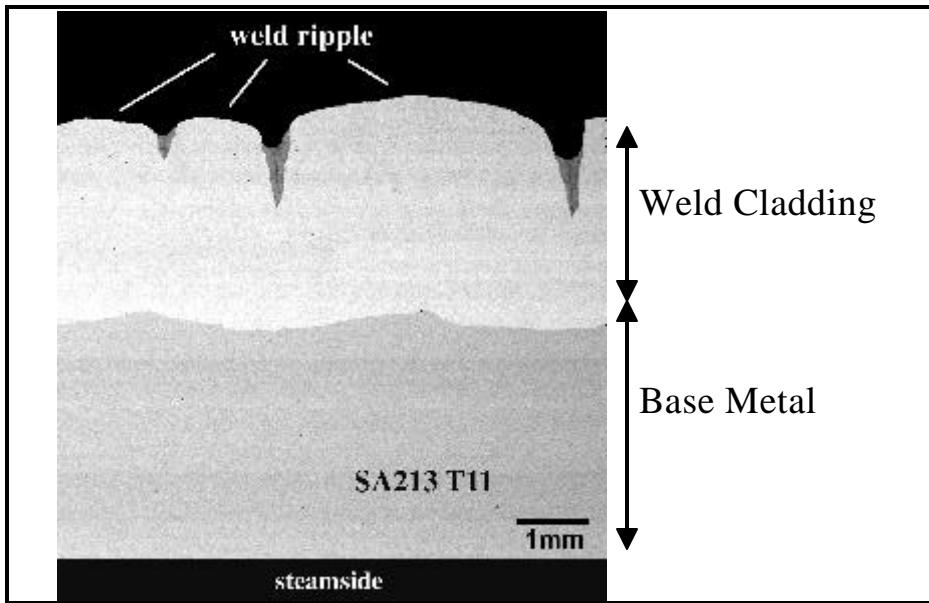


LEHIGH ENERGY UPDATE



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Cross Section View of Circumferential Cracks in a Weld Cladding

LEHIGH RESEARCHERS STUDY CRACKING OF WELD OVERLAY COATINGS

Since the early 1990's, U.S. utilities have been making major modifications to their fleets of coal-fired boilers to comply with NO_x regulations. In many cases, this involved installation of low NO_x burners and overfire air registers, often resulting in oxygen deficient regions in the vicinity of the burners. Some of the coal-fired utility boilers, which were converted to low NO_x operating conditions, subsequently experienced increased rates of waterwall corrosion. In response, some utilities turned to weld overlay coatings for corrosion protection. In 1998, reports began drifting back to the ERC that some boilers with weld overlay coatings were experiencing circumferential cracking of coated waterwall tubes. Since then, researchers at the Center have been working to determine why these coating failures are occurring.

The materials research team, led by Drs. Arnold Marder and John DuPont has been studying coatings for boiler tubes for more than a decade. Their work has included

investigations into the mechanisms of waterwall corrosion and the effects of furnace conditions and alloy composition on corrosion rate. They have looked at different types of coatings, including weld overlay, thermal spray and chromized. Their research has included laboratory experimentation, laboratory evaluation of tube specimens obtained from the field, and computer simulations.

As part of this activity, they recently completed a research program that evaluated the corrosion resistance of commercial weld overlay coatings in a

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DILUTION EXTRACTIVE PROBE IMPROVEMENTS NOW AVAILABLE COMMERCIALY

Utilities with fossil-fired power plants are required to use continuous emissions monitoring systems (CEMS) to measure quantities such as SO₂ and NO_x emissions. Among its many components, the typical CEM system includes a device referred to as a dilution extractive probe for removing a small sample of flue gas from the stack. Because of its design and the way it operates, the dilution extractive probe can be a source of measurement error that results in overreporting of emissions. The Energy Research Center and PPL Generation, LLC (PPL) have developed modifications to the standard dilution extractive probe system that eliminate a significant part of this sampling error (see Lehigh Energy Update, February 2000). PPL and the Energy Research Center are in the process of commercializing these improvements through a technology referred to as **DRCalc™**.

A typical dilution-extractive CEMS sampling system includes a probe with a critical or sonic orifice designed to extract a sample of flue gas from a stack or duct. The sample is mixed with dilution air in the probe. The diluted sample is then conveyed to analyzers for measurement of the compounds at lower concentrations. The diluted sample concentrations are then corrected back to source level readings by multiplying the analyzer readings by the dilution ratio, the ratio between dilution air and sample gas flow rates.

During normal operation, a sample of flue gas from the stack is drawn into the probe, mixed with clean, dry air and then sent to the gas analyzers in a diluted form.

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range of oxidizing/sulfidizing environments and various slag compositions. With these results they were able to better define the corrosion mechanism in low NO_x boilers through accelerated tests that included cyclic gas experiments. They have also looked at the stresses and strains which arise during the application of weld overlay coatings. Teaming with Dr. Herman Nied, a specialist in stress analysis and fracture mechanics, they investigated the effects of welding procedures on the quality of the weld overlay coating and on the potential for waterwall tube panel buckling.

In 1998, the group obtained five tube samples from three utilities, all with Inconel 625 weld cladding. Laboratory analysis showed the weld clad coatings were not visibly thinned, but they did contain longitudinal and circumferential cracks which were quite severe on four of the five tubes. The cause of the longitudinal cracks was attributed to improper welding procedures and recommendations were made on ways of avoiding these types of cracks.

The circumferential cracks found across the weld cladding are of greater concern since they are related to boiler operating environment. These ranged from minor to very severe, with almost half the circumferential cracks having fully penetrated the cladding, and in some cases, into the tube material beneath the cladding. Detailed chemical analysis showed each circumferential crack contained a sulfur "spine" which extended all the way down to the crack tip.

Comparison of cracks to those found in an earlier study of chrome moly low-alloy boiler tube steels showed a striking similarity. In the 1989 study, the materials group characterized circumferentially cracked low alloy steel tubes retrieved from service in several pulverized coal boilers. There were approximately 20 to 25 circumferential cracks per inch. Just as with the cracks recently found in weld overlay claddings, each crack was filled primarily with an iron oxide corrosion product, but each also possessed an iron sulfide "spine" running down to the crack tip.

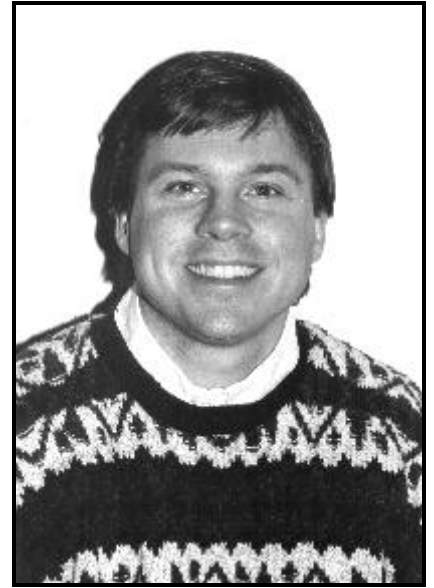
According to Marder, "Our research suggests the circumferential cracks are caused by a combined process of corrosion and thermal fatigue. Stresses in the tube walls can be caused by temperature gradients, resulting from fluctuations due to slag falls, sootblower

operation and changes in the flame. These stresses are magnified, in some cases, due to a thermal expansion mismatch between the cladding material and the base metal. In general, corrosion can be caused by both oxidation and sulfidation mechanisms. However, sulfidation is a more severe factor in coal-fired boilers because of the role which the sulfur plays in the crack propagation process. Susceptible locations on the cladding surface act as thermal stress concentrators and are potential sites for crack initiation and propagation. Corrosive sulfur species diffuse to the crack tip and react with the steel alloy at the tip. This weakens the alloy and permits continued growth of the crack with time."

DuPont adds, "Now that we think we know the causes of cracking of weld clad coatings, we are continuing our studies to determine why some weld overlay coatings experience circumferential cracking and others don't. Some coating alloys are obviously more susceptible to corrosion attack. There may also be some features of the weld overlay process which lead to initiation of corrosion induced cracking. Our goal is to be able to specify which alloys to use and how to perform the welding process to minimize the potential for failure."

Marder adds, "Based on discussions with our utility sponsors, we've developed proposals for two new research projects that we think will help power companies cope with waterwall degradation in low NO_x boilers. One project, "Development of Low Cost Weld Overlay Coatings for Low NO_x Waterwall Tubes," will apply material design principles to develop low cost core wire compositions for weld overlay coatings. The other project, "Remaining Life Assessment of Circumferentially Cracked Weld Overlay Coatings" will estimate remaining life of circumferentially cracked tubes as a function of stress level, coating composition and corrosion environment. Together, these two programs will enable utility companies to overcome the circumferential cracking problem found in certain existing weld overlay coatings and apply a new generation of low cost weld overlay coatings for the more stringent requirements expected in the future." •

ERC RESEARCHER CITED FOR WORK ON WELD CLADDINGS



Kevin Luer, a Ph.D. student in the Energy Research Center, recently won the Grand Prize awarded by the American Society of Metals in its Metallographic Contest at the Fall 1999 meeting. Kevin's award-winning poster described his analysis of the corrosion fatigue process that Alloy 625 weld claddings undergo when exposed to a combustion environment.

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For more information on weld overlay coatings research, please contact Dr. Arnold Marder at (610) 758-4197 or arm0@lehigh.edu.

("Dilution Probe" Continued from P. 1)

Dilution ratios of air-to-sample gas flow rates of 50 to 200 are typically used. The relationship between the gas concentration in the stack and the pollutant levels measured at the analyzers is constant if the dilution ratio does not change over time. In practice, however, the dilution ratio does change; and thus the dilution ratio determined at calibration conditions will differ from the value when the dilution probe is sampling flue gas. There are many factors that affect dilution air flow rate and sample gas flow rate. These include, for example, stack temperature and absolute pressure, flue gas molecular weight and dilution air supply pressure. As a consequence, the dilution ratio varies with stack conditions and probe operating conditions, resulting in errors in concentration measurements as large as 10% in some situations.

Previous attempts to correct for stack pressure and temperature variation do not adequately account for all the factors which affect the dilution ratio. Indeed, a PPL analysis of its own CEMS data indicated that the original correction algorithm used in the PPL CEM systems was inducing a significant positive measurement bias error. To resolve the discrepancy, PPL and the ERC worked together to develop the new dilution ratio calculation system and successfully implemented it on PPL stack CEM systems in 1999.

The Dilution Ratio Calculation System (**DRCalc™**) provides equipment and software for reducing the measurement bias error, correcting for variations in:

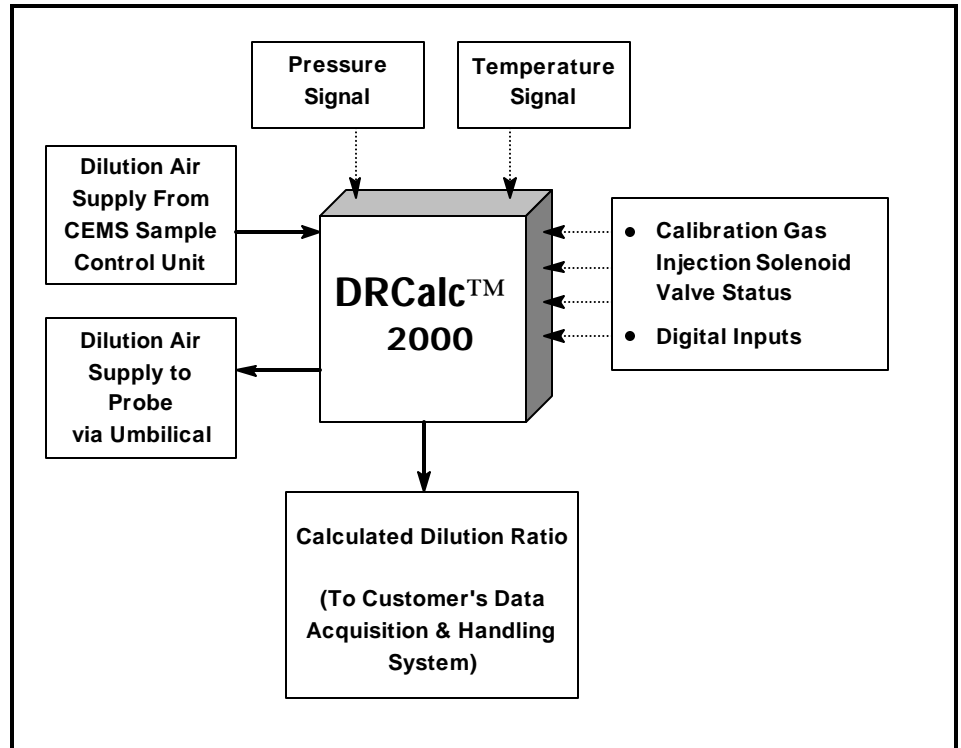


Figure 1: Typical DRCalc™ Arrangement

- ! Dilution air supply pressure,
- ! Dilution air supply temperature,
- ! Stack or duct pressure,
- ! Stack or duct temperature,
- ! Sampled gas molecular weight,
- ! Calibration gas molecular weight.

The **DRCalc™** unit consists of a computing device, which is connected to the CEMS and to the plant data acquisition system. In addition, the dilution air supply from the CEMS sample control unit is routed through **DRCalc™** to the dilution probe. Using this information, **DRCalc™**

determines the dilution ratio in real-time. The calculated dilution ratio is then multiplied by the analyzer-measured pollutant gas concentrations of the diluted sample to continuously compute the concentration of the pollutants in the stack gas. A patent is pending for the method used to calculate the dilution ratio.

DRCalc™ can be readily implemented in the design of new CEM systems and can also be easily adapted to an existing CEM installation. In the latter case, the dilution air supply from the sample control unit of the CEMS to the probe is routed through the **DRCalc™** unit, and wiring connections for various signals are made to the customer's CEMS. For an unheated EPM probe used in a 40 CFR 75 CEMS application, the stack pressure and temperature signals used to correct stack flow rate to standard conditions are wired into the **DRCalc™** unit.

Once all the connections are made, the Data Acquisition & Handling System (DAHS) is re-programmed to substitute the use of the **DRCalc™** output in lieu of a constant dilution ratio or an existing dilution ratio correction algorithm. The dilution ratio calculated by the **DRCalc™** unit is wired into the DAHS via a new or spare analog input. The monitoring systems are re-calibrated based on the new dilution ratio. Calibration and Linearity Error Tests are then conducted to verify

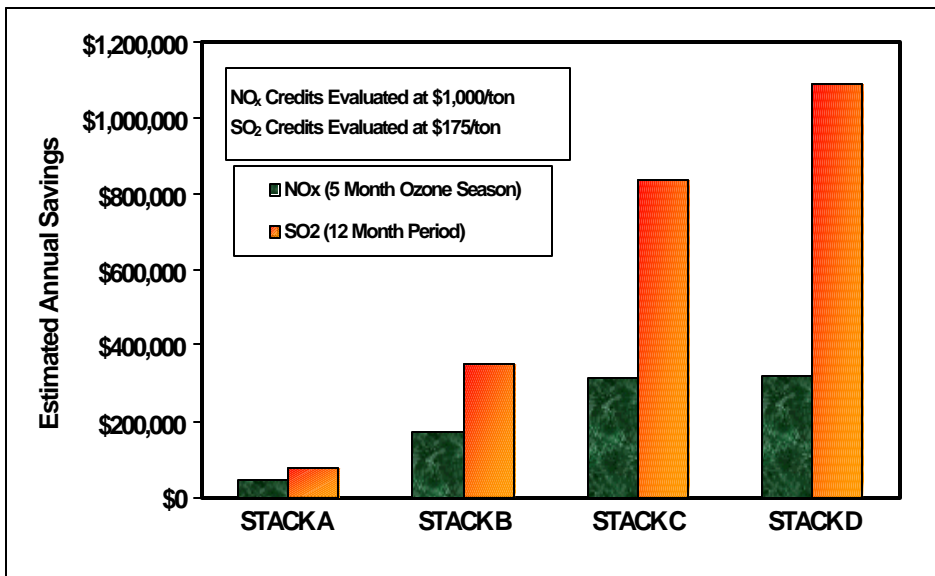


Figure 2: Economic Benefit for Four PPL Stacks

("Dilution Probe" Continued from P. 3)

the monitoring systems meet the EPA quality assurance requirements.

DRCalc™ can be rack or wall-mounted for ease of installation and with minimal programming changes to the Data Acquisition and Handling System (DAHS). A typical **DRCalc™** implementation is illustrated in Figure 1. Equivalent arrangements are available for probes equipped with temperature controlled heaters.

SAVINGS

PPL has implemented **DRCalc™** on all of its fossil-fired units, taking the steps necessary to ensure the modifications met the quality assurance requirements of the CEMS regulations. Evaluation of the results showed a 3.4% to 9.2% reduction in tons of NO_x and SO₂, compared to those that would be reported assuming a constant dilution ratio. The economic benefits for four PPL stacks are shown in Figure 2. The estimated annual savings are based on reduction in reported NO_x over the five month ozone season and on reduction in reported SO₂ over 12 months. These units range in capacity from 300 MW (Stack A) to 750 MW (Stack D). Total annual savings for the four stacks are \$3.2 million for the conditions specified in the figure. •

For more information on **DRCalc™**, please contact:

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ASH SLAGGING AND FOULING EXPERT JOINS ERC STAFF



Richard Conn
Senior Research Engineer

Dr. Richard Conn, an expert in ash slagging and fouling problems in boilers, recently joined the Energy Research Center staff as a Senior Research Engineer. Prior to joining Lehigh, Dr. Conn worked on fuel and ash problems in a variety of combustion systems, including pulverized coal boilers, heavy oil-fired package boilers, circulating fluidized beds, biomass-fired stokers, and municipal solid waste to energy class. At the Energy Research

Center, Dr. Conn's principal areas of activity will deal with the effects of coal properties, boiler design and boiler operating conditions on slagging and fouling and with the impacts of slagging and fouling on the ability to reduce emissions and improve heat rate.

Dr. Conn received his degrees in Chemical Engineering and Fuel Science from Pennsylvania State University. He has worked at the Foster Wheeler Development Corporation in the fuels and combustion area and at the York Shipley Company in York, Pennsylvania in design and development of advanced fluidized bed coal combustion and gasification processes and development of ultra-low NO_x combustion systems. He was also with the U.S. Department of Energy at the Morgantown Energy Technology Center, performing laboratory combustion studies with coal water fuels for gas turbines and with the University of North Dakota Energy and Environmental Research Center in Grand Forks, North Dakota, where he was involved in studies on fouling of low rank coals.

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