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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CENTER FOR PHOTONICS TECHNOLOGY

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Abstract

This report summarizes technical progress October 2006 – March 2007 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. During the second phase, an alternative high temperature sensing system based on Fabry-Perot interferometry was developed that offers a number of advantages over the BPDI solution.

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. The sapphire wafer-based interferometric sensing system that was installed at TECO's Polk Power Station remained in operation for seven months. Our efforts have been focused on monitoring and analyzing the real-time data collected, and preparing for a second field test.

Table of Contents

List of Figures and Tables

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.

During the second phase of this program, an alternative high temperature sensing system based on Fabry-Perot interferometry was developed that offers a number of advantages over the BPDI solution. This sensing system was installed and tested at TECO's Polk Power Station, remaining in operation for seven months. Our efforts have been focused on monitoring the installed probe and preparing for a second field test at TECO.

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.

- Monitoring of sensor in the gasifier at TECO's Polk Power Plant. **The temperature probe remained in operation for seven months, seeing temperature close to 1400°C.** During this time period, all thermocouples installed in the gasifier were replaced.
- Sensor probe design and assembly in preparation for the second TECO field test
- OTDR interrogation of installed probe
- Sensor probe retrieval and replacement at TECO's Polk Power Plant (April 2007)

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 sensors, 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.

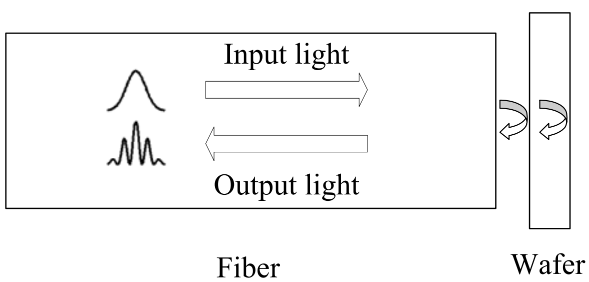

Figure 3.1. Sensing principle.

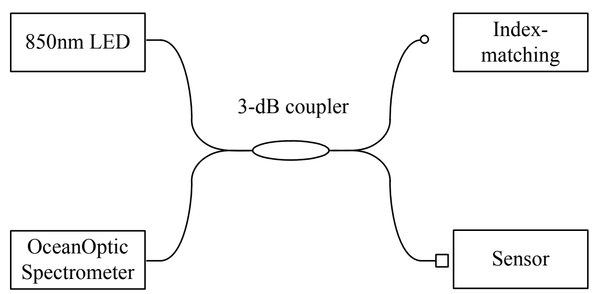

Figure 3.2. White-light interferometric system setup.

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.

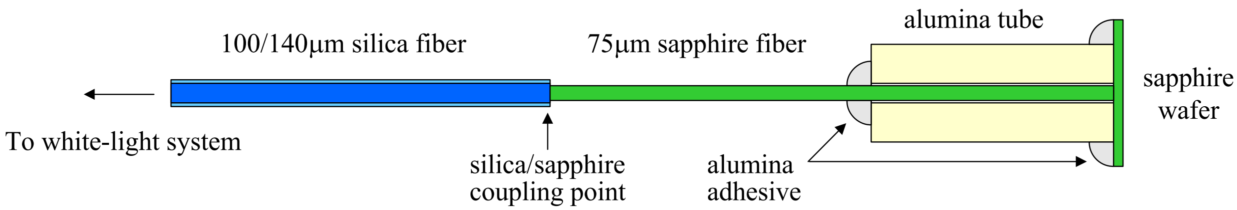

Figure 3.3. Diagram of the sensor head.

RESULTS AND DISCUSSION

4.0 First TECO Field Test

The fiber optic temperature sensor was installed at TECO's Polk Power Station in late May 2006, providing real-time temperature data (Figure 4.1) until December 2006 and thereby demonstrating that single-crystal sapphire is very well suited for long term high-temperature measurement. During that time, all thermocouples installed in the gasifier were replaced.

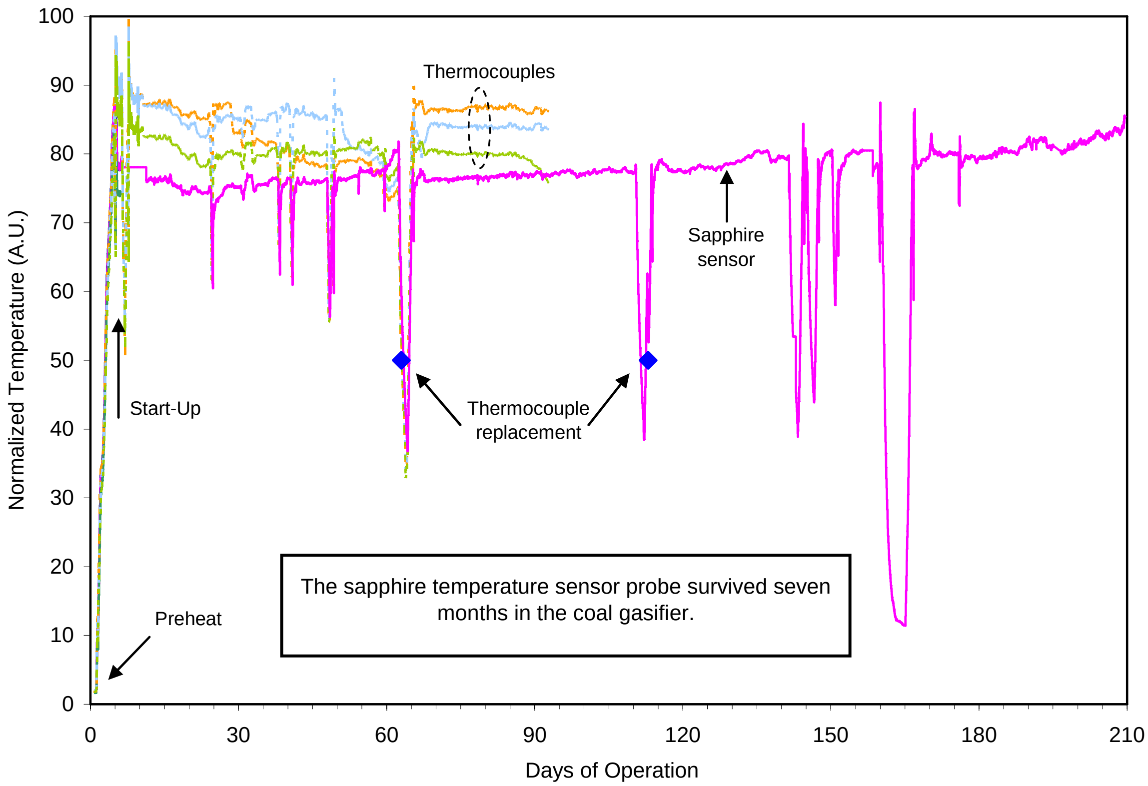

Figure 4.1. Comparison of sapphire fiber sensor temperature data to conventional thermocouple data. Both sets of thermocouples have now been replaced, as indicated by the blue diamonds on the graph. Thermocouple data from Day 11 to Day 98 consists of 4-hour averages; data for Days 99-210 is available from TECO.

5.0 Second TECO Field Test

Following the success of the first field test, a second test was planned in order to improve the sensing probe's survivability for long term multi-point measurement and optimize temperature response time to reveal greater detail on temperature fluctuations in the gasifier. During the reporting period, a new temperature sensing probe was designed and fabricated; it was installed at Polk Power Station in April 2007. Although the installation occurred after the end of the reporting period, it is discussed briefly in this report.

5.1 Sensor Fabrication

At the time that we began sensor fabrication for the second field test, one surviving sensor was still operating in the gasifier at TECO (structure b in Figure 5.1). All three sensors for the second field test were fabricated using this robust structure, which was also the simplest.

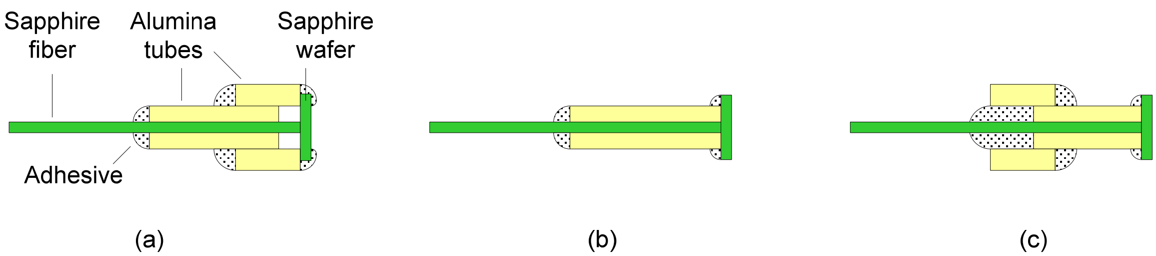

Figure 5.1. Three sensors with different structures used in the first field test.

The sensors were calibrated by comparing their outputs with readings from a B-type thermocouple in the range 25°C to 1450°C, resulting in accuracies of 3°C for the first two and 5°C for the third, whose signal was poorer than the others.

5.2 Sensor Packaging

Before packaging, the three sensors were separated by 0.5 inch, as shown in Figure 5.2. For the second field test, the probe packaging was modified by removing the innermost sapphire tube (Figure 5.3), allowing the first sensor to be placed 1 inch from the tube end, followed at 1.5 and 2 inches by the other two. The sensor whose signal was worst was placed closest to the refractory wall surface. The packaged probe is shown in Figure 5.4.

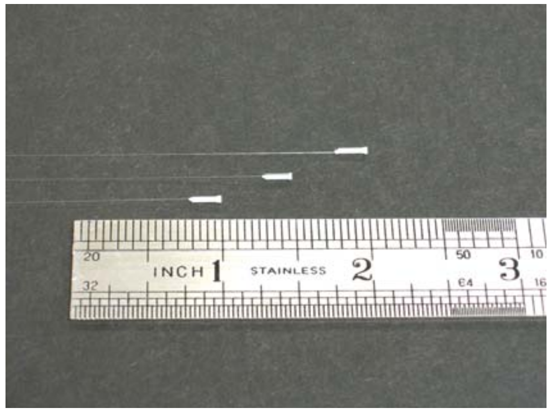

Figure 5.2. Sensor placement.

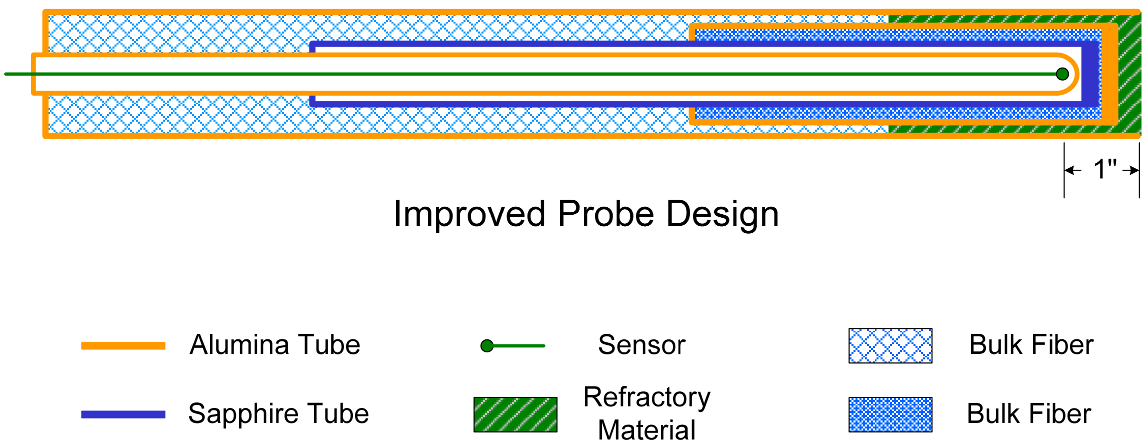

Figure 5.3. Probe packaging design for second TECO field test.

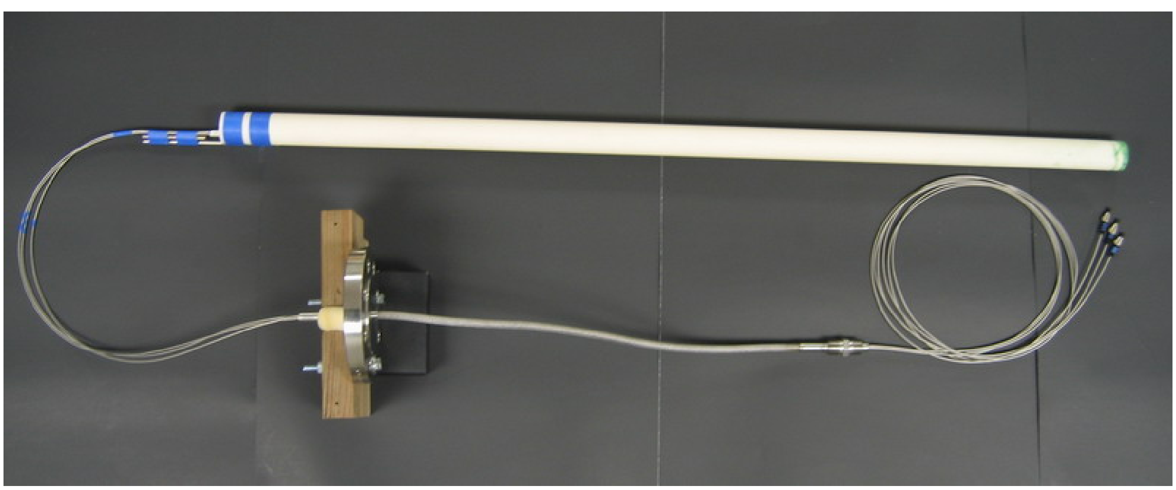

Figure 5.4. Packaged sensor probe for the second field test.

5.3 Interrogation of First Field Test Probe Using Optical Time Domain Reflectometry (OTDR)

Before installing the new probe, the OTDR was moved to the 13th floor of the gasifier and used to interrogate the old probe. We also interrogated the new probe before it was installed for comparison and future reference. The results are shown in Figure 5.5 and Figure 5.6. Comparing the two figures, the following points are notable.

- No reflection from the sapphire end can be detected for old probe.
- In the old probe, an abnormal reflection peak is found at 2.8 meters (very close to one of the two feedthroughs).
- Reflection at the sapphire and silica splicing point is lower in old probe (peaks located around 4 meters).

Further laboratory analysis will be necessary before conclusions can be drawn.

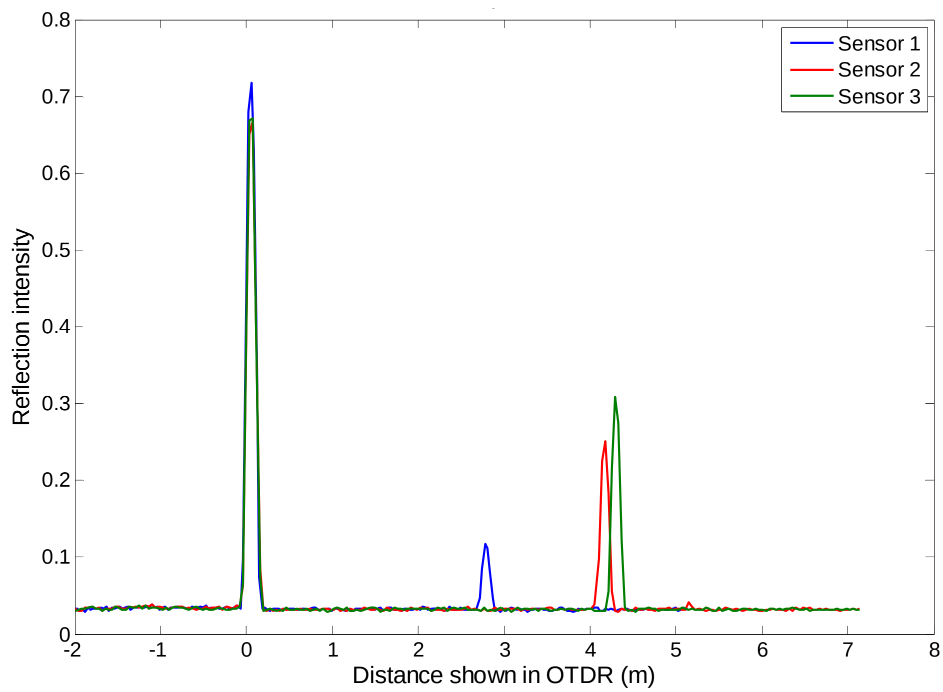

Figure 5.5. OTDR results for first probe (retrieved in April 2007).

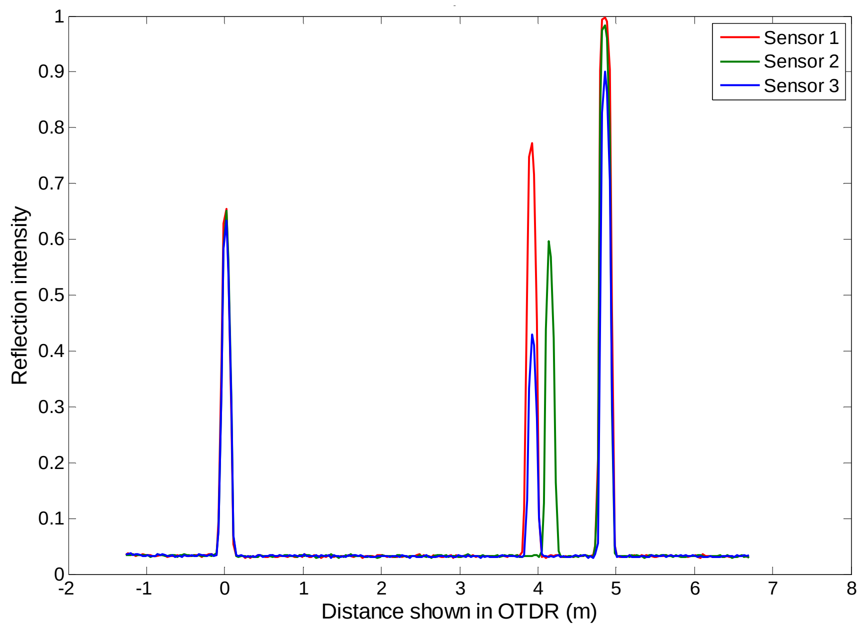

Figure 5.6. OTDR results for second probe (installed in April 2007).

5.4 Sensor Installation

Before installing new probe in April 2007, we were able to retrieve the old probe. As expected, the outermost packaging layer was trapped in the port. However, the probe was designed to allow retrieval of the core of probe, which includes sapphire fibers and innermost alumina tube. This was returned to Blacksburg, Virginia for laboratory analysis to assist in probe redesign and improvement.

The new probe was then moved to the working site and its three sensors recalibrated prior to installation. The coal gasifier chamber at TECO's Polk Power Station consists of high chrome brick, insulating refractory and metal vessel wall, with a flange type of test port on the wall. The probe housing was designed to have two metal spacers to connect with the test port and protect the temperature probe inside. Two fiber feedthroughs connect the inside sensors and the outside interrogation systems.

In the first field test, one output was sent to the DCS. For the second test, TECO requested all three sensor outputs. We therefore upgraded the hardware and software to enable three outputs by replacing the ADAM-4021 with ADAM-4024, and adding extra output codes to the original software.

Sensor output following startup is shown in Figure 5.7.

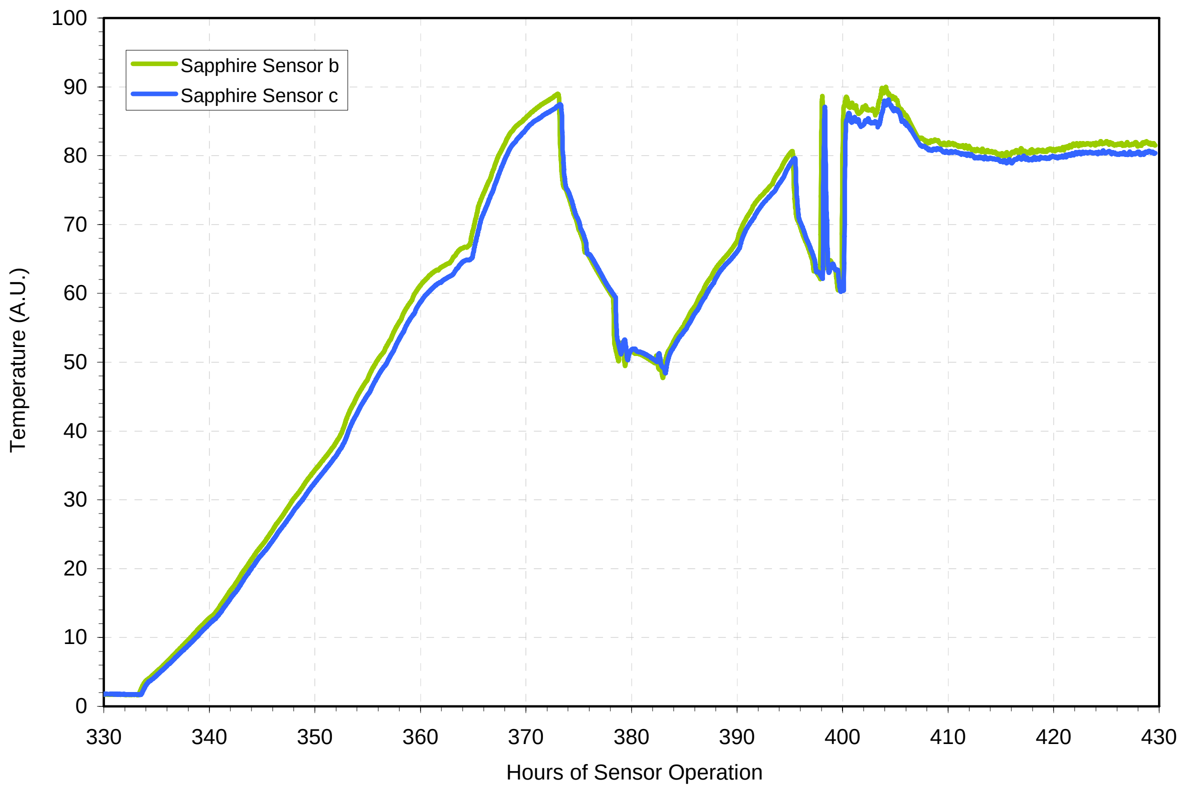

Figure 5.7. Temperature results following start up.

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, the sapphire-wafer-based fiber-optic high-temperature sensing probe installed at TECO's Polk Power Station survived seven months in the coal gasifier, providing real-time temperature data. Analysis of the critical system components resulted in downselection of the sensor head design and minor changes to the packaging design in preparation for the second field test at TECO. The second probe was installed in April 2007.

We have retrieved the first probe and will be retrieving the second probe shortly. Following a thorough laboratory analysis of both probes, and update to the report will be submitted.

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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
DCS, distributed control system
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
OTDR, optical time domain relfectometry
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
TECO, Tampa Electric Co.
VPN , virtual private network
VTPL, Virginia Tech Photonics Laboratory (now Center for Photonics Technology)