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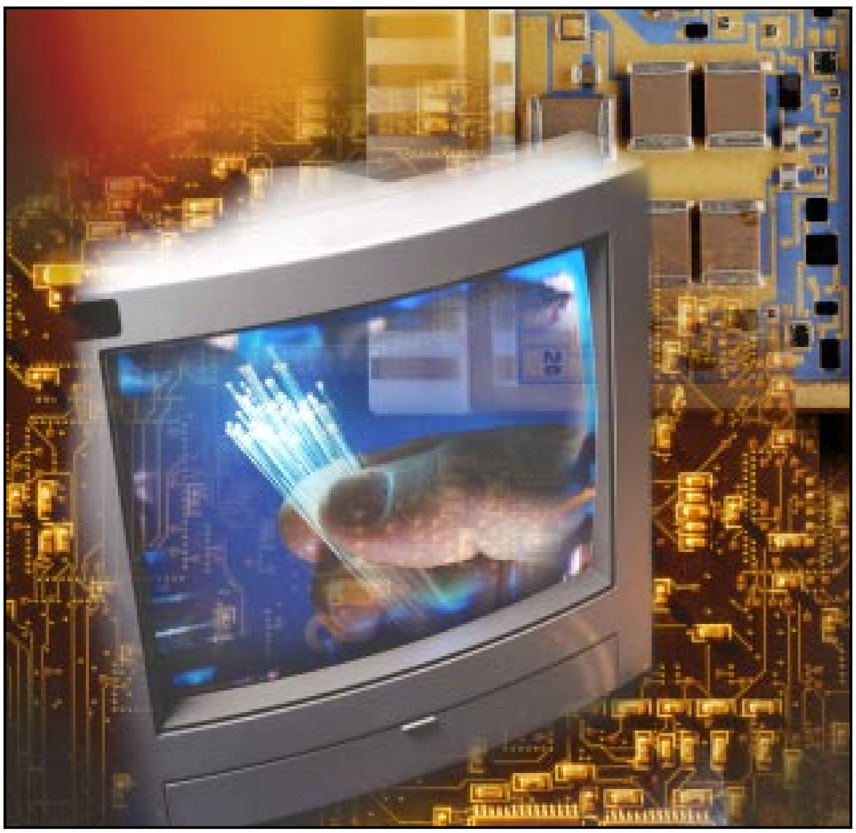
CLEAN COAL TECHNOLOGY



Software Systems in Clean Coal Demonstration Projects

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A report on three projects conducted under separate cooperative agreements between:

The U.S. Department of Energy and
- CQ Inc.
- Southern Company Services
- New York State Electric & Gas Corporation

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DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

CLEAN COAL TECHNOLOGY

Software Systems in Clean Coal Demonstration Projects

Executive Summary

The Clean Coal Technology (CCT) Demonstration Program is a government and industry co-funded effort to demonstrate a new generation of innovative coal utilization processes in a series of facilities built across the country. These projects are conducted on a commercial scale to prove technical feasibility and provide the information required for future applications.

The goal of the CCT Program is to furnish the marketplace with a number of advanced, more efficient coal-based technologies that meet strict environmental standards. These technologies will mitigate the economic and environmental barriers that limit the full utilization of coal.

To achieve this goal, beginning in 1985, a multi-phased effort consisting of five separate solicitations has been administered by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL). Projects selected through these solicitations have demonstrated technology options with the potential to meet the needs of energy markets while satisfying relevant environmental requirements.

This report discusses the development of three computer software systems under the CCT Program for application to the optimization of coal utilization technologies. These systems are as follows:

- Coal Quality Expert (CQE™), a program that provides detailed analyses of the impacts of coal quality, operational changes, and/or environmental compliance alternatives on emissions, performance, and power production costs.
- Generic NOx Control Intelligent System (GNOCIS™), an advanced software-based system that optimizes boiler operation to achieve reduced NOx emissions while improving unit performance.
- Plant Economic Optimization Advisor (PEOA™), a system designed to assist in meeting emissions regulations while optimizing overall plant economic performance.

These projects incorporate aspects of artificial intelligence (AI), which involves computer-based decision-making processes that mimic those of the human brain.

The most successful of the three computer programs is GNOCIS™, which has achieved significant market penetration in commercial applications. GNOCIS™ has been installed on units representing more than 10,000 MWe of generation capacity in both the United States and Europe, and more installations are planned. Work is in progress as part of the CCT Program to further extend the capabilities of GNOCIS™ to the optimization of other aspects of power plant operation.

CQE™ offers significant benefits in the selection of coal-based fuels and in the design and operation of coal-fired power systems. It has the capability of predicting power plant performance with a minimum number of bench-scale tests, resulting in lower cost to achieve the desired assessments compared with traditional approaches.

The demonstration of PEOA™ at Milliken Station was discontinued because of operating problems. Although this particular application of AI was not successful, the concept of using neural networks for power plant optimization is fundamentally sound, and future developments of this technology will undoubtedly prove to be feasible.

Software Systems in Clean Coal Demonstration Projects

Background

The Clean Coal Technology (CCT) Demonstration Program, sponsored by the U.S. Department of Energy (DOE) and administered by the National Energy Technology Laboratory (NETL), has been conducted since 1985 to develop innovative, environmentally friendly coal utilization processes for the world energy marketplace.

The CCT Program, which is co-funded by industry and government, involves a series of commercial-scale demonstration projects that provide data for design, construction, operation, and technical/economic evaluation of full-scale applications. The goal of the CCT Program is to enhance the utilization of coal as a major energy source.

The CCT Program has also opened a channel to policy-making bodies by providing data from cutting-edge technologies to aid in formulating regulatory decisions. DOE and the participants in several CCT projects have provided the Environmental Protection Agency (EPA) with data to help establish NOx emissions targets for coal-fired boilers subject to compliance under the 1990 Clean Air Act Amendments (CAAA).

Process Optimization

With increasing competition and tightening emissions standards, it has become imperative that power plant operators continually seek ways to increase efficiency consistent with achieving environmental goals. A number of commercial programs have been developed to aid in attaining the desired process optimization, using increasingly sophisticated computer-based technologies.

Instrumentation

Essential to the development of optimization systems is accurate measurement of process variables, including temperature, pressure, flow rate, and process stream properties. In recent years, the field of process instrumentation has seen many technical advances in reliability and accuracy. Without precise measurement of critical variables, optimization of plant efficiency or pollution control systems cannot be achieved.

Specifically applicable to pollution control technologies, efforts are under way to develop instruments that measure concentra-

Milliken Station

tions of ammonia (NH_3), nitrogen oxides (NOx), mercury (Hg), and particulates in power plant stack gas. The use of continuous emissions monitoring systems (CEMS) has been mandated by EPA under the CAAA; this in turn is dependent on accurate measurement of pollutants.

Software Development

Of equal importance is performance monitoring software to track variables such as process temperatures and flow rates, steam conditions and flow rates, and power production. Although progress has been made in the development of on-line software for performance monitoring, such systems have not achieved universal acceptance in the electric power industry. This Topical Report covers development of control and optimization software as part of the CCT Program.

At the same time, some work is in progress outside the CCT Program, such as an in-house system developed by AEP Generating Co. and installed at their Cardinal Station at Brilliant, Ohio. This Windows-based system uses off-the-shelf software to track several hundred data points to permit calculation of plant component efficiencies and overall heat rate. To improve some of the performance calculations, instruments demonstrating higher accuracy were added to monitor key variables.

Applications of Optimization in Electric Power Generation

Several areas involved in power generation are candidates for process optimization. For example, experience with CCT projects involving combustion modification has shown a tendency toward increased levels of unburned carbon (UBC) in power plant fly ash. This is often expressed in terms of loss on ignition (LOI). Because the analytical procedures for LOI and UBC are not the same, the terms are not strictly synonymous. However, these acronyms are often used interchangeably, and this report follows that practice.

Increased UBC increases the amount of coal needed to generate a given amount of electricity, thereby decreasing power plant energy efficiency. Of equal importance is the fact that UBC is undesirable from the standpoint of fly ash marketability. Fly ash can be sold as aggregate for concrete, among other things, provided that the UBC content meets specifications. In addition, higher UBC content decreases the resistivity of the fly ash particles, thus adversely affecting electrostatic precipitator (ESP) performance. Although UBC can be reduced by operational changes, such as increasing coal fineness, a significant problem still exists and is receiving considerable attention.

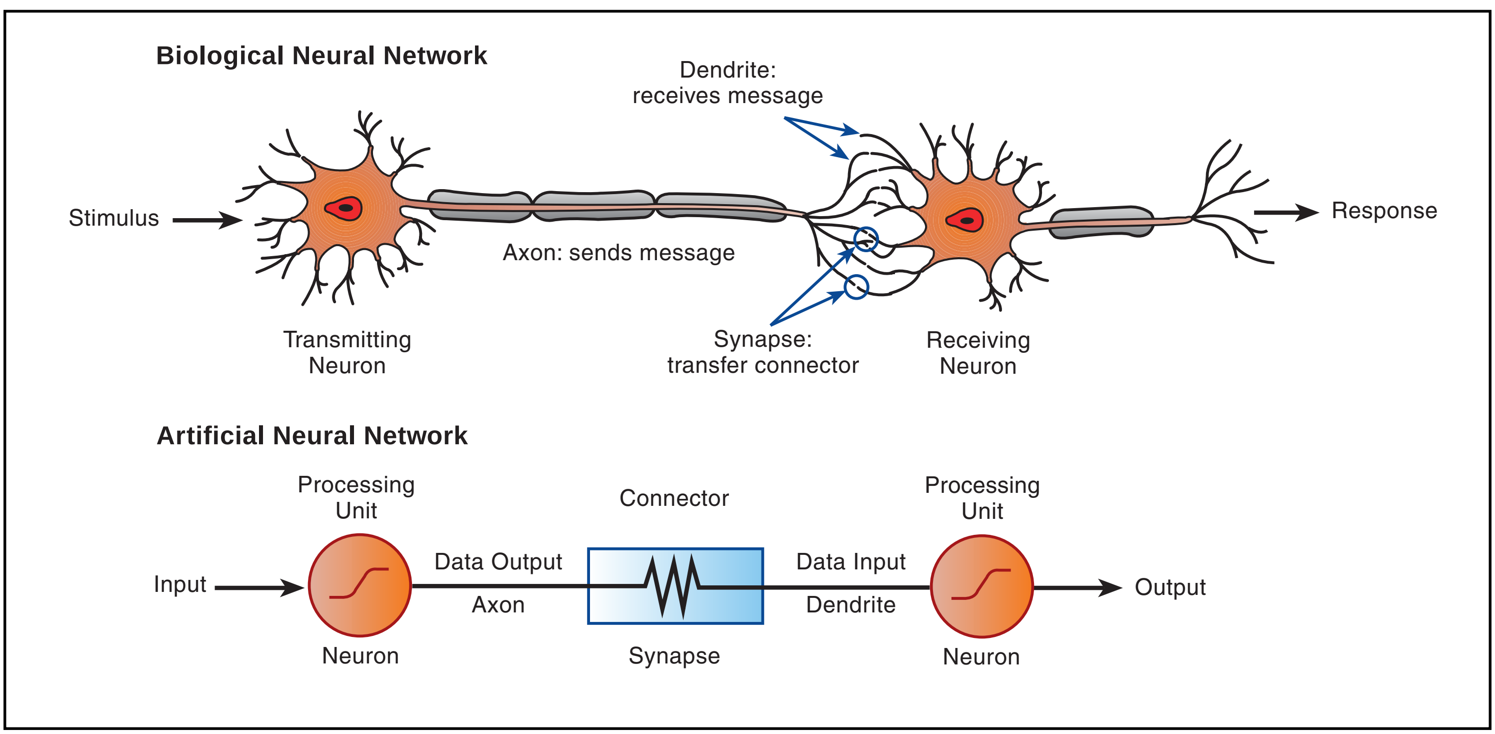
Experience has also indicated that combustion modification leads to difficulties in boiler optimization. This is a result of several factors, including heightened awareness of the impact of combustion conditions on NOx emissions and plant efficiency and increased sensitivity of combustion conditions to process adjustments.

The adverse impacts of using low-NOx burners (LNBs) can sometimes be mitigated by burner optimization; however, these measures are typically performed at only one operating condition and cannot fully take into account changes in plant operating conditions over extended periods. Further, NOx emissions can vary with time by as much as ±20% around the long-term average. A system that reduces the magnitude of these variations and drives NOx emissions down towards the lower end of this range could help achieve continuous compliance without additional controls. Such a strategy could also provide NOx credits for averaging or trading programs.

Optimization Approaches

A number of approaches to process optimization are being investigated, including the use of artificial intelligence (AI), which involves computer-based decision-making processes that mimic those of the human brain. One example of AI is neural networks, which "learn" from experience and can adapt to changing environments. The use of neural networks for process optimization is a relatively recent development, and only a limited

Analogy between biological neural networks and artificial neural networks



Artificial Intelligence

Artificial intelligence (AI) encompasses several modes, including:

- Fuzzy logic, which involves evaluating process variables in accordance with approximate relationships that have been determined to be sufficiently accurate to meet the needs of the control system.
- Expert systems, which incorporate existing knowledge about process variables to provide a basis for deciding appropriate settings for optimum performance.
- Neural networks, which mimic the capacity of the human brain to handle complex nonlinear relationships and "learn" new relationships.

Neural networks are considered by some to be best suited as advisors, i.e., advanced systems that make recommendations based on various types of data input. These recommendations, which change as power plant operations change, suggest how plant equipment or technologies can be optimized.

Neural networks are a class of mathematical algorithms that simulate the operation of biological neurons.The neural network "learns" the relationships between operating conditions, emissions, and performance parameters by processing test data. In the training process, a neural network develops a complex nonlinear function that maps the system inputs to the corresponding outputs. This function is passed on to a mathematical minimization algorithm that finds optimum operating conditions.

In the evolution of AI systems, neural networks surpass their older cousins, expert systems and fuzzy logic. The least specific type of AI software, fuzzy logic, is equipped with a set of approximate rules used whenever "close enough is good enough." Elevators and camera autofocusing systems are primary examples of fuzzy logic systems. Fuzzy logic stops an elevator at a floor when it is within a certain range, not at a specific, definite point.

Expert systems, on the other hand, learn by following a set of preestablished rules written in codes or computer language. Expert systems are programmed to incorporate established relationships between input and output information based on detailed knowledge of a specific process.

Neural networks are the latest type of AI to enter the power plant industry. As computational devices that use organized principles of biological nervous systems, neural networks do not assume relationships. Instead, they determine relationships by analyzing data, learning much the way humans do, i.e., by example and repetition. When it assigns an incorrect output to correspond with a given input, the network corrects itself by changing the matrices embedded in the program. While it can take considerable time to complete this learning curve — depending on the complexity of the problem — neural networks outperform any other current approach to recognizing patterns and relationships.

Modeled after the human brain, which is made up of interconnected neurons that contain a limited amount of information, neural networks are constructed of simple data processing units with limited capabilities. When connected together, they form the most powerful AI system known, capable of such performance as estimating the lifespan of mechanical parts, diagnosing malfunctions in automobiles, and recognizing human speech. Most importantly, they are "smart" systems that are beginning to mimic the complex learning ability of the human brain.

Process Optimization in Electric Power Generating Plants

Today's competitive power plant environment has placed renewed emphasis on process optimization. Efficient power generation must take into account many factors including unit output, emissions, and fuel properties as well as operating costs. Power plants embody a mix of control problems that can be very challenging. In addition to internal control loops, optimization involves consideration of the rapid changes in load, including frequent startups and shutdowns resulting from close coupling to the power grid. This variability in load in turn is exacerbated by deregulation of the power industry.

Artificial intelligence (AI) has become a significant factor in the development of process controls. AI is being used to improve power plant operation by selection of optimum control settings to achieve the balance required among the numerous variables involved. Neural networks are the most advanced form of AI at present.

Application of AI depends on state-of-the-art engineering tools for modeling and controlling multivariable systems, which in turn make extensive use of the improved computing power that has only recently become available commercially. These approaches are made possible through utilization of the latest advances in Information Technology (IT).

number of commercial applications to power production have been made to date. However, neural networks represent cutting-edge technology that should see increasingly wide use in the years ahead.

As indicated above, a typical optimization problem in power plant operation involves minimizing NOx emissions without exceeding specifications for LOI. Reducing NOx emissions by combustion modification, such as by use of LNBs, inherently results in increased LOI because of reduced carbon burnout. Some power plants have been unable to meet stringent NOx emissions specifications without exceeding target levels of LOI required for fly ash sales. AI has begun to provide the optimization capability needed to meet these divergent criteria. AI is being employed to achieve operating conditions required to handle the tradeoffs between NOx reduction and combustion efficiency, and it does so in a manner beyond the capabilities of a human operator.

Neural networks are able to model multivariate, nonlinear relationships on a continuous basis, thereby providing the necessary feedback and control required by complex processes such as combustion in power plant boilers. They can provide reliable real-time recommendations based on performance objectives provided by the user. A further application of AI is to operate in a supervisory mode, where control settings are implemented through existing digital control systems (DCS).

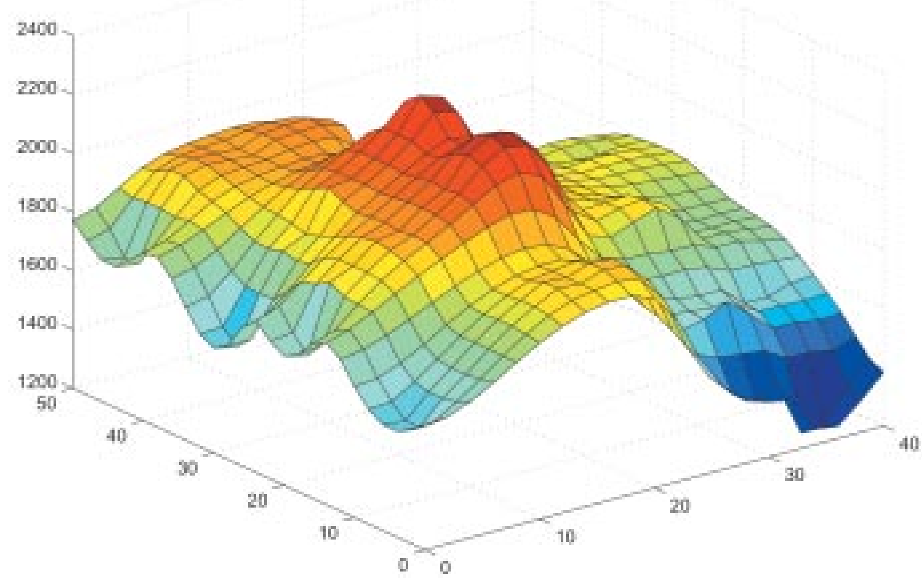
Software Developments

This report focuses on software developed as part of the CCT Program, including a computer program for predicting the effect of coal quality on power plant performance, an AI program initially applied to the optimization of combustion modification technologies for NOx emissions reduction, and a program designed to achieve least-cost operation of an entire power plant. These projects are described in the following sections.

Coal Quality Expert (CQE™)

Introduction

The project *Development of the Coal Quality Expert™* was selected in December 1988 under Round I of the CCT Program. Participants included ABB Combustion Engineering, Inc. (ABB/CE) and CQ Inc., with co-funding from Black & Veatch (B&V), EPRI (formerly the Electric Power Research Institute), and The Babcock & Wilcox Company (B&W). The project was completed and the final report was issued in June 1998.



Nonlinear, multivariate constrained optimization (Pavilion Technologies bulletin)

Project Description

The CQE™ project was undertaken to develop a software product that could be used either as a stand-alone work station or as a network application by utilities, coal producers, and equipment manufacturers to perform detailed analyses of the impacts of coal quality, capital improvements, operational changes, and/or environmental compliance alternatives on emissions, performance, and power production costs.

The project involved (a) characterization and cleanability analyses of various coals, (b) bench- and pilot-scale combustion testing of the coals in question, and (c) full-scale utility demonstration tests. Data obtained from these tests were used to develop the algorithms, subroutines, and programs included as part of the CQE™ technology.

The project was originally conceived by EPRI to incorporate the results and products of several ongoing R&D projects into computer software that would become a standard for studying fuel-related issues in the power industry. The CQE™ model, which addresses the effects of fuel quality from the coal mine to the busbar and the stack, is an integration and improvement of predecessor software tools, particularly the Coal Quality Impact Model (CQIM). It was designed to answer critical questions to be considered before a utility can be certain that it is operating its power plants within emissions limitations at the lowest cost.

The CQE™ software is composed of (1) technical models that evaluate performance issues; (2) environmental models that examine emissions and regulatory issues; and (3) financial models that relate performance to costs, including consumables (fuel, sorbents, etc.), waste disposal, and operating and maintenance. CQE™ is designed to quantify these relationships, using a minimum of coal quality information as input data.

CQE™ utilizes several previously existing models. These codes and models were developed by EPRI (with DOE support in some cases) as part of other programs and were not the focus of the CQE™ project. The previously existing models are described as follows:

Coal Quality Impact Model (CQIM): CQE™ uses the CQIM code to evaluate performance of many auxiliary systems in coal-fired power plants. The CQIM code can also be used to perform maintenance/availability, derating, sensitivity, and economic analyses as well as to model coal cleaning, blending, and transportation.

NOx Prediction Model (NOxPERT): This model predicts NOx emissions as a function of coal parameters, operating data, and furnace type.

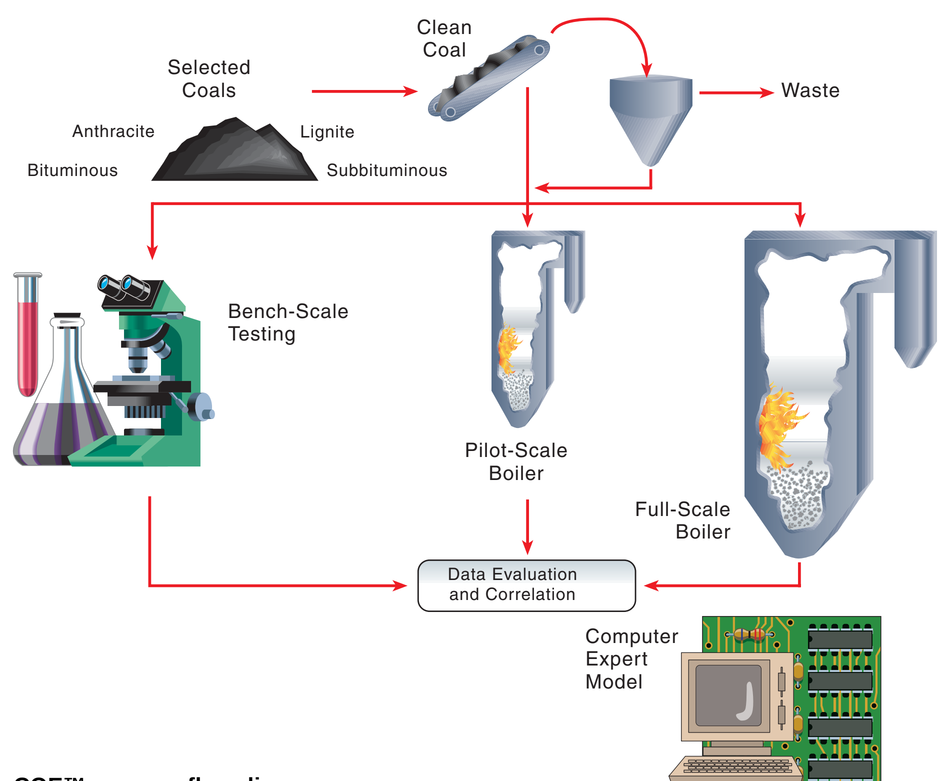
Common Systems Evaluator: This program models equipment systems serving more than one unit at a plant.

Acid Rain Advisor (ARA): ARA was designed to assist the user in evaluating options for compliance with the CAAA. ARA provides the means to rapidly select combinations of SO_2 reduction technologies at various units in a system, while viewing system-wide results. ARA can be used either on a stand-alone basis, in conjunction with CQIM, or within CQE™.

Boiler Expert: The CQE™ software incorporates a boiler expert model, which consists of the SLAGGO and FOULER routines developed by PSI PowerServe and the University of North Dakota Energy and Environmental Research Center. CQE™ expands boiler performance modeling beyond CQIM capabilities to interface with and use results from these routines, which are described in the following paragraphs

Slagging Expert (SLAGGO): SLAGGO simulates the entire cycle of ash formation, deposit initiation, growth and removal processes based on coal properties and boiler design and operating parameters. SLAGGO consists of several models and submodels including ash formation, ash transport, deposit growth, thermal properties, and deposit removal models as well as mineral matter transformation and alkali vaporization submodels; pyrite kinetics were excluded. Coal properties, boiler internal aerodynamics, and transport mechanics are accounted for to predict changes in cleanliness of the waterwall and superheater tubes in the furnace. Deposit removal by sootblowing is also modeled.

Fouling Expert (FOULER): FOULER predicts convective pass fouling based on boiler design, temperature and gas distributions, ash size and composition distributions, and sootblowing and load drop parameters. Thermal resistivities of each heat exchange section are utilized to iteratively calculate boiler temperature profiles, and a cleanliness factor is determined from the difference in heat transfer between dirty and clean tubes. Time intervals between sootblowing cycles can be optimized with FOULER.



CQE™ process flow diagram

Project Objectives

The goal of this project was to develop and demonstrate a software system that could be run on a personal computer to provide coal burning utilities with a predictive tool to assist in the selection of optimum quality coal for a specific boiler based on operational efficiency, cost, and environmental emissions. Data for the algorithms to be included in the CQE™ model were obtained from bench- , pilot- , and full-scale boiler field tests.

Software Description

Traditional methods of evaluating coals for power plant use involve testing on a large scale over a considerable period of time. CQE™, however, permits the use of much smaller quantities of coal over significantly shorter time periods. By incorporating algorithms based on large amounts of available data, CQE™ has the capability of predicting power plant performance with a minimum number of bench-scale tests of cleanability and fuel characterization. The net result is a much lower cost to achieve the desired assessments.

CQE™ allows users to construct models representing their actual unit configurations, capture complex interactions between economic and technical analyses, and quantify the economic effects of coal cleaning and power plant performance.

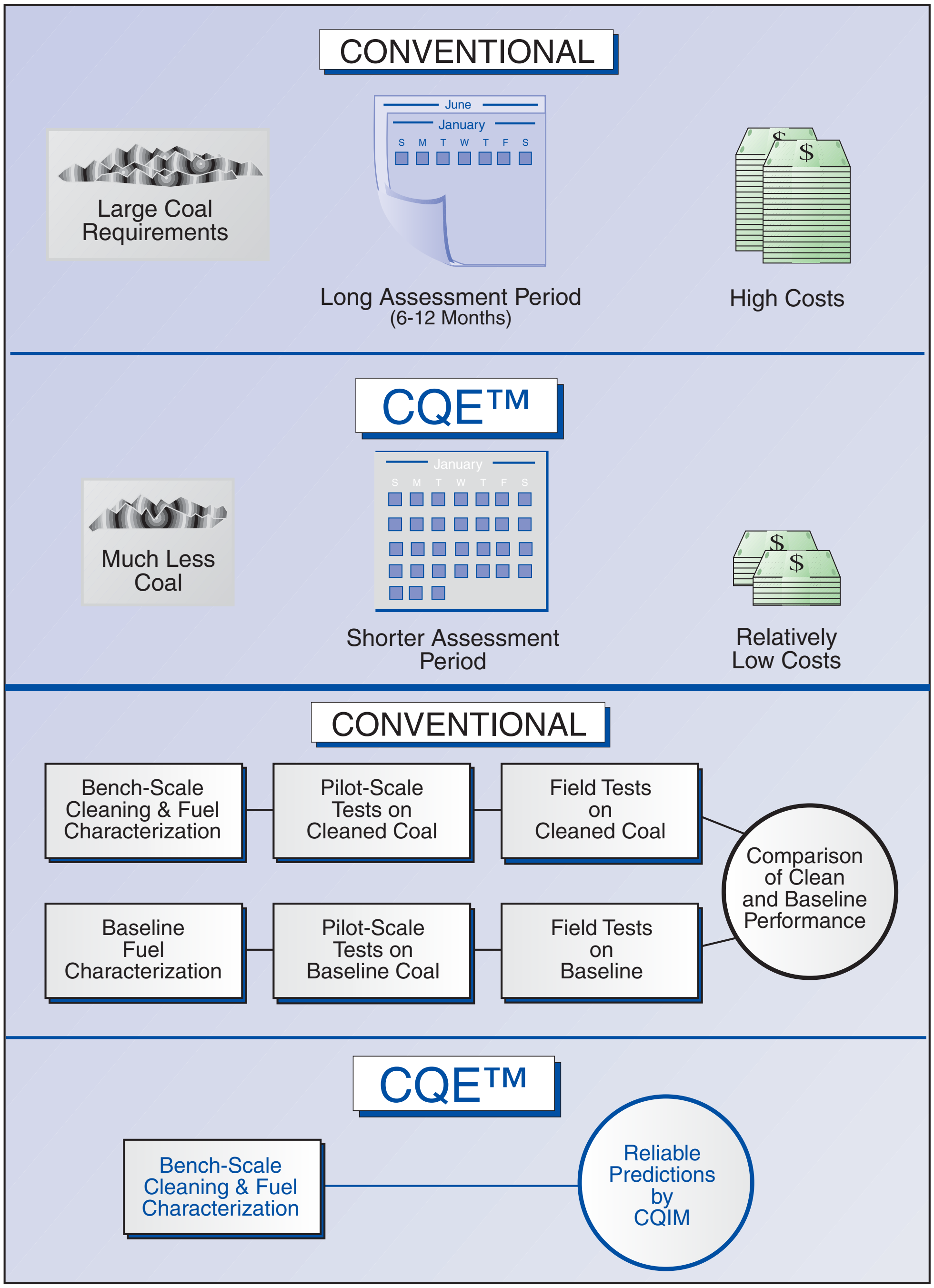
Development of the Software

CQE™ includes more than 100 algorithms based on the data generated in this project. The design philosophy incorporates sophisticated modeling techniques, including object-oriented design, coupled with an object database management system that permits different views into the data based on the specific situation being evaluated.

To develop the software tool, the CQE™ project included numerous supporting tasks to collect and analyze data to form the basis for the algorithms, methodologies, and submodels and to verify the accuracy and integrity of the software.

Coal Characterization Studies

CQ Inc. conducted 13 detailed coal cleanability characterization studies to provide baseline data for the CQE™ model. This step involved extensive investigations of physical and chemical properties of all components of the coal and assessments of the theoretical potential for removing ash-forming, sulfur-bearing, and trace element-bearing minerals associated with the coal.



Comparison of coal quality assessment methods

These coal characterizations were completed in conjunction with field combustion testing at the following sites:

- Public Service of Oklahoma's Northeastern Station
- Mississippi Power Company's Jack Watson Station
- Northern States Power Company's Allen S. King Station
- Alabama Power Company's Gaston Station

Additional combustion testing was done at New England Power Company's Brayton Point Station.

Pilot-Scale Combustion Tests

Pilot-scale combustion tests were conducted to support the coal cleanability characterization and field testing efforts. Fifteen different coals or coal blends from six different power plants were tested in ABB/CE's Fireside Performance Test Facility and B&W's Small Boiler Simulator. The purpose of this phase of the work was to provide data useful in predicting full-scale boiler combustion performance from pilot-scale tests while providing detailed quantitative performance data for CQE™ algorithm development.

Utility Boiler Field Tests

Boiler field testing was vital in establishing correlations between field- , pilot- , and bench-scale testing that were used to develop CQE™ algorithms and models. Correlations for fouling and slagging sample analyses were of special interest. Comprehensive test burn evaluations were performed at the utility test sites listed above. CQIM models, one for each boiler tested, were developed. The main objectives of this phase were to:

- Evaluate the accuracy of CQIM predictions vs. test data
- Assess the benefits of calibrating CQIM using detailed test burn data
- Identify elements of the CQIM predictions in which test burn results of improved equipment models could be used to enhance the predictive capabilities of CQIM and CQE™

The conclusions from the field tests address such issues as relative slagging/fouling rates for baseline and alternative coals, sootblowing requirements, and furnace exit gas temperature (FEGT). In addition to coal cleaning, which is an essential ingredient of strategies for improved coal utilization, CQE™ also incorporates a wide range of factors involved in power generation from coal.

Results

After completion of the tests, a CQE™ prototype model was showcased at trade shows and at an international coal conference in London, England in 1993. Final model development and verification were performed in 1994 and a CQE™ alpha version was released in March 1995. A beta version was issued in June 1995 and Version 1.1 was released in June 1996. Another beta version was released in 1999.

The CQE™ program has been made available to EPRI member utilities and is operational. Further refinement of the algorithms and input/output techniques will be performed as continued use is made of the program. Three products are available: use licenses, consultant licenses, and commercialization licenses. Further information can be found on the Vista™ Fuels Web server: http://147.182.5.102/. Vista™ is a joint venture of EPRI and B&V.

Commercialization of the Technology

The ARA software became available in 1992, with two commercial sales made, one in 1993 and one in 1995. Debugging of the CQE™ software proceeded through the end of the project. CQE™ has been distributed to about 35 utilities in the United States and one in the United Kingdom through membership in EPRI. B&V executed the first CQE™

commercialization license, and CQ Inc. is also licensed to commercialize the program. Under the terms of that license, B&V and CQ Inc. are working collaboratively to sell use and consultant licenses worldwide.

Product Advantages

With its array of capabilities, CQE™ has significant value to power generation companies, equipment manufacturers, environmental assessment firms, litigators, fuel suppliers, government organizations, and engineering firms.

Built on the foundation of CQIM, CQE™ brings new dimensions to the fuel analysis and decision-making process:

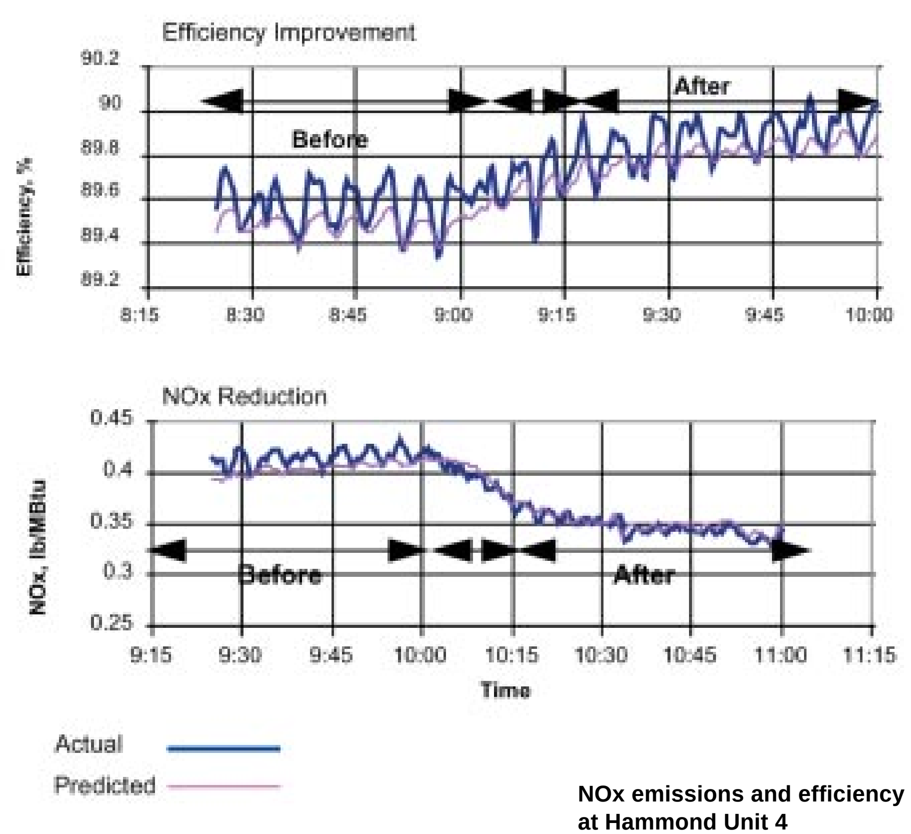
- Flexible modeling capabilities allow users to represent a broad range of equipment and system arrangements.
- Specialized applications address specific processes, including fuel purchasing, clean air compliance, and engineering support.
- Common data and output across a network support overall corporate fuel assessment needs.

CQE™ has the capability of predicting power plant performance with a minimum number of bench-scale tests. The result is a much lower cost to achieve the desired assessments compared with traditional approaches.

Conclusions

Development of the CQE™ model included a large number of bench-scale coal characterization tests, pilot-scale combustion tests, and full-scale utility boiler field tests. The resulting CQE™ software offers significant benefits in the selection of coal-based fuels and the design and operation of coal-fired power systems. By incorporating algorithms based on available data, CQE™ has the capability of predicting power plant performance with a minimum number of bench-scale tests of cleanability and fuel characterization.

The coal characterization tests performed in the course of this study measured the effectiveness of physical coal cleaning in removing ash-forming minerals, pyritic sulfur, and trace elements from bituminous and subbituminous coals. The ARA software, developed as part of the CQE™ project, can be used to select CAAA compliance strategies, either within CQE™ or as a stand-alone program.



NOx emissions and efficiency at Hammond Unit 4

Generic NOx Control Intelligent System (GNOCIS™)

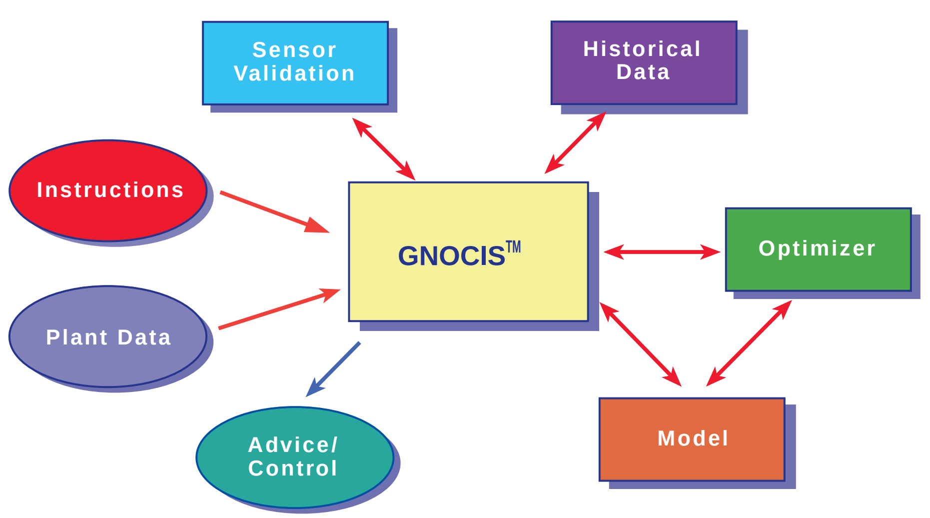
Introduction

AI has the potential to aid in optimizing boiler operation with a view to reducing emissions, minimizing UBC, and maximizing overall power plant efficiency. The Generic NOx Control Intelligent System (GNOCIS™), is an AI program developed to provide process control that achieves NOx reduction consistent with economic and operational constraints.

Project Description

The project *Demonstration of Advanced Combustion Techniques for a Wall-Fired Boiler* was selected in September 1988 under CCT Round II. The Participant was Southern Company Services, Inc. (SCS) and the test site was at Georgia Power Company's Plant Hammond, Unit 4, at Coosa, Georgia. Georgia Power and Southern Company Services are subsidiaries of Southern Company, a large producer of electricity from coal in the United States. The primary objective of the demonstration at Hammond Unit 4 was to determine the long-term effects of commercially available wall-fired low-NOx combustion technologies on NOx emissions and boiler performance. The original goals of this project have been completed and several technical reports have been issued.

A subsidiary goal of the project was to evaluate advanced instrumentation and controls applied to combustion processes. One of the systems tested was GNOCIS™. Since completion of these activities, the scope has been expanded to include further development of GNOCIS™ for power plant optimization. This extension of the CCT project is now underway.



Major elements of GNOCIS ™

Description of GNOCIS™

GNOCIS™ is an enhancement to a plant's DCS targeted at improving utility boiler efficiency and reducing emissions. GNOCIS™ development was funded by a consortium consisting of EPRI, PowerGen, Southern Company, URS Corporation (formerly Radian International), U.K. Department of Trade and Industry, and U.S. DOE. GNOCIS™ utilizes a neural network model of the combustion characteristics of the boiler that reflects both short- and long-term trends in boiler operating characteristics.

A constrained-nonlinear optimizing procedure is applied to identify the best operating set points for the plant. These recommended set points are implemented automatically without operator intervention (closed-loop), or, at the plant manager's discretion, conveyed to the plant operators for implementation (open-loop). The software is designed for continuous on-line use and is applicable to units burning coal, gas, or oil, and all combustion firing geometries.

Georgia Power Company's Plant Hammond Unit 4

GNOCIS™ is offered commercially by PowerGen, URS, and Southern Company. As of December 2001, GNOCIS™ has been installed on units representing more than 10,000 MWe of generation capacity in both the United States and Europe. Although results have been site specific, NOx emission reductions of more than 10% and efficiency improvements of more than 0.5% are not uncommon.

These commercial applications to date have shown that in many instances, simultaneous NOx reduction and improved boiler efficiency can be achieved. Given the (1) relatively low cost of optimization compared to other control technologies and (2) increasing volume of documented results, optimization has proven itself to be an increasingly viable alternative for NOx reductions and heat rate improvements.

Developmental Testing at Kingsnorth and Gaston

Prior to demonstrating GNOCIS™ as part of the CCT project at the 500-MWe Hammond Unit 4, development and testing of the technology was conducted at PowerGen's 500-MWe Kingsnorth Unit 1 and at Alabama Power Company's 250-MWe Gaston Unit 4.

Kingsnorth Station is situated on the banks of the Medway estuary in Kent, England. It is a coastal site with four 500-MWe tangentially fired units that were commissioned between 1970 and 1973. It is supplied with coals from a variety of worldwide sources. This plant was chosen for trials because (1) the use of LNBs had created LOI problems, (2) it had a modern control system with which GNOCIS™ could be interfaced, and (3) the range of coal feeds provided a challenging application.

For the Kingsnorth plant, GNOCIS™ was designed to make recommendations for excess oxygen, burner tilt, and feeder speeds. At this site, testing showed that implementing GNOCIS™ recommendations provided a 4 percentage point reduction in LOI with no increase in NOx emissions. Alternatively, NOx emissions were reduced by 10% while maintaining acceptable LOI.

Alabama Power's Gaston Unit 4 served as the other initial development site for GNOCIS™. This wall-fired unit is equipped with LNBs and uses Eastern bituminous coal from various sources as its fuel. At this site, GNOCIS™ was designed to operate in either closed- or open-loop fashion. Controlled variables were grinding mill coal flow and excess oxygen level, while parameters being optimized were NOx emissions, boiler efficiency, and LOI. For the Gaston plant, boiler efficiency improvements of 0.5 percentage point and LOI reductions of about 3 percentage points were obtained.

Hammond Demonstration

The objective of the commercial demonstration at Plant Hammond was to evaluate and demonstrate the effectiveness of advanced digital control/optimization methodologies as applied to the combustion modification technologies for NOx abatement installed during the CCT project, namely, LNBs and advanced overfire air (OFA).

The major tasks for the Hammond project included design and installation of the DCS, instrumentation upgrades, advanced controls/optimization design and implementation, and plant characterization of the unit both before and after activation of the advanced strategies. GNOCIS™ testing at Hammond commenced during the winter of 1995 in both open-loop/advisory and closed-loop/supervisory modes, representing one of the first applications anywhere of AI for commercial scale power plant control.

Using results from unit testing and projected unit load profiles, GNOCIS™ provided a range of benefits depending on whether the unit is operated to minimize NOx emissions, maximize overall plant efficiency, or minimize LOI. For the minimum NOx case, the annual savings (based on fuel cost savings only) were projected to be $238,000, increasing to $392,000 for the maximum efficiency case and decreasing to $191,000 for minimum LOI. At a typical GNOCIS™ installation cost of $250,000, these savings represent an excellent return on investment.

Future Work

Since its installation at Kingsnorth, Gaston, and Hammond, GNOCIS™ has been applied to many more sites. GNOCIS™ has now been installed on units representing more than 10,000 MWe of generation capacity, and other installations are planned. This is one of the major successes of the CCT Program. Enhancements and other applications of GNOCIS™ continue to be pursued.

In the extension of the CCT project at Plant Hammond, now underway, work is being conducted to expand the scope of the optimization envelope to encompass other power plant processes including sootblowing and ESP operation, as well as overall plant efficiency. This developmental effort has been driven largely by the success of GNOCIS™ as applied to boilers and the potential of further improvements in emissions control and plant performance. This extension has an expected completion date of March 2002.

Plant Economic Optimization Advisor (PEOA™)

Introduction

The *Milliken Clean Coal Technology Demonstration Project* was selected in September 1991 under Round IV of the CCT Program. The primary goal of this project was to demonstrate SO_2 and NOx removal from power plant stack gas by a combination of advanced technologies. It was conducted at New York State Electric & Gas Corporation's (NYSEG) Milliken Station (now owned and operated by AES). Operation was initiated in June 1995 and completed in May 1999.

The Saarberg-Holter-Umwelttechnik (S-H-U) process was used for SO_2 control, along with LNBs for NOx control. In addition, deep staged reburning using micronized coal was tested in this project, but this technology was not made a permanent part of the Milliken Station system. The S-H-U process is described in Topical Report No. 12, *Advanced Technologies for the Control of Sulfur Dioxide Emissions from Coal-Fired Boilers*, June 1999, and micronized coal reburning is described in Topical Report No. 14, *Reburning Technologies for the Control of Nitrogen Oxides Emissions from Coal-Fired Boilers*, May 1999. Both the SO_2 control and the NOx control demonstrations were highly successful in meeting project goals.

As part of the project, work was also done on the development of PEOA™, an on-line electronic performance system. DHR Technologies, Inc., was responsible for the PEOA™ effort.

Description of PEOA™

PEOA™ was designed to assist plant personnel in meeting the requirements of Title IV of the CAAA and in optimizing overall

The Clean Coal Technology Program

The Clean Coal Technology (CCT) Program of the U.S. Department of Energy (DOE), a model of government and industry cooperation, supports DOE's mission to foster a secure and reliable energy supply system in the United States that is environmentally and economically sustainable. The CCT Program represents an investment of over $5 billion in advanced coal-based technology, with industry and state governments providing a significant share — 66% — of the funding. With 26 of the 38 projects having completed operations, the CCT Program has already yielded Clean Coal Technologies that are capable of meeting existing and emerging environmental regulations and competing in a deregulated electric power marketplace.

The CCT Program provides a portfolio of process options that will enable continued use of the United States' huge economically recoverable coal reserves (over 270 years at current consumption rates) to meet the nation's energy needs economically and in an environmentally sound manner.

As the new millennium begins, many of the Clean Coal Technologies have reached commercial status. Industry stands ready to employ them both domestically and internationally to respond to the energy and environmental demands of the 21st century. For existing power plants, there are cost-effective environmental control devices to minimize emissions of sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (PM). The CCT Program has taken a pollution prevention approach as well, providing technologies that remove pollutants or their precursors from coal before combustion.

Also ready is a new generation of technologies that can produce electricity and other commodities, such as steam and synthesis gas, at high efficiencies consistent with concerns about global climate change.

Additionally, new technologies have been introduced into major coal-using industries, such as steel production, to enhance environmental performance. Thanks in part to the CCT Program, coal — abundant, secure, and economical throughout much of the world — can continue in its role as a key component in supplying U.S. and world energy needs.

The CCT Program also has global importance in providing clean and efficient coal-based technologies to a burgeoning energy market in developing countries. World energy consumption is expected to increase 63% by 2020, and coal, the predominant indigenous fuel in much of the world, will be the fuel of choice for electricity production. CCT processes offer a cost-effective means to mitigate potential environmental problems associated with this unprecedented energy growth.

Most of the CCT demonstrations have been conducted at commercial scale, in actual user environments, and under circumstances typical of commercial operations. Each project addresses one of the following four market sectors:

- Advanced Electric Power Generation
- Environmental Control Devices
- Coal Processing for Clean Fuels
- Industrial Applications

The software programs described in this Topical Report were developed under Environmental Control Devices and Coal Processing for Clean Fuels.

plant economic performance. This demonstration was intended to show the capability of PEOA™ to smoothly integrate with the power plant DCS, performance monitoring instruments, and information systems on a variety of network topologies, operating systems, and hardware platforms.

PEOA™ was proposed as a means of integrating key aspects of plant information management and analysis to assist plant personnel with process optimization, including emissions monitoring and compliance. PEOA™ is designed to incorporate all major aspects of plant operation, including steam generator and turbine, emissions control, heat transfer, auxiliary systems, and waste management. PEOA™ was intended primarily for use by plant operators but could also be useful for engineers and managers.

PEOA™ automatically determines and displays key operational and control set points for optimized cost operation. The system provides operators with on-line emissions monitoring and diagnostic capabilities, along with rapid access to reports and trend information.

PEOA™ is a neural networking system that uses optimization algorithms to evaluate key emissions data, such as NOx, SO_2, O_2, CO, CO_2, LOI, and opacity; other operational parameters, such as boiler and turbine operation, gypsum sales, and emissions credits; and the impacts of coal quality and coal mixing. The system provides "what-if" capabilities to allow users to employ the optimization features to evaluate various operating scenarios.

In addition to providing optimized set point data, PEOA™ also provides plant operators and engineers with expert advice and information to help optimize total plant performance. It is an open, client/server-based system using object-oriented development technologies.

PEOA™ models the plant and then uses this model to find the least cost operating conditions given certain constraints. As discussed previously, a neural network "learns" the input/output relationships by using past data. Therefore, the data must be valid to achieve the expected results from the network model.

Originally, an on-line performance monitor (OPM) was to be installed to provide data validation for PEOA™, as well as calculations and graphical representations of plant performance. However, the OPM system was dropped from the demonstration program for cost reasons, with the result that PEOA™ was required to perform its own calculations and data validation had to be done manually.

Results

To accomplish the data verification that had initially been intended for OPM, NYSEG reviewed all pertinent data points to ensure that the information was accurate. Two initial tests of PEOA™ were conducted, one short-term and one longer-term. The results were promising but inconclusive. After a limited amount of additional testing of the system, it was determined that difficulties experienced in applying PEOA™ at Milliken were not easily remedied, and the optimization effort was discontinued.

Although this particular application of neural networks to power plant optimization was not successful, the concept is fundamentally sound, and future developments of this technology will undoubtedly prove to be feasible. DHR Technologies has sold six modules of their PEOA™ system, although these were in applications not related to electric power generation.

Market Potential of Software Systems

With a wide range of capabilities, CQE™ is of potential interest to power generation companies, equipment manufacturers, environmental assessment firms, litigators, fuel suppliers, government organizations, and engineering firms.

Significant market penetration of GNOCIS™ has already been achieved, and additional applications are anticipated. Partly as a result of successes to date in minimization of NOx emissions, further development of GNOCIS™ technology is in progress with a view to extending its capability to control other aspects of boiler operation. This is likely to result in many more applications in the electric power generation industry.

Conclusions

Under the CCT Program, significant progress has been made in the development of computer software for optimization of electric power generation.

The CQE™ software developed under this Program offers significant benefits in the selection of coal-based fuels and in the design and operation of coal-fired power systems. By incorporating algorithms based on available data, CQE™ has the capability of predicting power plant performance with a minimum number of bench-scale tests of cleanability and fuel characterization. The result is a much lower cost to achieve the desired assessments compared with traditional approaches.

With GNOCIS™ installations representing more than 10,000 MWe of generation capacity, the development of this AI system represents one of the major successes of the CCT Program. Designed as a low-cost alternative to major capital expenditures for retrofits, GNOCIS™ software offers continuous optimal operation of boilers over a wide range of conditions. Enhancements to GNOCIS™ are underway to increase its range and scope of application in the generation of electric power.

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Contacts for CCT Projects and U.S. DOE CCT Program

Participant Contacts

Clark Harrison, President
CQ Inc.
160 Quality Center Rd.
Homer City PA 15748
(724) 479-3503
(724) 479-4181 *fax*
clarkh@cq-inc.com

John N. Sorge, Project Manager
Southern Company Services, Inc.
14N-8195
P.O. Box 2625
Birmingham AL 35202-2625
(205) 257-7426
(205) 257-5367 *fax*
jnsorge@southernco.com

James Harvilla, Project Manager
New York State Electric & Gas Corporation
Corporate Drive - Kirkwood Industrial Park
P.O. Box 5224
Binghamton NY 13902-2551
(607) 762-8630
(607) 762-8457 *fax*
jharvila@spectra.net

U.S. Department of Energy Contacts

C. Lowell Miller
Director, Coal Fuels & Industrial Systems
U.S. Department of Energy, FE-24
Germantown MD 20874-1290
(301) 903-9451
(301) 903-2238 *fax*
lowell.miller@hq.doe.go

Joseph B. Renk
Project Manager - CQE™
National Energy Technology Laboratory
P.O. Box 10940
Pittsburgh PA 15236-0940
(412) 386-6406
(412) 386-4775 *fax*
joseph.renk@netl.doe.gov

James R. Longanbach
Project Manager - Wall-Fired Project
National Energy Technology Laboratory
P.O. Box 880
Morgantown WV 26507-0880
(304) 285-4659
(304) 285-4469 *fax*
james.longanbach@netl.doe.gov

James U. Watts
Project Manager - Milliken Project
National Energy Technology Laboratory
P.O. Box 10940
Pittsburgh PA 15236-0940
(412) 386-5991
(412) 386-4775 *fax*
james.watts@netl.doe.gov

List of Acronyms and Abbreviations

ABB/CE .... ABB Combustion Engineering, Inc.
AI .... artificial intelligence
ARA .... Acid Rain Advisor
B&V .... Black & Veatch
B&W .... The Babcock & Wilcox Company
Btu .... British thermal unit
CAAA .... Clean Air Act Amendments of 1990
CCT. .... Clean Coal Technology
CEMS .... continuous emissions monitoring systems
CO .... carbon monoxide
CO_2 .... carbon dioxide
CQE™ .... Coal Quality Expert
DCS .... digital control system
CQIM .... Coal Quality Impact Model
DOE .... U.S. Department of Energy
EPA .... .U.S. Environmental Protection Agency
EPRI .... formerly the Electric Power Research Institute
ESP. .... electrostatic precipitator
FEGT .... furnace exit gas temperature
GNOCIS™ .... Generic NOx Control Intelligent System
Hg .... mercury
LNB. .... low NOx burner
LOI .... loss on ignition
MWe .... megawatts of electric power
NH_3 .... ammonia
NOx .... nitrogen oxides
NYSEG .... New York State Electric & Gas Corporation
O_2 .... oxygen
OFA. .... overfire air
OPM .... on-line performance monitor
PEOA™ .... Plant Economic Optimization Advisor
SCS .... Southern Company Services
S-H-U .... Saarberg-Holter-Umwelttechnik
SO_2 .... sulfur dioxide
UBC .... unburned carbon

To Receive Additional Information

To be placed on the Department of Energy's distribution list for future information on the Clean Coal Technology Program, the demonstration projects it is financing, or other Fossil Energy Programs, please contact:

Robert C. Porter
Director, Office of Communication
U.S. Department of Energy, FE-5
1000 Independence Ave. SW
Washington DC 20585
(202) 586-6503
(202) 586-5146 *fax*
robert.porter@hq.doe.gov

Otis Mills, Jr.
Public Information Office
U.S. Department of Energy
National Energy Technology
Laboratory
P.O. Box 10940
Pittsburgh PA 15236-0940
(412) 386-5890
(412) 386-6195 *fax*
otis.mills@netl.doe.gov

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