing the power plants of emerging nations.

Advanced clean coal technologies can ensure that the U.S. and global economies continue to expand into the 21st century, fueled by economic, secure and abundant coal.

Economic growth creates jobs for a growing population. It means

As global demand for coal Increases. worldwide carbon dioxide emissions will do the same. If all power producers were to use the most efficient clean coal technologies, global carbon dioxide emissions could be cut by more than half, compared with the levels that would be provided by existing power plant technologies.

Heading Off the Greenhouse Effect

Earth's temperature is regulated largely by atmospheric gases. Carbon dioxide (CO_2), methane, and other gases allow the sun's energy to penetrate to the Earth but trap heat radiated from the Earth's surface. The phenomenon is termed the "greenhouse effect."

There are still key questions about the greenhouse effect-for example, the role of fossil fuel combustion versus global deforestation. U.S. coal combustion contributes to less than 8% of the total worldwide release of CO_2, and CO_2 constitutes only half of the "greenhouse gases."

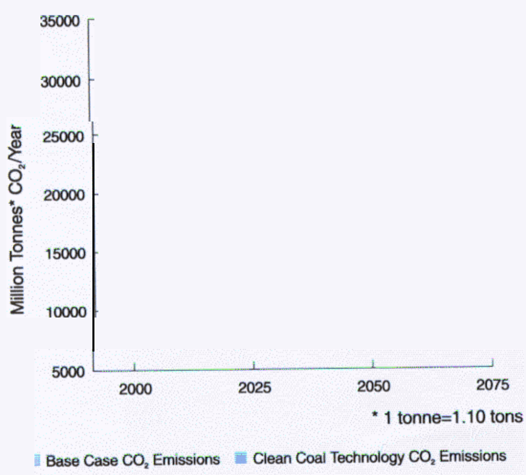
Energy efficiency investments and technological improvements, including those in the Clean Coal Technology Program, can offer alternatives to regulation.

Many clean coal technologies are effective in reducing CO_2 because they increase power generating efficiencies. In higher efficiency systems, less CO_2 is produced per unit of fuel consumed.

For example, technologies like pressurized fluidized bed and gasification combined cycle boost generating efficiencies into the 40% to 45% range. This can reduce CO_2 emissions by 17% to 27%. Future technologies such as gasifier/fuel cell combinations could lower CO_2 emissions by up to 40%.

Also, because a conventional scrubber actually *adds* CO_2 to the atmosphere (because of its reaction chemistry and effect in reducing plant efficiency), finding alternatives to the scrubber can reduce atmospheric CO_2

Worldwide CO_2 Reduction

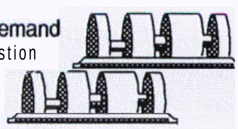


A Modular Approach to Utility Planning

Repowering concepts allow utilities to add new capacity in highly efficient modules. The modules can be brought into tie rate base quickly and the most costly investment (the gasification plant) deferred until justified by fuel economics.

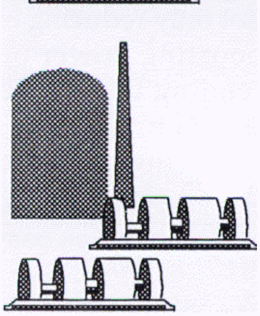
Phase I

In me first phase, peak demand is met by installing combustion turbines fueled by natural gas.



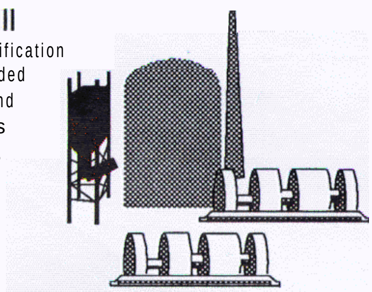
Phase II

As demand for electricity increases, a steam cycle is added to create a combined cycle plant for intermediate and baseload service.



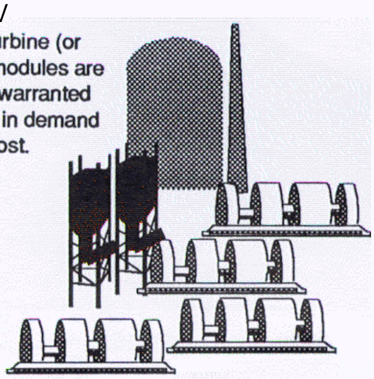
Phase III

A coal gasification plant is added when oil and natural gas prices rise.



Phase IV

Gasifier-turbine (or fuel cell) modules are added as warranted by growth in demand and fuel cost.



Retrofit and Repowering

Beginning with Round #2 of the Clean Coal Technology Program, proposers were required to submit candidate projects that could be used to *retrofit* or *repower* existing plants.

Retrofit technologies generally are pollution control devices that can be installed on older power plants without making major changes in the plant design. Some retrofit concepts do not reduce sulfur emissions by the 90% required for new plants (unless possibly used in combination with each other) but offer a means of reducing sulfur emissions by 50% to 70% (called for in most new legislation to reduce acid rain) at far less cost than a scrubber. Retrofit technologies include:

* Precombustion coal cleaning
. Limestone injection multistage burners
. In-duct sorbent injection
. Gas reburning
. Advanced slagging combustors
• Advanced scrubbers

Repowering technologies, in general, replace a major portion of an existing plant (such as the boiler) with new power generating equipment while retaining other portions of the plant (such as the steam generating equipment). Pollution control is inherent in the process, but it is not the only advantage. A repowered plant can produce more power-sometimes twice as much or more-than the original plant, as well as extending a plants lifetime by 20 to 30 years.

Repowering comes into play when existing coal-fired plants reach the end of their useful lives—typically around 25 to 40 years after they were built-and a utility must decide whether to retire or rebuild the facility. Repowering also becomes attractive when power generation needs have increased and a utility wants to avoid the problems of finding and obtaining approval for a new site. Many repowering concepts also rely on standardized, shop-fabricated components. This minimizes the costly customized, onsite construction typical for conventional technologies. Several examples of repowering technologies are:

. Atmospheric fluidized bed combustors
• Pressurized fluidized bed combustor combined cycle
* Integrated gasification combined cycle
• Utility-scale fuel cells

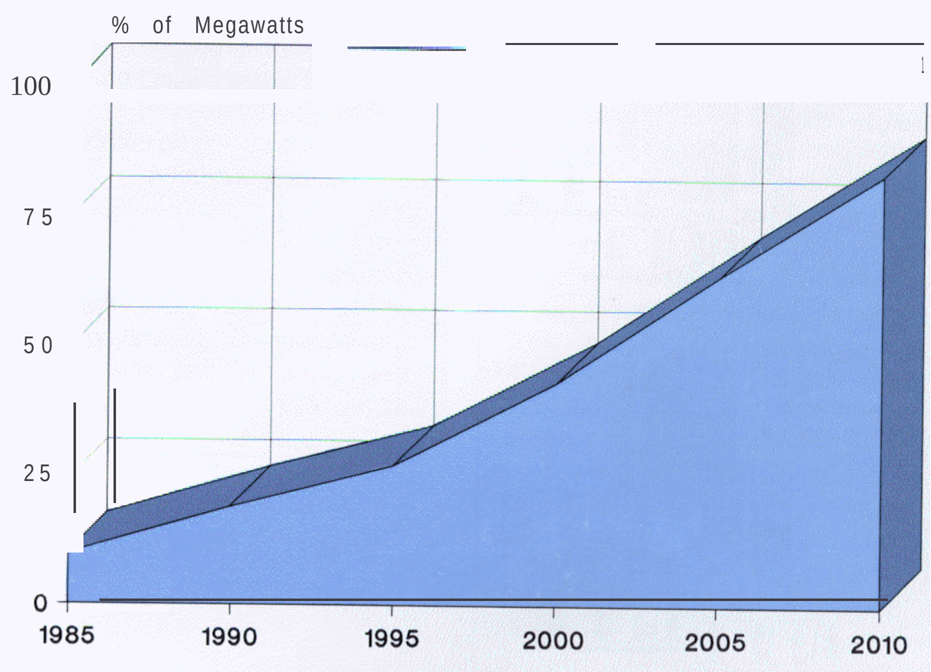
greater opportunities for an expanding workforce. But a growing economy demands more electricity. As much as 100,000 to 150,000 megawatts of additional new power beyond what is currently planned—the equivalent of 200 to 300 moderately sired (500 megawatt) power plants-could be required in the U.S. by shortly after the turn of the century. Many new plants will be fired by natural gas, but utilities will also look to coal particularly for baseload power.

At the same time, much of the nation's existing power generating fleet is aging. By the mid-1990s, more than half of all coal-fired boilers in the U.S. will be 30 years old or older, and the percentage of older plants will rise more sharply around the year 2000.

These trends--aging plants, growing electricity demand and new environmental laws-could pose serious problems for utilities wishing to use coal unless new technology is available.

Many clean coal technologies, however, offer the option of repowering older power plants (see page 35), not only reducing emissions but boosting power output and extending useful lifetimes of existing plants by 20 to 30 years without requiring new sites

U.S. Coal-Fired Power Plants 30 or More Years Old



By the year 2000 44% of the nation's coal-fired power capacity will be 30 years old or older. The aging nature of U.S power plants could raise reliability and supply problems unless they can be "repowered" with new, more efficient clean coal technology

Clean Coal Technologies in the International Marketplace

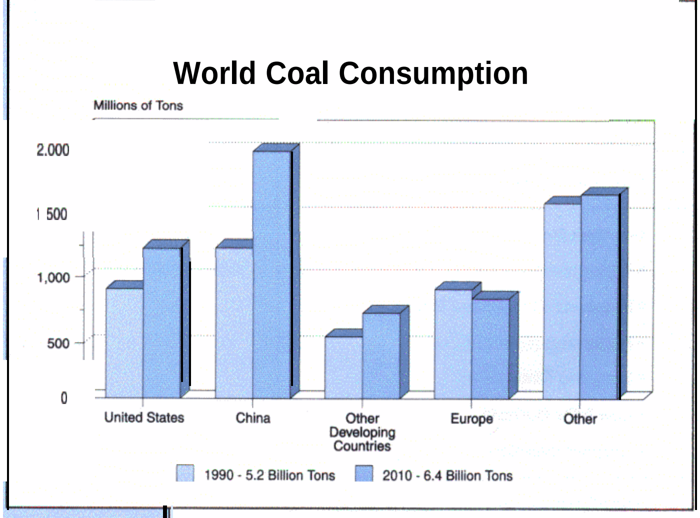
The world relies on coal to supply about 28% of its total energy. In 1987 total annual worldwide consumption of coal topped 5 billion short tons; by the year 2000 total global consumption could exceed 6.6 billion short tons annually.

Japan's consumption of coal is expected to increase almost 50% by the end of the century. Europe is expected to increase its use of coal by another 30% with the largest tonnage increases in Germany and Italy. Newly industrializing countries are expected to have the greatest increase in coal consumption, almost 60% between now and the year 2000.

The projected global increase in coal consumption comes at a time when many nations are experiencing the same environmental concerns as the U.S. For example, the European Economic Community members have agreed to cut their SO_2 emissions by 30% by 1993 and their NO_x emissions by a like amount by the mid-1990s, and the World Bank is now placing environmental covenants on requirements for loans.

This parallel growth in worldwide energy demand and global environmental concern provides significant new opportunities overseas for clean coal technology. The U.S. is currently the second largest coal exporting country in the world, but for most years between World War II and 1983, the U.S. ranked as the leading exporter (Australia took over the number one position in 1984). If the U.S. is to return to preeminence in world coal markets, it will likely need to promote new, cleaner, more efficient coal-burning technologies-and by demonstrating that these new technologies run well on U.S. coals, boost the export of domestic coal as part of a U.S. sales "package."

Many of the U.S.-demonstrated technologies may be especially applicable for certain markets overseas. For example, many boilers in Europe are small in comparison to U.S. scales, typically less than 50 megawatts. Modular coal technologies-like fluidized bed combustors—which retain their high efficiencies at small sizes may be ideal candidates. Other technologies that lend themselves to the cogeneration of usable heat and electricity could be especially important for developing nations, while larger, baseload coal-based power concepts could attract interest from larger, more developed countries. Still other nations, such as Poland, might look to the U.S. for lower cost pollution control technologies to retrofit older, dirtier plants without adding greatly to their already substantial economic burdens.



The same technologies will also torm the foundation for a new generation of "grassroots" coal-tired power stations.

The coal-burning plants of the 21st century will be extremely clean—virtually eliminating concerns over acid rain pollutants and dramatically reducing emissions of greenhouse gases.

They will be built in high-efficiencv modules of 200 to 300 megawatts (rather than the costly 1,000-megawatt scales of today). This modular approach will shorten construction periods and allow power companies to match changing demand patterns more quickly and precisely.

They will be highly efficient, extracting 45% to 50% of the available energy from coal, rather than today's utility-wide average of 33%.

And they will be economical, producing electricity for consumers at costs equal to or less than today's technology.

In the 1970s, such power plants existed onlv in the minds of researchers. Today, due largely to the Clean Coal Technology Program, these clean, highly efficient technologies are on the horizon.

They are the pioneers of a new coal era.

Clean Coal Technologies Commercial Status