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Instrumentation and Diagnostics

Technology Status Report

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EXECUTIVE SUMMARY

This Technology Status Report describes research and accomplishments for the Instrumentation and Diagnostics (I&D) Projects within the Advanced Research and Technology Development (AR&TD) Program of the United States Department of Energy (DOE) Office of Fossil Energy (FE).

Process understanding and control can be improved through the development of advanced instrumentation and diagnostics. The thrust of the I&D Projects is to further develop existing measurement and control techniques for application to advanced coal-based technologies. Instrumentation and diagnostics assists in the commercialization of advanced coal technologies by furnishing information that leads to increased system efficiencies, reduced capital and operating costs, decreased solid waste generation, and reduced pollutant emissions.

The projects are grouped according to chemical analysis, particle characterization, thermophysical properties, process control systems, and multiphase flow characterization. The following are project highlights.

- **Chemical Analysis:** An inductively coupled plasma (ICP) instrument has been developed to analyze trace elements in gasification and combustion process streams. Laser-induced breakdown spectroscopy (LIBS) or laser spark spectroscopy (LSS) can be used for *in situ* analysis of gases, particles, and deposits, although *in situ* calibration is still needed. In addition, a laser-based optical diagnostic technique based on photodissociation has been developed to monitor trace levels of alkali compounds *in situ*. The technique promises to be compatible with the harsh conditions of coal combustion.
- **Particle Characterization:** An *in situ* two-color Mie scattering technique with LSS can simultaneously measure the size, velocity, and elemental composition of coal particles during combustion. Optimal configurations have been identified for measuring particle sizes from laser Doppler velocimeter signals. Millimeter wave spectroscopy can be used to measure the temperature of particles and may be able to measure the composition of major gas species and the gas-phase temperature.
- **Thermophysical Properties:** A high-temperature, fluorescence thermometry technique has accurately measured gas temperatures during field testing in combustion and gasification environments. A sodium line emission pyrometer has measured temperatures in a coal combustor. "Smart" optical fibers

were installed on a ceramic cross-flow filter and successfully detected strains caused by changes in process conditions.

- **Process Control Systems:** Expert systems have been developed to improve the control of advanced coal-based processes. Specifically, a control scheme was developed, which tunes the proportional and integral gains to position a particle in an electrodynamic balance, and a bed level monitor was designed for a fixed-bed gasifier system.
- **Multiphase Flow Characterizations:** Capacitance flowmeters were developed to determine the mass flowrate, solid volume fraction, and particle velocities of coal slurries.

1.0 INTRODUCTION

This Technology Status Report summarizes AR&TD I&D Projects. These I&D techniques measure and control process conditions in advanced coal-based conversion and utilization technologies. Some promising advanced coal-based technologies include pressurized fluidized-bed (PFB) combustion combined-cycle systems, integrated gasification combined-cycle (IGCC) systems, direct coal-fired gas turbines, coal-fueled diesels, and fuel cells. The development of new and efficient advanced coal-based systems has created an urgent need for understanding these processes, monitoring key parameters, and controlling the critical functions. Determining the effects of process parameters can show the potential advantages of the process, as well as its limitations. Information derived from instrumentation measurements is useful in scaling the process to larger sizes and in developing economics.

Frequently, off-the-shelf instrumentation and diagnostics do not meet the special requirements imposed by FE processes. The main thrust of the I&D Projects is to determine measurement requirements and modify the latest instrumentation to meet those requirements, although new instrumentation techniques have been initiated. The goal of I&D Projects is to demonstrate feasibility. It is anticipated that the private sector will commercialize viable instrumentation and diagnostics techniques that were demonstrated in the AR&TD program.

Developing instrumentation requires knowledge of the processes and an understanding of instrumentation behavior in different environments. Advanced FE processes can be a difficult application for instrumentation. The environments of advanced FE processes are typically high-temperature, high-pressure (HTHP), corrosive, erosive, and dynamic. It is desirable to have cross-cutting techniques that have applications for many processes. Data are needed to improve system efficiencies, reduce pollutant formation, and curtail waste disposal in the advanced FE processes.

2.0 BACKGROUND

Several reports describe instrumentation and diagnostics for energy applications (Nelson et al. 1987; Haran 1986; Hardesty 1984; Liptak and Leiter 1980; O'Fallon et al. 1976). These reports identify instrumentation needs, assess available instrumentation, and describe instrumentation techniques. The status of many AR&TD instrumentation and diagnostic projects is included in Contractors Meeting Proceedings (Gailing and Goldberg 1989; Hickerson 1988; and Holcombe 1987). In addition, DOE's Morgantown Energy Technology Center (METC) has created an information system to track FE instrumentation research efforts. This information system stores and organizes abstracts from published documents on FE instrumentation research. Appendix A provides a list of abstracts arranged by author that were in the information system database as of July, 1990.

Many advanced coal-based processes require HTHP operating conditions to achieve the efficiencies necessary to be cost effective. Intrusive sensors must be mechanically strong and resistant to both chemical attack and particle erosion in these environments. Coal contains species that can react with materials of construction to cause corrosive failures. Chemical attack or corrosion is mainly a function of temperature and composition. Erosion is primarily a function of particle size and stream velocity. The mineral matter in coal can produce particles of sufficient size to be very erosive.

Figure 1 is a schematic of a simplified advanced coal-based system. The shaded area shows where the most "challenging" operating conditions exist and is the area of emphasis for most of the AR&TD I&D Projects research. This area begins with feeding coal into the conversion units (gasifier or PFB combustor) and ends after the gas turbine. Typical operating conditions for this system are temperatures greater than 800 K and pressures greater than 10 bar. This system includes both oxidizing and reducing gas environments.

Hot gas cleanup approaches are especially targeted for diagnostics development. Hot gas cleanup devices remove coal-derived contaminants, including particles, sulfur, and trace metals. System efficiencies remain high because these contaminants are removed from the hot process streams without the significant loss of thermal energy. In coal gasification systems, it is advantageous to remove contaminants prior to combustion. The lower gas volume upstream of the combustor results in smaller vessels, and thus reduces the capital costs.

3.0 ACTIVITIES

I&D Project descriptions have been grouped by activities. These activities are chemical analysis, particle characterization, thermophysical properties, process control systems, and multiphase flow characterization. The investigations include development of sensors to measure key parameters, improvements to methods for transferring signals, refinements to diagnostics to quantify and understand the processes, and development of control systems to regulate the processes. Many of the instrumentation and diagnostics methods can be applied to several advanced coal processes. The process conditions dictate the specific requirements for temporal resolution, spatial resolution, sensitivity, selectivity, and durability. Non-intrusive and real-time measurements are desirable so that processes are not changed by the act of measuring and so that diagnostics can be performed as the processes take place.

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Figure 1. Simplified Advanced Coal-Based System, Focus for Instrumentation and Diagnostics

3.1 Chemical Analysis

Coal is a chemically and physically heterogeneous material that consists principally of carbon, hydrogen, and oxygen with lesser amounts of sulfur and nitrogen. Other constituents include the ash-forming inorganic compounds that are distributed as discrete particles of mineral matter throughout the coal substance or as atomically dispersed elements associated with the organic fraction (Elliott 1981). Advanced coal-based processes convert the coal into combustible gases, char, or liquid products. During this conversion, contaminants can be released from the coal.

Historically, extractive sampling techniques have been used to determine the composition of the process gas streams. Gas chromatography and mass spectroscopy are on-line methods that are used to routinely analyze major gas constituents. The trace species composition of a process gas stream can change rapidly because of normal variations in coal composition. Thus, real-time measurements of trace contaminants under HTHP conditions remains a challenge. Real-time measurements are needed for controlling contaminant cleanup systems. Off-line analyses in the laboratory are not sufficiently responsive for control of the contaminant cleanup systems. Without a real-time measurement and control system, the downstream equipment may be damaged or the process may pollute the environment. For example, determining the amount of sulfur and alkali will assist in understanding the mechanisms of hot corrosion of turbine blades. In addition, measurements can track the gradual performance deterioration of mixed-metal oxide desulfurization sorbents. Contaminants can be divided into the following groups (Nelson et al. 1987):

Sulfur Compounds:	H ₂ S, COS, CS ₂ , RSH, Thiophene, SO ₂ , SO ₃
Nitrogen Compounds:	NH ₃ , HCN, HCNS, NO _x
Halogen Compounds:	Cl ₂ , HCl, HF, HBr, alkali halides
Trace Elements:	As, Cd, Ge, Hg, Pb, Se, Sn, Te, V, Zn
Hydrocarbons:	CH ₄ , C ₂ H ₆ , benzene, toluene, phenols, oils, tars

The following are the I&D Projects for developing chemical analysis techniques.

On-Line Extractive Methods for Elemental Analysis (Morgantown Energy Technology Center) -- The purpose is to develop ICP spectroscopy to analyze trace elements.

An ICP spectrometer is being developed and modified to analyze a slip stream extracted from process gas for elemental (percentage, minor, and trace) constituents. The ICP can analyze both gas phase and particles in a process stream. The ICP operates using an inert gas torch. The torch receives radio frequency energy through copper coils surrounding a quartz tube. A spark begins a cascade reaction of electrons, and then the reaction becomes self-sustaining. The plasma can attain temperatures of 6,000 to 10,000 K. The magnetic fields create a doughnut-shaped plasma, which allows the sample to be introduced through the center of the plasma. The sample gas decomposes, the atoms emit light, and the monochromator analyzes the elemental emissions. A schematic of the ICP torch is shown in Figure 2.

In order to eliminate the typical quenching effects of process gas on the plasma, a high-power (in excess of 4,000 watts) helium-assisted argon plasma has been developed. To handle high-temperature, particle-laden streams, the plasma torch has been specially designed to accommodate flow rates of 5 liters/minute. The high flow rates ensure that particulate matter in the sampling stream remains entrained. A prototype ICP system constructed for field testing transfers emissions from the plasma via six mini-monochromators. Each monochromator is dedicated to the analysis of a single element. The elements chosen for initial monitoring include Fe, Ca, Mg, Pb, Cr, Cd, Zn, As, Se, Na, and K. The detection limits for Ca and Mg are in the low parts-per-trillion (ppt) range. The limits for the other elements are in the low parts-per-billion (ppb) range. The ICP has performed successfully on a bench-scale pressurized combustor and on a fixed-bed gasifier process stream. ICP field tests are planned at the Texaco subpilot-scale gasifier and the Foster Wheeler second-generation PFB combustion system (Romanosky et al. 1989; Geiling and Goldberg 1989; Holcombe 1987).

In Situ Methods for Elemental Analysis of Hot Gas Streams by Laser-Induced Breakdown Spectroscopy (Morgantown Energy Technology Center) -- The goal is to develop a spatially resolved in situ technique for the elemental analysis of fossil fuel process streams.

LIBS uses a very intense, short pulse of laser light to form a spark in the process stream through an optical window. Spark temperatures of up to 30,000 K fragment all molecules into their constituent atoms. These atoms can be in both excited or ionized forms, which generate light emission at element specific wavelengths. The light emitted from the spark is analyzed to

Figure 2. Schematic of the Inductively Coupled Plasma Spectroscopy Torch

determine the elemental composition. LIBS delineates the atomic constituents of either gases or solids. As shown in Figure 3, the METC LIBS includes a Neodymium-doped yttrium aluminum garnet (Nd:YAG) laser and two parallel monochromators for one for analysis and the other for calibration. This LIBS system is unique since it uses only a single optical port for both the laser input and emissions output. Most elements can be detected with a sensitivity in the parts-per-million range. The technique requires multiple light emission measurements to attain this sensitivity. An *in situ* calibration method is still under development. Recent laboratory work has shown that LIBS can be used for *in situ* analysis of deposits on the interior surfaces of turbine blades or barrier filters. However, improvement of sensitivity and reduction of noise will be necessary for the application of this technique to be viable (Chisholm 1989).

Figure 3. The METC Laser Induced Breakdown Spectroscopy Arrangement

Optical Detection of Corrosive Compounds (Los Alamos National Laboratory) -- The purpose is to develop a laser-based optical diagnostic technique for in situ monitoring of trace levels of alkali compounds in coal-gas combustion streams.

Ultraviolet photodissociation is a spectroscopic property that can be used to detect alkali compounds. This technique uses an ultraviolet laser to excite a compound to a state that dissociates along a repulsive potential to yield an excited alkali atom. This atom then emits light at its characteristic wavelength. The intensity of this emission is proportional to the original concentration of the parent compound. The major advantage of this detection scheme is that it can determine compounds, while most other techniques can only determine elemental composition.

Compounds with different alkali (e.g., Na^+ and K^+) can be readily distinguished by the emission wavelengths of the excited atoms. Discrimination between compounds of the same alkali but

with different anions (e.g., Cl^- and OH^-) is more difficult. However, it can be achieved by examining the dependence of the alkali emission on the excitation wavelength. Figure 4 shows the laboratory equipment arrangement for alkali detection. The atomic emission intensities correlate with the densities of the alkali compounds for at least five orders of magnitude. As little as 0.03 ppb NaCl, 0.08 ppb NaOH, 0.4 ppb KCl, and 5 ppb KOH can be measured with a single laser pulse, making this a very sensitive diagnostic technique. Results show that this photo-fragment fluorescence diagnostic technique will be well suited to combustion conditions (Oldenberg 1989).

Investigation of Semiconductor Gas Sensing Devices for Coal Gasification Process Streams (Westinghouse) -- A proof-of-feasibility study addressed whether metal oxide semiconductor (MOS) detectors could serve as sensing devices in highly reducing coal gasifier streams.

Semiconductor gas sensors operate by measuring the change in resistance of a material in response to a surrounding gas. The gas reacts with the surface of the semiconductor, or with material previously absorbed on the semiconductor. Then, the charge carriers are either injected, withdrawn, or released. This changes the semiconductor's conductivity. Reactions between the MOS and its surroundings include oxidation or reduction, ion exchange, and absorption. Prior measurements using this technology were made on various gases, including several hydrocarbons and their derivatives, halogenated hydrocarbons, alcohols, ethers, ketones, esters, nitrogen compounds, and inorganics.

This effort addresses whether or not MOS detectors can be reliable sensors in the reducing gas conditions of coal gasification processes. The technique depends on the reaction of the gases with absorbed ionic oxygen species, which releases electrons to the conduction band of the MOS material. Several MOS materials have been shown to be worthy of experimental evaluation. However, the MOS reducing gas sensor can not operate reversibly in a reducing gas environment without some oxygen. Laboratory experiments showed that plasma spraying and sol-gel synthesis would increase the oxygen responsiveness to reducing gas exposure (Mattox 1985; Hubbard and Gordon 1987).

3.2 Particle Characterization

Characterization of particles includes determination of size and distribution, shape, velocity, concentration, and trajectory. This characterization is essential to monitoring and understanding processes occurring in coal-fired turbine combustors, coal-fueled diesels, and hot gas particle control devices. Particles larger than 10 micrometers (μm) can erode turbine

Figure 4. The Laboratory Arrangement of the Photofragment Fluorescence Spectroscopy for Alkali Detection

blades, which limits the life of a turbine (Bedick 1989). Particles can also decrease efficiency because of deposition on turbine blades. In addition, smaller particles follow the gas flow, pass through the turbine and can be emitted to the atmosphere as a pollutant. Most advanced particle-control devices being developed are for the secondary or tertiary stages of particle control. Typically, cyclones are used for the primary particle control. Also, *in situ* cleanup techniques may involve injection of particles (dolomite) into the process that would then be used to capture undesirable species (such as sulfur compounds). Thus, particle characterization can improve capture efficiency methodologies.

The following are the I&D Projects for developing particle characterization techniques.

In situ Real-Time Analysis of Particles (Sandia National Laboratories) -- The purpose is to develop optical diagnostic techniques to measure particle composition, size, and velocity in combustion environments.

laser creates the plasma or spark at the particle. Light emitted is collected and imaged on an entrance slit of a monochromator. A linear array detector is placed in the monochromator exit focal plane and measures the emission spectra.

The technique can simultaneously detect C, H, O, N, Li, Na, K, Mg, Ca, Ba, Sr, Al, Ti, Fe, Mn, and Si. Practical detection limits for a single particle are less than 100 parts per million (ppm) by weight for most metals (Ottesen et al. 1988).

In situ Particle Characterization (The University of Tennessee Space Institute) -- The purpose is to develop software and circuitry for measuring the size of particles from laser Doppler velocimeter signals.

The basis of this technique is a commercial dual-beam laser Doppler velocimeter (LV). Using software and additional circuitry, particle size information can be obtained from the LV signals. The configuration of the particle size interferometer (PSI) consists of a linearly-polarized laser source, a beam splitter, transmitting and receiving lenses, a photomultiplier tube, and a signal processor. Figure 6 shows the dual-beam laser Doppler velocimeter. The PSI splits the source laser beam into

Figure 6. Configuration of the Dual-Beam Laser Doppler Velocimeter

two parallel and equal intensity beams. The focal volume is at the cross-over region of the beam. The probe volume can be viewed as a region of many uniformly spaced fringes. The receiving lens collects the scattered light from the particles passing through the probe volume and focuses the collected light at the photodetector. The signal from the photodetector is converted to particle velocity and size information.

Appraisal of the different characteristics of the LV signals provides particle size and particle velocity measurements simultaneously. Particles with diameters between 0.5 and 5.0 μm have been investigated. LV light-scattering characteristics are

complex and often non-monotonic functions of the particle size, index of refraction, laser light wavelength, laser intensity and polarization, and the characteristics of the detector. Although different components of the LV signal have been considered, this analysis concentrated on Doppler phase, visibility, and scatter-intensity. No individual signal characteristic or optical configuration was found that would universally resolve size-signal relationship uncertainties. However, optimal configurations were identified for selected applications. (Giel and Son 1988).

Feasibility of Millimeter Wave Diagnostics for Coal Conversion and Combustion Systems (Argonne National Laboratory) -- The use of millimeter wave (MMW) technique was explored for in situ diagnostics of particle-laden multiphase streams.

The intent was to determine if MMW can be used for molecular species identification, gas-phase or particle temperature measurement, or particle size and loading. In situ techniques depending on light are limited to streams with few particles. The light is absorbed by the particles reducing the output signals. The longer MMW should penetrate farther than optical techniques into particle laden streams.

Determining some major molecular species and gas-phase temperatures using MMW spectroscopy appears possible in atmospheric-pressure combustors. Particle temperature measurement using MMW radiometry appears likely. However, the particle concentration must be between 10^8 to 10^{10} particles/m³ of nominally 100 μ m particles. Determining particle size, size distribution, and loading appears possible when the particle concentration is low (Gopalsami and Raptis 1986).

3.3 Thermophysical Properties

Advanced conversion systems require the measurement of thermophysical properties of gases, liquids, solids, and multiphase mixtures of each. These properties need to be measured to understand and predict events in a FE process, as well as to design future processes. The thermophysical properties that are being investigated include temperature, strain, viscosity, and deposition.

3.3.1 Temperature

Temperature is an important measurement since it is an indication of the operating state of a system. For example, temporal and spatial temperature measurements are essential to understanding chemical kinetics. In addition, temperature measurements can indicate heat transfer, corrosion, slagging, and

fouling rates. Most processes require temperature monitoring for safety.

Selection of a temperature sensor includes considerations of cost, accuracy, measurement range, response time, size, and maintenance. The difficulties imposed on sensors in FE processes include operation under HTHP conditions, exposure to erosive particles, and variations in process flow patterns. Currently, thermocouples are the sensors used most often for measurement of temperature. However, alternate temperature measurement techniques are being developed because of the limitations of thermocouples. For example, the thermocouple has a short life expectancy if not protected from erosion. Response time is slow and heat losses are high when a thermocouple is covered by a protective sheath. Other methods of temperature measurement include optical pyrometers, infrared cameras, thermistors, and resistance temperature detectors.

Several advanced optical diagnostic methods are being developed to meet the special requirements imposed on temperature monitoring in FE processes. The optical methods avoid many of the problems associated with the severe conditions of FE processes. For example, measurements can be made *in situ* from the light absorbed or emitted from a process stream without intrusive probes. Fiber optics also minimize heat losses and offer the capability of high speed data transmission. Major limitations of optical techniques are gaining optical access and penetrating into particle-dense streams. The optical access must transfer the proper light energy to the signal processor.

The following are the I&D Projects for developing temperature measurement techniques.

High-Temperature Fluorescence Thermometry System (FTS)
(Morgantown Energy Technology Center) -- The purpose is to accurately measure temperatures in combustion and gasification environments.

The FTS is an *in situ* optical sensing device designed to monitor the temperature of a process stream in near real-time. The FTS is based on the temperature dependent fluorescence decay characteristics of a crystalline sensor synthesized on the end of a sapphire rod. The fluorescence decay time constant is a function of the fluorescent material and sensor temperature. The fluorescence based sensor is immune to electrical noise and insensitivity to variations caused by fiber microbending or changes material emissivities. The Nd:YAG sensor is excited via a pulse from a solid state laser diode whose wavelength falls within the absorption band of the fluorescent crystal. By calculating fluorescence growth and decay, the temperature can be determined from measuring a time constant. Thermometry is

insensitive to amplitude variations, optical attenuations, electrical interferences, and emissivities. A simplified schematic of the fluorescence thermometry technique is shown in Figure 7. This device will be field tested in product gas streams at the Texaco entrained-bed gasification facility. For this testing, two probes were calibrated over the temperature

Figure 7. A Simplified Schematic of the Fluorescence Thermometry Technique

range of 975 to 1,300 K. The expected operating temperature will vary from 1,150 to 1,280 K. (Shifflett 1989).

Nonisothermal pyrometry techniques were investigated in another METC effort. In many FE processes, the only means by which nonintrusive, *in situ* temperature measurements can be made

is through the use of optical techniques. Pyrometry is one such technique. Conventional pyrometric techniques require isothermal targets (sites for temperature measurement). FE processes often do not have isothermal targets, thus nonisothermal techniques are needed. Eight different pyrometers were evaluated to determine their response to nonisothermal targets. The targets had two or more temperature modes, where a mode represented an isothermal section of the target. The effect of varying emissivity was explored using computer simulations of the different techniques and targets. As a result, three nonisothermal pyrometry techniques were proposed: the changed single-color technique, the changed two-color technique, and the two-single-color technique (Hensel 1988).

An Investigation of Nonintrusive Radiometers for Entrained-Bed Gasifier Temperature Measurement (TRW) -- The sodium line emission pyrometer (SLEP) was used to measure temperatures in a coal combustor.

Theoretical considerations of the Na emission intensity in typical coal conversion facilities have shown a way to exploit this emission for temperature measurement. The Na is typically in thermodynamic equilibrium with the gas and the measurements, therefore, yield gas temperatures. The implementation of the SLEP requires an optical access port. This was provided by an aerodynamic window, which consists of a pinhole and a set of transfer lenses. The pyrometer utilizes a fiber optic cable to transfer the collected emission, a high-resolution echelle spectrometer, a linear detector array, and an optical multichannel analyzer. SLEP compares the intensity of the sodium emission with the Planck's blackbody function to compute the gas temperature. The SLEP was tested on TRW's coal combustor. The measurement accuracy was only limited to the noise in the electronic detection system. Temperatures between 1,700 and 2,000 K with an accuracy of ± 10 K were measured. (Fairchild 1985).

3.3.2 Strain

Another property being measured is strain (i.e., material displacement under load). In situ strain measurements play an important role in validating the structural analysis predicted by models. Finite element models can be used to predict maximum strain and stress at various mechanical loads (e.g., vibrations, clamping forces, differences in thermal expansions, and pressures) and material properties (e.g., yield strength, thermal conductivity, modulus of elasticity, and coefficient of thermal expansion). The models can predict whether or not a component can survive the mechanical loading.

The following is the I&D Project for developing strain measurement techniques.

Smart Structures for Fossil Energy Applications (Virginia Tech University) -- The goal of the project is to measure in situ strain of ceramic cross-flow filters.

Sensing devices based on fiber optics offer many advantages. They are thin, flexible, and immune to electromagnetic interference. The fibers can be coated to protect the optical fibers from the harsh FE process conditions. The term "smart" cross-flow filters refers to various fiber optic sensing systems that can be attached to a ceramic filter to sense strain levels, temperature, and dust-cake buildup. Ceramic cross-flow filters are used to remove particles from HTHP process gas streams (Bossart 1989). The sensors can also be installed as an integral part of the ceramic barrier (cross-flow) filters. Information collected by the smart structure system can be used to identify weak areas of the filter. This information can be used to improve the design of the filter. Smart cross-flow filters incorporate clad and coated sapphire optical fibers as the sensing elements. Possible claddings and coatings have been identified for sapphire fibers. Cladding materials successfully used are SiO_2 , $\text{Al}_6\text{Si}_2\text{O}_{13}$, and SiO_xN_y . The cladding causes a difference in the index of refraction that should lessen the light attenuation. Coating materials that have been considered are Ta_2O_5 , TiO_2 , $\text{Al}_6\text{Si}_2\text{O}_{13}$, and ZrO_2 . The coatings must have the strength and durability to protect the sapphire.

Successful tests of a smart cross-flow filter were completed in the Westinghouse bench-scale PFB combustor simulator. The smart cross-flow filter used an in-line, intensity-based sensor and a Fabry-Perot optical fiber sensor. Figure 8 shows an experimental setup for the test of multiple fiber optic air-gap strain sensors. This initial test used silica optical fibers instead of sapphire. The intensity-based sensor uses an air-gap splice. Strain is derived from changes in the splice length, which causes a proportional change in the light intensity. The Fabry-Perot interferometer measures reflection at the glass-air interface. A diffraction pattern forms from the reflections at each side of the glass and fiber interfaces (Claus et al. 1989; Murphy et al. No date).

3.3.3 Viscosity

Viscosity is a measurement of a fluid's resistance to flow. It has a direct impact on the power required for moving the fluid (i.e., the pumping requirements). Viscosity affects the operation of nozzles and atomizers. It is difficult to determine

viscosity in FE processes because the fluids are generally multiphase and non-Newtonian (not linear with shear rate).

Figure 8. Experimental Setup for Testing Multiple Fiber Optic Air-Gap Strain Sensors

The following is the I&D Project for developing viscosity measurement techniques.

A Feasibility Study on Advanced Techniques for On-Line Monitoring of Coal Slurry Viscosity (Argonne National Laboratory) -- The purpose of this project is to survey available coal-slurry rheological data and to evaluate an ultrasonic method for measuring slurry viscosity.

Viscosity measurement techniques can be classified into three principal methodologies: mechanical, ultrasonic, and electromagnetic. Mechanical viscometers have been on the market for a long time, but have only recently been used for non-Newtonian fluid characterization. Ultrasonic viscometers have good potential for development as on-line monitors. Industrial application of electromagnetic methods is unlikely, but electromagnetic methods have been used in basic research.

The ultrasonic method used for measuring slurry viscosity was based on acoustic attenuation. It is desirable for viscosity measurements to be a function of ultrasonic frequency and change over a range of coal concentrations. This method involved the correlation of acoustic viscosity, a sum of shear waves, and bulk viscosity. An acoustical wedge was constructed of aluminum and was attached to the slurry piping. The acoustical wedge is shown in Figure 9. The air and wedge interface provided the reference reflected signal. The shear wave reflected from the air interface remained constant. The shear wave from the wedge measured the viscosity of the boundary layer liquid just inside the pipe. This technique was not useful in determining the viscosity of the bulk slurry. The boundary layer viscosity needs to be correlated with the actual slurry viscosity (Sheen and Raptis 1987).

3.3.4 Deposition

Particles can decrease system efficiency by depositing on turbine blades and causing an increased flow resistance. Deposition problems are caused primarily by the mineral matter in coal and its behavior after combustion. Methods were investigated to measure deposition rates to examine factors controlling deposit formation. Particle adherence to surfaces is mainly a function of particle size, particle composition, particle velocity, angle of incidence, surface composition, and the temperatures of the gas, particle, and surface (METC 1985).

The following is the Instrumentation and Diagnostic Project for developing deposition measurement techniques.

Ash Deposition Sensor Development (Morgantown Energy Technology Center) -- *Deposition sensors and deposition rate sensors capable of in situ, real-time measurement in FE streams will be developed in this project.*

Three types of deposition measurement sensors have been developed: a heat flux sensor for coal-water fueled combustors, a dual-pendulum prototype deposition sensor, and a surface acoustic wave technique. The prototype heat flux sensor was a simple, rugged, low-cost unit, with high sensitivity. It could operate in high pressure under highly corrosive conditions. However, the sensor was somewhat limited in high-temperature applications, because of its sensitivity to thermal radiation and loss of heat through the sides of the sensor (Sun and Bajura 1985).

A dual-pendulum deposition sensor was used to monitor deposit formation. It had the same temperature limitations of the heat flux sensor and about the same degree of accuracy. However, the dual-pendulum sensor was more intrusive. It required more costly supporting electronics, was less rugged, and was more

subject to mechanical and electrical interference than the heat flux unit.

Figure 9. Aluminum Acoustical Wedge Used to Determine Slurry Viscosity

The surface acoustic wave technique was restricted to low temperature applications. However, it was a rugged, nonintrusive, and accurate sensor, although it required a great many costly electronic support systems (Fasching and Smith 1987).

3.4 Process Control Systems

The maturing of advanced coal-based technologies has motivated the development of process control systems. Sensory units provide input data for flexible, computerized process control systems with adaptive, decision-making capabilities. Direct-synthesis controllers quantify process information in a systematic and relatively simple way. Adaptive direct-synthesis controllers improve control by adapting model parameters to measured process variables (Badavas 1984).

Current emphasis has shifted from systems identification to expert control systems. During unplanned process interferences and emergencies, expert control schemes and smart sensors should provide optimal operation of coal-based technologies.

The following is the Instrumentation and Diagnostic Project for developing process control systems.

Process Control Expert Systems (Morgantown Energy Technology Center) -- The purpose of this project is to investigate artificial intelligence (AI) expert system techniques and advanced microprocessors for enhanced control of FE processes.

One expert system is used to position a particle in an electrodynamic balance by tuning the proportional and integral control parameters. This system was nonlinear in response to the controlled variable, and thus, a linear mathematical solution of the control parameters was impossible. Process changes occurred too quickly for control by manual tuning methods. A real-time, process simulation overcame these problems. The expert system ran concurrently with this simulation and tuned the control parameters to satisfy the stability criterion. These parameters were incorporated into the control system to set proper control stability, overshoot, and settling time. The process operation could be standardized and repeated because of the expert system (Lawson et al. 1989).

An expert control system was also designed earlier to determine the bed level of a fixed-bed gasifier system by sequencing coal feed and ash removal. However, the expert system was not tested since the gasifier became non-operational (Keech 1988). In addition, it was impractical to reprogram the existing system for each different operating procedure or bed characteristic. An expert system technique could provide the flexibility to change the operating constraints of the monitor without reprogramming.

3.5 Multiphase Flow Characterization

Many advanced coal-based technologies require the movement of solids (e.g., coal feed and ash removal) in their processes. Accurate mass flowrate measurements are necessary for on-line control of the movement of solids in FE process. Most conventional mass flowrate techniques penetrate the process stream. Non-intrusive mass flowrate methods are being investigated to eliminate blockage or impedance of flow by the controlling device. Nonintrusive mass flow measurements also avoid erosion from the solids.

Many of these processes transport coal with a carrier gas or liquid. Thus, the process streams that contain both solids and

fluids are called multiphase flow. Multiphase flow streams are difficult to characterize because the flowrate is non-linear with the shear rate (i.e., a non-Newtonian fluid).

Proper coal feed rates can prevent explosions in entrained flow gasifiers and pulverized coal combustors that use dry coal feed systems. Explosions can occur at high temperatures when there is an intermittent loss of coal feed, but the oxidant continues to flow to the gasifier. Less abrupt coal feed changes without corresponding adjustments to the oxidant flow can cause fluctuations in reactor temperature. These thermal fluctuations over-stress refractory linings or metal shells, which lowers the vessel life.

The following is the Instrumentation and Diagnostic Project for developing multiphase flow characterization techniques.

Capacitance Flowmeter (Argonne National Laboratory) -- The purpose was to measure the solid feed rate in a coal gasification plant's gas-solid feed, interstage, and recycling lines.

The basis of the capacitance flowmeter technique is measurement of the frequency and amplitude of capacitance noise. In an experiment, two flowmeters were installed in the horizontal leg of the piping test loop located at Argonne. In one capacitance flowmeter, electrodes were protruded through the pipe's ceramic liner to determine the solid component flowrate. The second flowmeter used a densitometer with electrodes flush with the pipe's interior surface. This flowmeter determined the solid volume fraction. Only the solid-component intrinsic density, the dielectric constant, and the duct cross-sectional area were needed to determine the solid flowrate. Short-lived radioactive particles were used to calibrate particle velocities.

In another experiment, the performance of a capacitive flowmeter was experimentally tested in a gas-entrained solid flow stream. The solid feedrates were varied from 0.5 to 2 kg/s with solid volume fractions extending from 0.004 to 0.016. Based on test results, the capacitive sensors should provide a reliable means of determining mass flowrate, the solid volume fraction, and particle velocities (Bobis et al. 1986).

4.0 CONCLUSION

Instrumentation needs usually evolve from a desire to measure or control critical parameters to improve effectiveness, operability, reliability, or safety of a system. Often off-the-shelf commercial instruments and diagnostics require adaptation to operate in FE processes. Development activities performed in the AR&TD I&D Program are intended to support all FE processes. The activities involve the determination of the theoretical, analytical, and experimental feasibility of instrumentation and diagnostic devices and techniques.

AR&TD instrumentation and diagnostics techniques need to consider the working environments of FE processes. Coal-based process streams are often HTHP and include corrosive compounds and erosive particles. Real-time measurements are needed to adjust to rapidly changing conditions. Nonintrusive measurements are desirable to avoid eroding of the sensors or blocking the streams. In situ measurements eliminate problems of extractive sampling methods. Instrumentation requirements are more demanding during process development than during commercial operation of a plant, because operating limits have not been established for when a process is under development. Operating limits provide design criteria to scale systems at a minimum cost.

I&D is an integral part of the development of advanced coal-based technologies. The purpose of I&D is to provide information that can be used to increase system efficiencies, reduce operating and capital costs, minimize waste disposal, and reduce pollutant release into the environment. Improved FE instrumentation and diagnostics is necessary to achieve commercialization of advanced coal-based processes.

5.0 ABBREVIATIONS AND ACRONYMS

AI	Artificial intelligence
AR&TD	Advanced research and technology development
DOE	U.S. Department of Energy
FE	Fossil Energy
FTS	Fluorescence Thermometry System
HTHP	High-temperature, high-pressure
I&D	Instrumentation and diagnostics
ICP	Inductively coupled plasma
IGCC	Integrated gasification combined-cycle
LED	Light emitting diode
LIBS	Laser-induced breakdown spectroscopy
LSS	Laser spark spectroscopy
LV	Laser Doppler velocimeter
METC	Morgantown Energy Technology Center
MMW	Millimeter wave
MOS	Metal oxide semiconductor
Nd:YAG	Neodymium-doped yttrium aluminum garnet
PFB	Pressurized fluidized-bed
ppb	Parts per billion
ppm	Parts per million
ppt	Parts per trillion
PSI	Particle size interferometer
SLEP	Sodium line emission pyrometer

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APPENDIX A

The Fossil Fuel Instrumentation Research Database System (FFIRDS) is a consolidated system that organizes, files, and retrieves FE instrumentation and diagnostics information. Appendix A lists abstracts by author in the database as of July, 1990. The FFIRDS has an advantage over typical library instrumentation databases, since it contains instrumentation developments that were started as part of the development of advanced coal-based technologies. Instrumentation development tends to be less documented and published when it is part of a larger development project for advanced coal-based technologies.

FFIRDS is menu-driven and relatively user-friendly. It uses both dBase III plus and WordPerfect for data entry, storage, retrieval, sorting, and creation of reports. The information for project reports is organized into FFIRDS by these fields: Title, Technology Area, Process Area, Authors, Address of Performing Organization, Phone Number, Contract Number, Date of Report, and Abstract. The technology areas are Multiphase Flow, Chemical Composition, Temperature Measurement, Thermophysical Properties, Particle Characterization, Process Control, Nondestructive Testing, and General. The process areas are Gasification, Liquefaction, Combustion, Heat Engines, Heat Recovery, Fuel Cells, Cleanup Control, and Coal Preparation.

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