# On-Line Self-Calibrating Single Crystal Sapphire Optical Sensor Instrumentation for Accurate and Reliable Coal Gasifier Temperature Measurement

## Semi-Annual Technical Progress Report

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# Abstract

This report summarizes technical progress April – September 2005 on the Phase II program "On-Line Self-Calibrating Single Crystal Sapphire Optical Sensor Instrumentation for Accurate and Reliable Coal Gasifier Temperature Measurement", funded by the Federal Energy Technology Center of the U.S. Department of Energy, and performed by the Center for Photonics Technology of the Bradley Department of Electrical and Computer Engineering at Virginia Tech.

The outcome of the first phase of this program was the selection of broadband polarimetric differential interferometry (BPDI) for further prototype instrumentation development. This approach is based on the measurement of the optical path difference (OPD) between two orthogonally polarized light beams in a single-crystal sapphire disk. The objective of this program is to bring the sensor technology, which has already been demonstrated in the laboratory, to a level where the sensor can be deployed in the harsh industrial environments and will become commercially viable.

Due to the difficulties described on the last report, field testing of the BPDI system has not continued to date. However, we have developed an alternative high temperature sensing solution, which is described in this report. The sensing system will be installed and tested at TECO's Polk Power Station. Following a site visit in June 2005, our efforts have been focused on preparing for that field test, including he design of the sensor mechanical packaging, sensor electronics, the data transfer module, and the necessary software codes to accommodate this application.. We are currently ready to start sensor fabrication.

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# 1.0 Introduction

In the first phase of this program, five different optical temperature sensing schemes were thoroughly investigated to determine an optimal approach for high temperature measurement in coal gasification systems. Based on comparative evaluation and analysis of the experimental results, the broadband polarimetric differential interferometry (BPDI) was chosen for further prototype instrumentation development. This approach is based on the self-calibrating measurement of the optical path difference (OPD), *i.e.* phase retardation between the two orthogonally polarized light beams in a single-crystal sapphire disk, which is a function of both the temperature dependent birefringence and the temperature dependent dimensional sizes.

Due to the difficulties described on the last report, field testing of the BPDI system has not continued to date. However, we have developed an alternative high temperature sensing solution, which is described in this report. The sensing system will be installed and tested at TECO's Polk Power Station. Following a site visit in June 2005, our efforts have been focused on preparing for that field test.

# 2.0 Executive Summary

This report summarizes the technical progress over a six month period of the Phase II program "On-Line Self-Calibrating Single Crystal Sapphire Optical Sensor Instrumentation for Accurate and Reliable Coal Gasifier Temperature Measurement", funded by the Federal Energy Technology Center of the U.S. Department of Energy, and performed by the Center for Photonics Technology of the Bradley Department of Electrical and Computer Engineering at Virginia Tech.

During the reporting period, research efforts under the program were focused on the following.

- Design and assembly of sensor electronics and data transfer module,
- Modification of the signal processing algorithm and related software,
- Analysis of the packaging requirements
- Packaging design

Once we receive our machined components, we are ready to fabricate, package and test our sensors in preparation for installation at TECO.

# EXPERIMENTAL

# 3.0 Sensing Principle and Structure

Traditional extrinsic Fabry-Perot interferometric (EFPI) sensors usually use two fibers to construct the Fabry-Perot (FP) cavity. For these sensor, it is difficult to generate interference fringes for multi-mode illumination due to their high sensitivity to the surface smoothness, the surface flatness, the distance and the parallelism of the two surfaces of the FP cavity. For highly multi-moded sapphire fibers which are widely used in high-temperature applications, this is even more difficult. Very careful alignment is usually required. Our solution to this problem is to use a sapphire wafer as the interferometer. Since high surface quality and excellent parallelism can be readily achieved in the current wafer lapping/polishing industry, fringes can be easily generated even for highly multi-moded sapphire fiber and large cavity length (thick wafer). The choice of a relatively large thickness is important as it offers great convenience to the signal processing, as described below.

The sensing principle is shown in Figure 3.1. Reflections at both sides of the diaphragm will interfere with each other, producing a modulated spectrum, whose pattern is determined by the optical thickness (OT) of the wafer. The OT is the product of the refractive index and the thickness of the wafer, both of which have thermal dependence, resulting a temperature-sensitive OT and spectrum. Therefore the temperature can be demodulated from the change in the reflected spectrum.

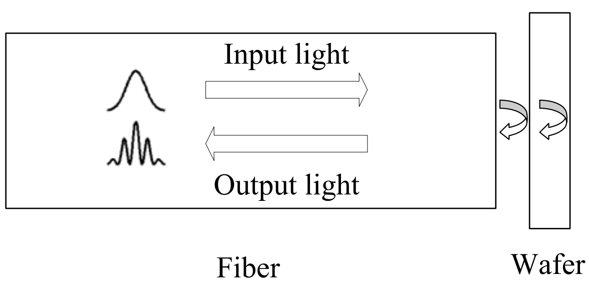


**Figure 3.1. Sensing principle.**

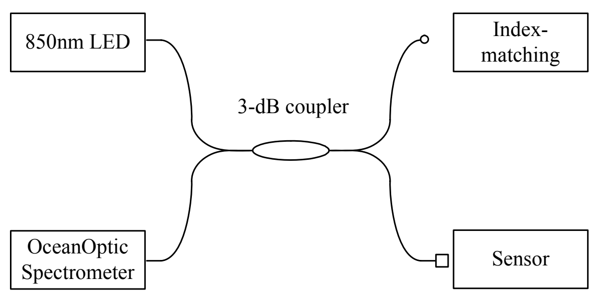


**Figure 3.2. White-light interferometric system setup.**

A diagram of the system is shown in Figure 3.2, consisting of a 850nm LED source, a multimode (MM) 3-dB coupler and an OceanOptics S2000 spectrometer. Figure 3.3 shows an enlarged view of the prototype sensor. A 99.8% alumina tube is used as supporting structure, to which both a 59µm-thick sapphire wafer and a 75µm (diameter) sapphire fiber are bonded by high temperature alumina adhesive. The sapphire fiber is coupled with a 100/140µm MM silica fiber which is connected to the system.

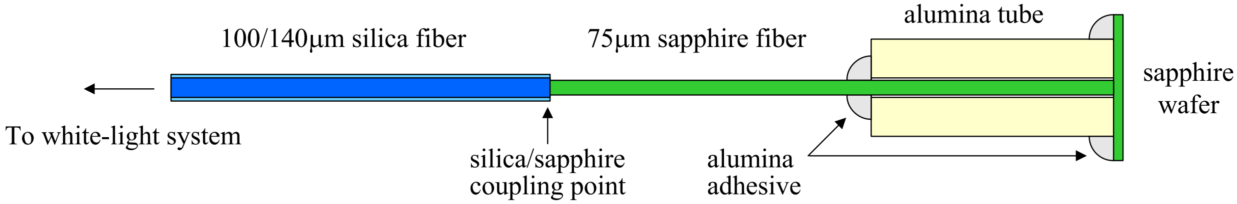


**Figure 3.3. Diagram of the sensor head.**

# RESULT AND DISCUSSION

# 4.0 Sensor Probe Packaging Design

## 4.1 Packaging Requirements

The optical sapphire temperature sensor developed is intended for direct high temperature measurement in the primary and secondary stages of slagging gasifiers. Several engineering issues have to be resolved at the prototype development stage, including the following.

*High temperature capability* — The operating temperature in the coal gasifier is in the range of 1200ºC~1600ºC, depending on the physical location in the chamber. To measure high temperatures accurately in a wide measurement range with high resolution, proper fabrication materials are needed.

*High pressure capability* — Background pressure as high as 500psig can be encountered in the coal gasifier chamber. The sensor optical elements should be able to withstand such environmental pressure. The sensor enclosure should meet the industrial safety requirements, while not conflicting with sensor optical architecture.

*Chemical corrosion resistance* — With temperatures exceeding 1200ºC, pressure exceeding 500psig, and chemically corrosive agents such as alkalis, sulfur, transition metals and steam, proper fabrication materials are needed to implement the sensing probe

*Deployable* — Optical temperature sensors designed for harsh environment applications must be capable of remote operation and be flexible enough for easy deployment. Features of mechanical vibration-proof, high mechanical strength, and remote monitoring and control capability are thus necessary.

## 4.2 Current Packaging Design

This section describes a packaging example designed to meet all these requirements, as shown in Figure 4.1. The sensor is mounted to the coal gasifier shell through a mounting flange. Functionally, the sensor is divided into three sections: the probe, the 1st and the 2nd pressure isolation chamber. The 1st pressure isolation chamber sees coal gasifier operation pressure when coal gasifier is in operation. The 2nd pressure isolation chamber sees room pressure when 1st pressure isolation chamber is working. The pressure boundary of the 1st pressure isolation chamber is the flange connection on the mounting nozzle, the flange connection with the 2nd pressure isolation chamber and the fiber feedthrough. The pressure boundary of the 2nd pressure isolation chamber is the flange connection with the 1st pressure isolation chamber and the fiber feedthrough. In case the 1st pressure isolation chamber fails, the 2nd pressure isolation chamber will take the role as the pressure boundary, preventing hot air from discharging from the sensor mounting nozzle. The double pressure isolation design minimizes the chance of accident during coal gasifier operation.

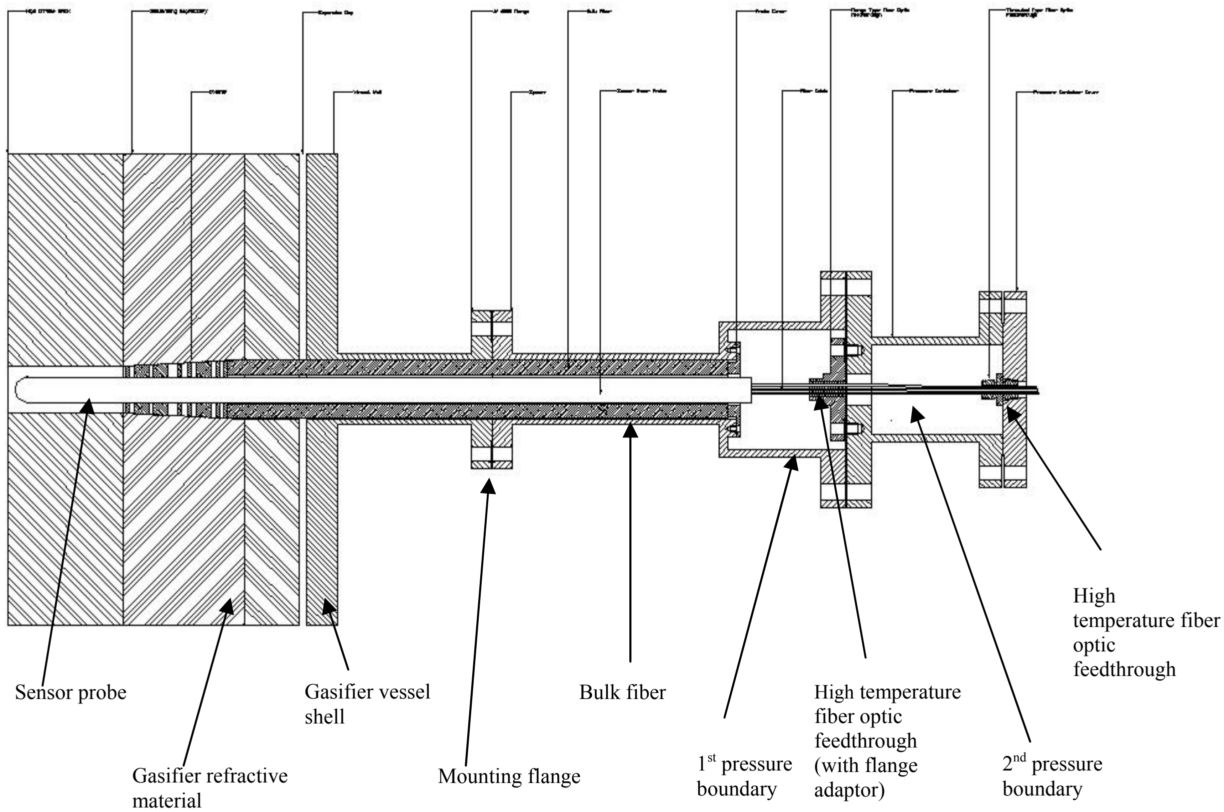


**Figure 4.1. Overall sensor probe packaging design.**

The detailed view of the 2nd pressure isolation chamber is shown in Figure 4.2. The chamber material could be carbon steel or stainless steel. The wall thickness should allow the chamber to withstand the sudden coal gasifier operation pressure impact. The gasket used in the flange connection should be graphite, because during the coal gasifier operation, when the heat transfer is balanced, the pressure isolation chambers see temperatures that are much higher than room temperature. The use of graphite is to prevent the gasket from failure under high temperature. The threaded adaptor fiber feedthrough is connected to the sensor electronics.

The fiber feedthroughs are used to guide the light power to and from the sensing probe and are used with sheathed fiber optic cables that run continuously through a flange adaptor and then a threaded adaptor. The customized fiber feedthrough assembly is shown in Figure 4.3. The fiber feedthrough can withstand 800F and 500psig. The fibers are connected together through fiber connectors and adaptors, which could be SMA, FC or ST types. The fiber connector should be angle polished to reduce reflection, which would cause large background noise in sensor spectrum detection.

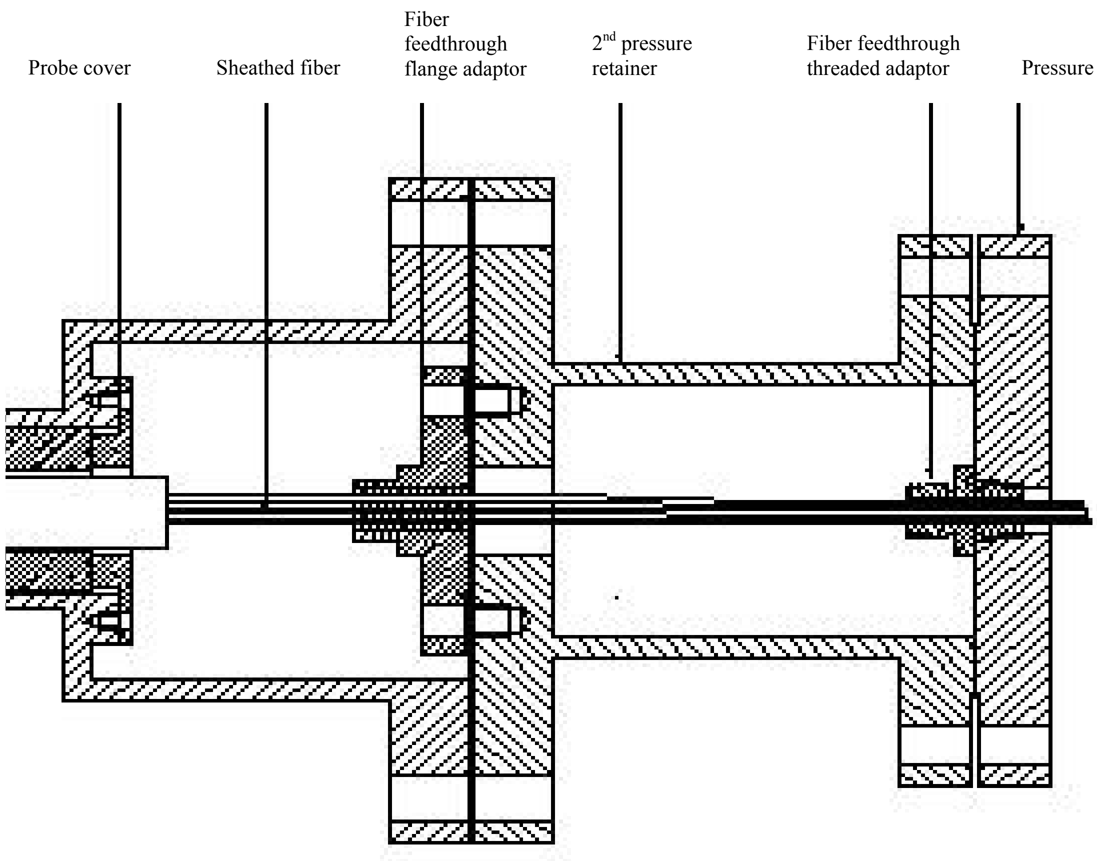


**Figure 4.2. Close up of 1st and 2nd pressure boundaries.**

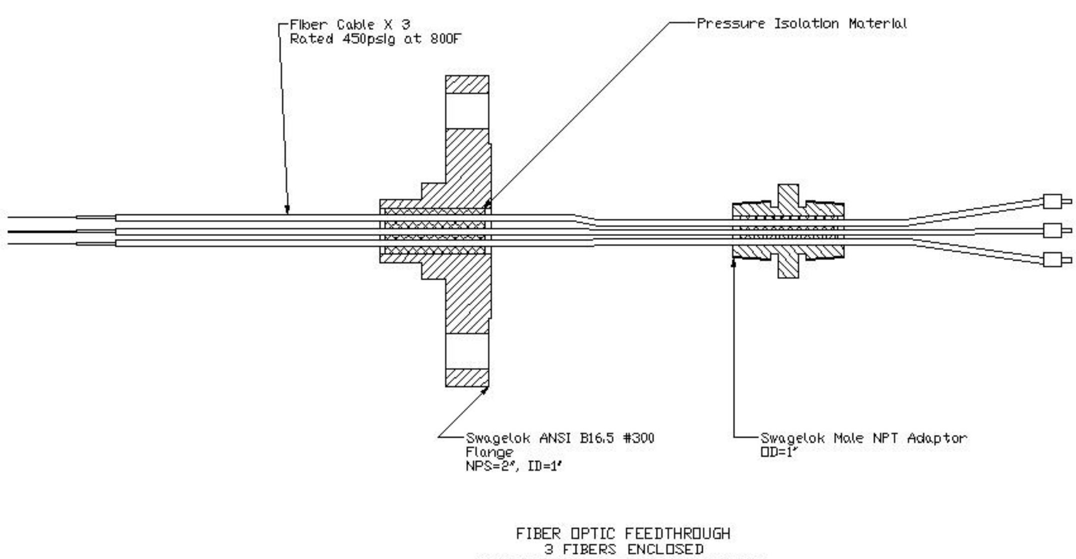


**Figure 4.3. Fiber optic feedthrough assembly.**

The detailed view of the sensor probe is shown in Figure 4.4 and Figure 4.5. The sensor is enclosed in a closed-end inner alumina tube. The alumina spacers are attached to it to match the diameter of the inner and outer alumina tube. This is to minimize impact-induced damage during installation and vibration during operation. The sensor protected by the inner alumina tube is inserted into an 18" long one-end-closed sapphire tube. The whole sapphire tube is made of single-crystal sapphire and therefore can withstand high temperature and aggressive corrosion. The inner alumina tube and the sapphire tube are enclosed by a outer 99.8% alumina tube to provide support as well as corrosion protection to the sensor. These tubes are bonded together by high temperature ceramic glue that has a similar thermal expansion coefficient as the alumina and sapphire. Thus, the sensor has three layers of corrosion protection: high purity alumina—single crystal sapphire—high purity alumina, and this structure is believed to be capable of corrosion protection in the coal gasifier environment. The outer alumina tube is bonded to a stainless steel tube that provides support and protection. An aluminum pipe is connected with the stainless steel tube via a reduction coupler to provide extra protection to the sensor head during installation. The sensor probe is ended with a fiber connector that connects with the fiber feedthrough of the 1st pressure isolation chamber.

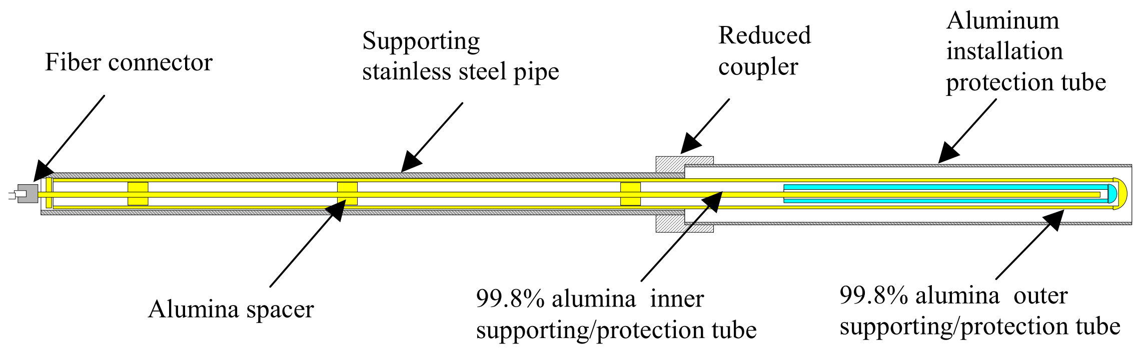


**Figure 4.4. Probe design.**

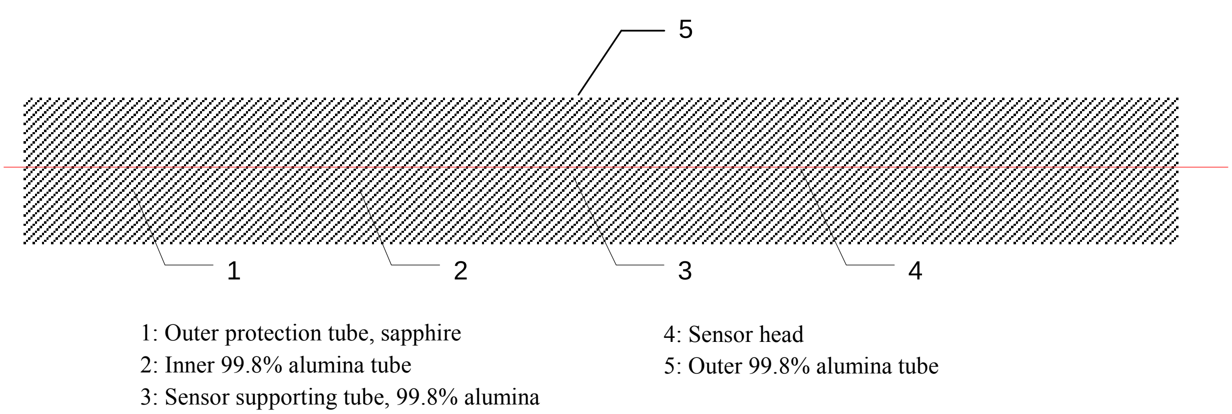


Figure 4.5. Sensor head close up.

# 5.0 Field Testing at TECO

Tampa Electric Co. (TECO) in Florida will be our new sensor testing partner. The fiber optic temperature sensor is to be installed and tested at TECO's Polk Power Station. In preparation for the test, we met with TECO engineers in June 2005 to address the following issues.

1. We presented the tentative mechanical packaging schematic to TECO, and discussed the safety requirements of the packaging.
2. We discussed the best method to transfer sensor spectrum data from the coal gasifier facility to the plant office, and also how to add a channel of analog output to the distributed control system (DCS) of the plant.
3. We discussed the internet access from Virginia Tech to the sensor interrogation computer placed at the power station using their LAN with authorization.
4. We checked the coal gasifier facility, especially the port where our developed sensor is to be mounted.

In the following four months, we have been working on the design of the sensor mechanical packaging, sensor electronics, the data transfer module, and the necessary software codes to accommodate this application, including the identification of vendors for customized components. We are currently ready to order components and start sensor fabrication. When we receive our machined components, we will start to package the fiber optic sensors. The mechanical packaging will be performed in laboratory followed by sensor testing. When the sensor is proven to be in good condition after a series of testing, we can install the fiber optic sensor during the scheduled window at TECO's Polk Power Station.

### 5.1 Proposed Sensor Probe Installation Process

Based on our visit to TECO, the field test installation has been broken down into several steps as follows:

1. Mount the spacer onto the coal gasifier mounting flange.

2. Use a substitute thermocouple sheath (alumina tube with 1 7/8" OD) centered in the thermowell, pack bulk fiber into the nozzle around the substitute sheath from the orifice of the spacer 4" pipe.

3. Retrieve the substitute thermocouple sheath, and install the real probe.

4. After the probe is installed, cover the probe cover to prevent the insulation bulk fiber from falling out of the 4” pipe.

5. Install the pressure container and the pressure container cover.

6. Wind the fiber optic cable with the protective flexible conduit to the NEMA enclosure, and connect the cable to the sensor interrogation box

### 5.2 Sensing System

The measurement system can be divided into two parts: the optical measurement instrument at the test site and the signal-processing unit in the control office (Figure 5.1).

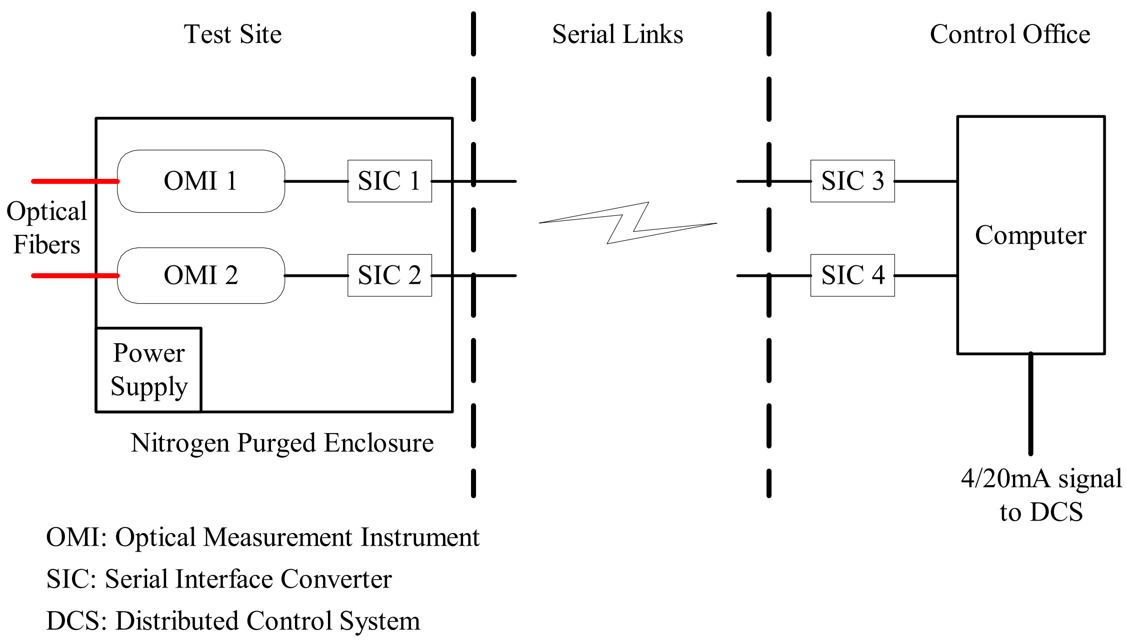


**Figure 5.1. Measurement system for field test at TECO.**

The optical measurement instrument developed to detect the optical spectra from sensors at the test site consists of the following.

- A broadband light source with a central wavelength of 850nm.
- An optical spectrometer (Ocean Optics).
- Some optical components.
- Data acquisition device.
- Data communication device.

The light from the broadband light source is launched to the optical fiber sensor. A portion of the light will be reflected and collected by the optical spectrometer. The spectrum of the light reflected from the interferometric sensor is measured and used to determine the optical path imbalance of the sensor and thus to determine the temperature.

The optical spectrum is digitized by a data acquisition device and can be transferred to a host computer by mean of a standard RS232 communication interface. However, the RS232 interface has a communication link limitation of 50 ft. The distance between the test port and the control office is larger than 500 ft, Therefore, we use two pairs of RS232/RS422 converters to extend the communication capability of the serial interface. A photograph of one measurement instrument is shown in Figure 5.2. All the optical and electrical components mentioned above were installed into a standalone box with dimensions 7.2×11.0×13.8 inches (H, W, L). The two independent measurement instruments are similar expect that one box has dual optical channel that can support two sensors at the same time while the other box has only one optical channel and can only support a single sensor. For the field test, they will be enclosed in a NEMA enclosure with nitrogen purge for safety reasons.

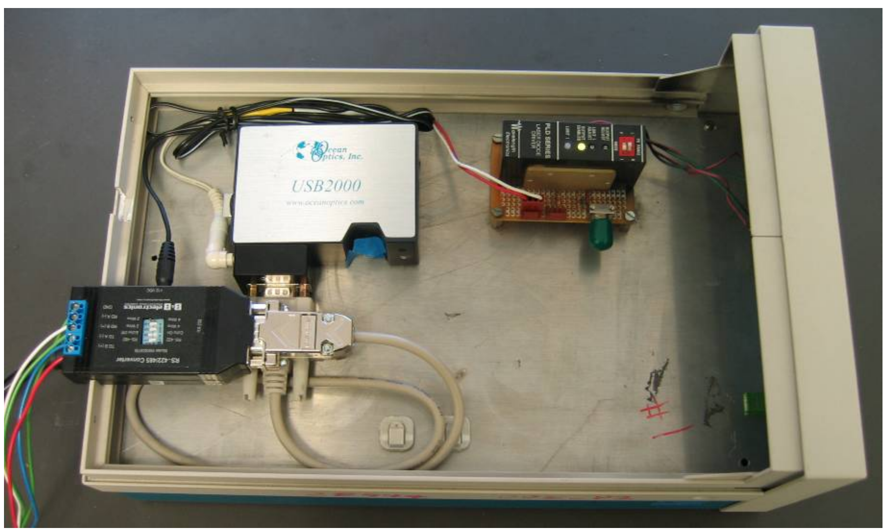


**Figure 5.2. Optical measurement instrument to be used at the test site, containing a broadband light source λ=850nm, an optical spectrometer (Ocean Optics), optical components, a data acquisition device, and a data communication device.**

The signal-processing unit in the control office consists of:

- A personal computer running a Microsoft Windows operating system.
- Data communication devices.
- Signal conditioner to provide signal to control system at TECO.
- Application software.

The core of the signal-processing unit is a personal computer. Two RS232/RS422 converters are used to convert the serial links back to computer-friendly RS232 standard. A digital to analog device with a RS485 interface (Advantech ADAM4201) is used to generate a 4/20 mA signal feed it to the TECO's distributed control system for real-time monitoring and data logging. We use a serial device server (MOXA NPort 5430) to provide multiple RS422/RS485 ports. The device can be manipulated by a personal computer via an ethernet port. A photograph of the devices in the control office is shown in Figure 3.


**Figure 5.3. Photograph of the devices in the control office.**

A signal-processing program was written to retrieve the optical spectrum from the optical measurement instrument and to determine the temperature readings from calibration curves. A mixed-language programming environment was used.  The graphic user interface (Figure 5.4) was programmed in Visual Basic. The data acquisition and signal demodulation modules were programmed in Visual C++. The temperature readings from the sensors were designed to be sampled in a period of 3 seconds. The communication bit rate between the measurement instrument and the computer was designed to be 56k bps. Monitoring and data logging are also performed by the personal computer. The historic temperature reading data as well as the raw optical spectra are recorded.

The computer in the control room will be connected to internet so that the computer can be remotely controlled. antivirus and firewall software will be installed for security purposes.

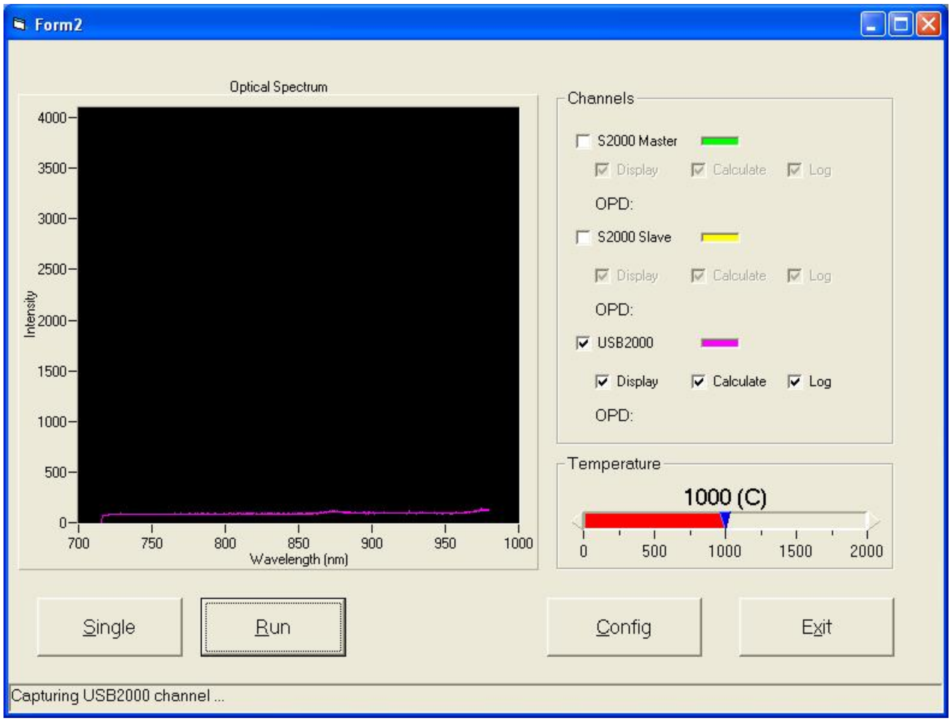


**Figure 5.4. Graphic user interface of the application software.**

# CONCLUSIONS

## 6.0 Conclusions and Future Work

The main objective of this project is to bring the sensor technology, which has already been demonstrated in the laboratory, to a level where the sensor can be deployed in the harsh industrial environments and will become commercially viable. During the reporting period, a site visit to TECO's Polk Power Plant allowed us to design appropriate mechanical packaging, plan for sensor installation, and set targets for data processing and related software. Once we receive the necessary components, we are ready to fabricate packaged sensor and evaluate them in the laboratory prior to installation at TECO.

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## List of Acronyms and Abbreviations

A/D, analog to digital
APP, Advanced Pressure Products, Inc.
BPDI, broadband polarimetric differential interferometry
CCD, charge couple device
CPT, Center for Photonics Technology
CTE, coefficient of thermal expansion
EFPI, extrinsic Fabry-Perot interferometer
EMI, electromagnetic interference
FP, Fabry-Perot
FWHM, full width half maximum
GPM, gallons per minute
GRIN, graded index
ID, inner diameter
LED, light emitting diode
MM, multimode
MMF, multimode fiber
OD, outer diameter
OPD, optical path difference
OT, optical thickness
PC, personal computer
PZT, lead zirconium titanate
RFLWN, raised face long weld neck
SCIIB, self-calibrated interferometric/intensity-based
SLED, superluminescent light emitting diode
SMF, single mode fiber
SNR, signal to noise ratio
VTPL, Virginia Tech Photonics Laboratory (now Center for Photonics Technology)