Overview of Advanced Fiber Optic Sensor Equipment for Energy Production Applications

John W. Berthold and Richard L. Lopushansky
Davidson Instruments, Inc. 4800 Research Forest Drive, The Woodlands, TX 77381

ABSTRACT

Over the last several years, fiber optic sensor technology has matured to the point that it is now ready for use in industrial applications. Fiber optic sensors have the potential for significant cost savings to the customer, primarily because installation is straightforward and maintenance is minimal. Substantial improvements in the performance of process control systems are a major benefit that has now been demonstrated and is now understood by many in the energy and petrochemical industries. This paper describes the basic principles and components that make up an industrial fiber optic sensing system, the results of an extensive characterization program performed on Fabry-Perot sensors configured to measure various parameters, the multiplexing approach for a multi-sensor system, data communications options, and potential applications of the technology within industry. The results of a beta test program performed on a thirty- two channel temperature measurement system are reported also. The test program was conducted in an operating catalyst tube reactor to measure changes in the reactor temperature profile versus time.

Keywords: Pressure, temperature, vibration, flow, level

1. INTRODUCTION

Low power fiber optic process control instrumentation is ideal for use in refineries, chemical plants, power plants, oil production facilities, or in any hostile environment because the sensors pose no danger even in hazardous areas where explosive vapors may exist. Most of the fiber optic systems described in this paper operate at less than 50% of the power level deemed intrinsically safe. Instrumentation installation and maintenance costs can be significantly reduced because low power fiber optic sensing systems do not require explosion-proof conduit and containment.

For many years, fiber optic sensors have been touted to be immune to electromagnetic interference and suitable for use near high voltage electrical systems. Because optical fibers cannot conduct current, fiber optic sensors eliminate problems associated with lightning and ground loops. They are tolerant of high concentrations of hydrogen and corrosive environments. The small size and lightweight characteristics of fiber optic sensors make the sensors ideal for most industrial applications.

Fabry-Perot fiber optic sensors for both temperature and pressure have been designed and demonstrated to operate at temperatures from up –55°F to 1000°F. This performance allows fiber optic sensing technology to make measurements of process conditions that cannot be made with conventional electronic sensing technology. In addition, fiber optic sensors can be used in severe cold where need for impulse lines, capillary tubes and the associated weatherization hardware can be eliminated. Significant process improvements and increased margins of safety will be realized through the application of this enabling technology.

Fiber optic sensors can and have been used in industrial environments to measure temperature, pressure, differential pressure, vacuum, linear and rotary position, strain, vibration, and acceleration. Specific signal conditioners for optoelectronic conversion can be designed for high resolution, fast dynamic response, and/or for long transmission distances. The signal conditioners can communicate with any open architecture ranging from digital RS-232 to 4-20mA analog. The signal conditioners can be dedicated to a single sensor for high-speed data acquisition or they can be multiplexed in large numbers to a variety of sensors to drive down the installed system cost.

Ruggedized cabling and multipoint connectors are used to interface and transmit optical signals from harsh environments to non-hazardous locations where the signal conditioners are located. In the process control industry, fiber optic instrumentation is rapidly becoming recognized as safe, economical, and reliable.

2. OVERVIEW OF SENSOR TECHNOLOGY

All of the sensors described in this paper are based on Fabry-Perot displacement sensor technology.

For individual measurement parameters such as temperature or pressure, the transducer is designed to measure displacement that results from a change in that parameter. For example, the displacement transduction mechanism for a temperature sensor is based on the difference in the coefficient of thermal expansion between two materials. The displacement transduction mechanism for a pressure sensor is the deflection of a diaphragm. Temperature, pressure, vacuum, density, strain, acceleration, rotary and linear position, and vibration can all be measured by designing transducers that convert the measurement parameter to a change in displacement that can be measured by a Fabry-Perot displacement sensor.

The full-scale design displacement of any sensor is less 12μm. The resulting stress on transducer components is very small and the measured displacements are very repeatable. For example for pressure sensors, the deflection is so small enough that the maximum stress at design pressure is generally less than 25% of the elastic limit of the diaphragm. The optical interrogators inside the signal conditioners can resolve sub-nanometer displacements, which provides for large dynamic range and repeatability that is more than adequate for most industrial applications.

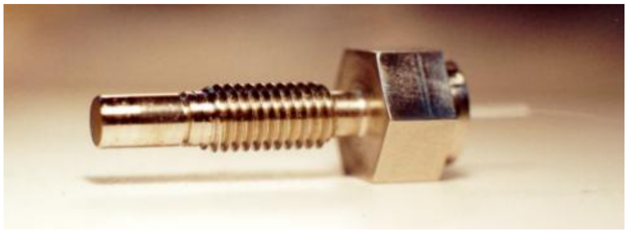

Fig. 1. Miniature temperature compensated pressure sensor.

In comparison, electronic sensors rely on a variety of technologies to perform a measurement. For example, thermocouples produce an electromotive force (EMF) and require a different signal conditioner than a strain gage that produces a change in resistance or a piezoelectric crystal that produces a change in dynamic voltage. Since each of the Fabry-Perot fiber optic sensor/transducers discussed in this paper contains the same basic Fabry-Perot displacement sensor, the same signal conditioner can be used for any sensor by simply defining the type of sensor along with the calibration constants. Thus, a variety of sensors may be multiplexed to share a single signal conditioner, which reduces overall cost and increases reliability. In addition, multiplexing facilitates thermal compensation to be built into a pressure sensor to increase the effective range and resolution of the sensor.

The fiber optic signal conditioner uses interferometry to determine the displacement of each sensor. In all cases, changes in displacement are measured through a phase shift of the modulated light. The sensor detects the change in separation (gap) between two parallel mirrors (Fabry-Perot configuration) to perform displacement measurements, and the absolute measurement of the gap is converted into engineering units based on the calibration constants for a given sensor. Finally the signal is transmitted by the signal conditioner to a control system via a variety of standard communication protocols – digital or analog.

Several signal processing schemes are employed for various applications. Some applications require dynamic measurements with update rates exceeding 10kHz while signal conditioners for other applications operate at slower speeds but have high resolution. The variety of signal conditioners requires a variety of light sources, detectors, and related hardware. Light sources include tungsten lamps, light emitting diodes, and diode lasers.

3. PRODUCTION PRESSURE SENSORS

Shown in Fig. 1 is a miniature production pressure sensor. The screw thread size is 10-32. The pressure diaphragm is on the left end and two optical fibers exit the right end. One fiber delivers light to the transducer diaphragm for pressure measurement and the other fiber delivers light to a temperature sensor. Characterization data for two similar pressure sensors with 3000 psi range is shown in Fig. 2. These are early manufactured units intended to be the same. The sensitivities (slopes) of each are nearly identical but the offsets different. Repeatability is better than 0.2% of full scale. More recent performance data is shown in Fig. 3 for manufactured units with 2500 psi range.

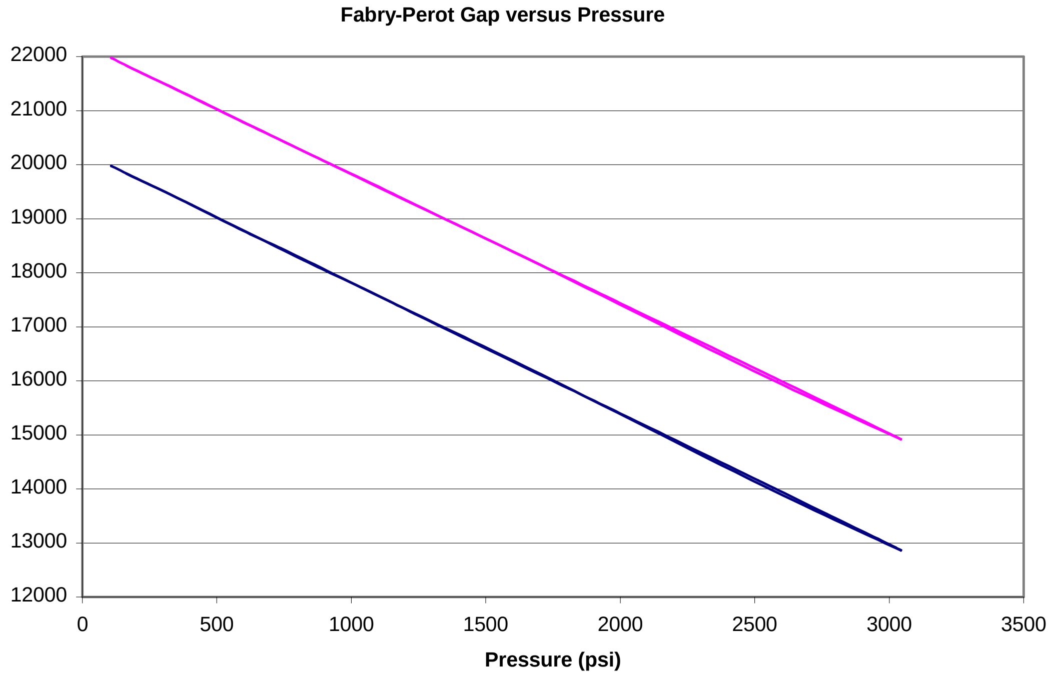

Fig. 2. Measured gap versus pressure for two production pressure sensors.

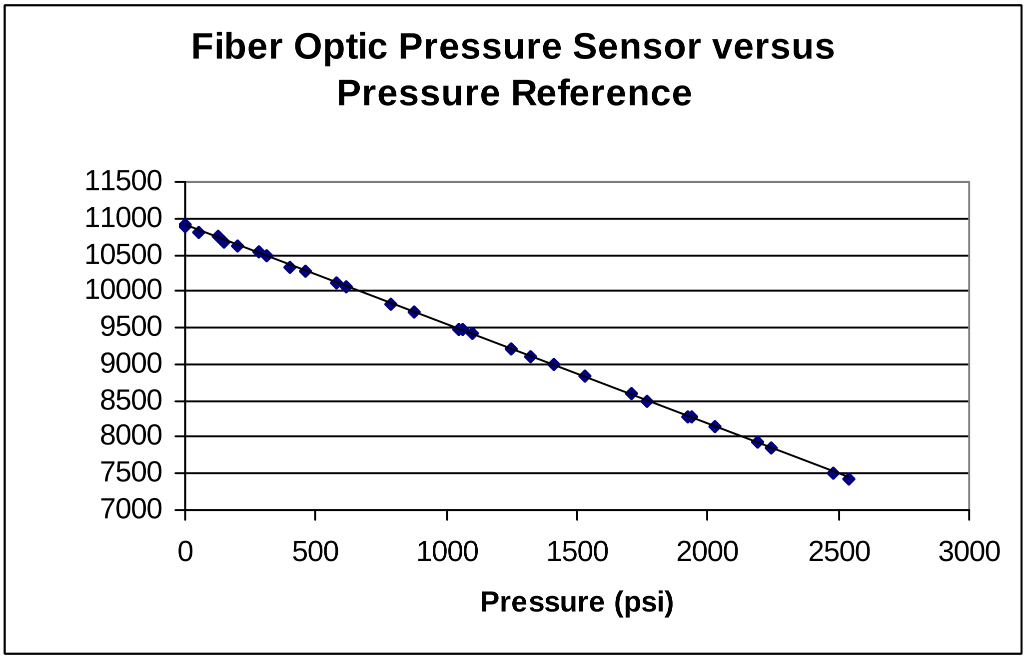

Fig. 3. Measured gap versus pressure for manufactured 2500psi pressure sensor.

4. PRODUCTION STRAIN SENSORS

Fig. 4 shows characterization data for a fiber optic strain gage compared to an electrical resistance foil strain gage used as a reference. The agreement between the two gages is approximately 50 microstrain (1.5% of full scale).

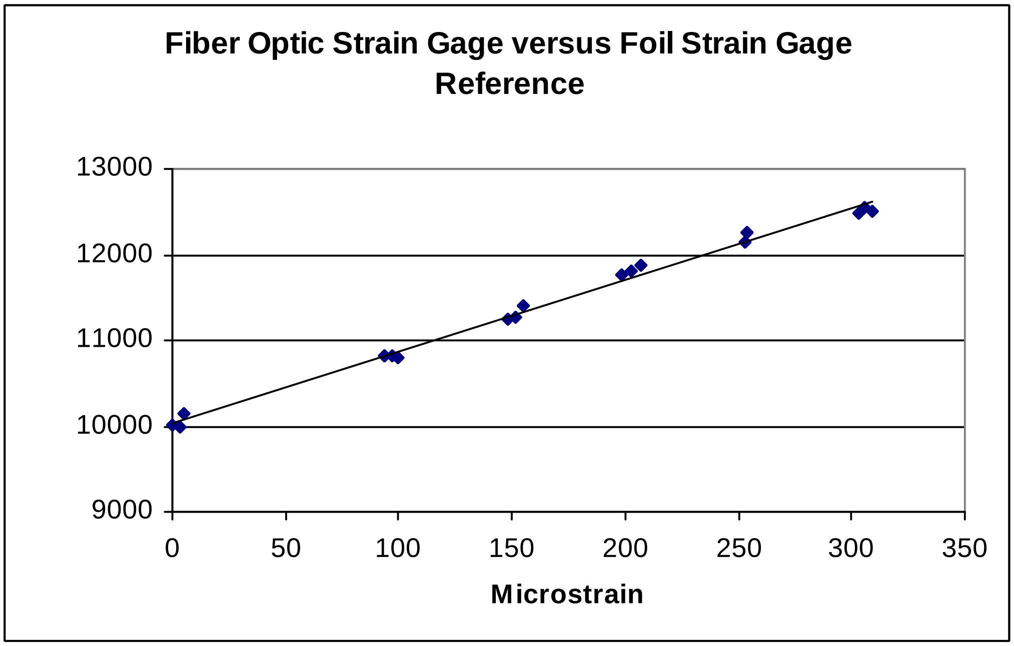

Fig. 4. Measured gap versus microstrain for fiber optic strain sensor.

5. PRODUCTION POSITION SENSORS

Fig. 5 shows characterization data for a fiber optic position sensor taken with a differential screw reference. The linear dynamic range is 10,000:1.

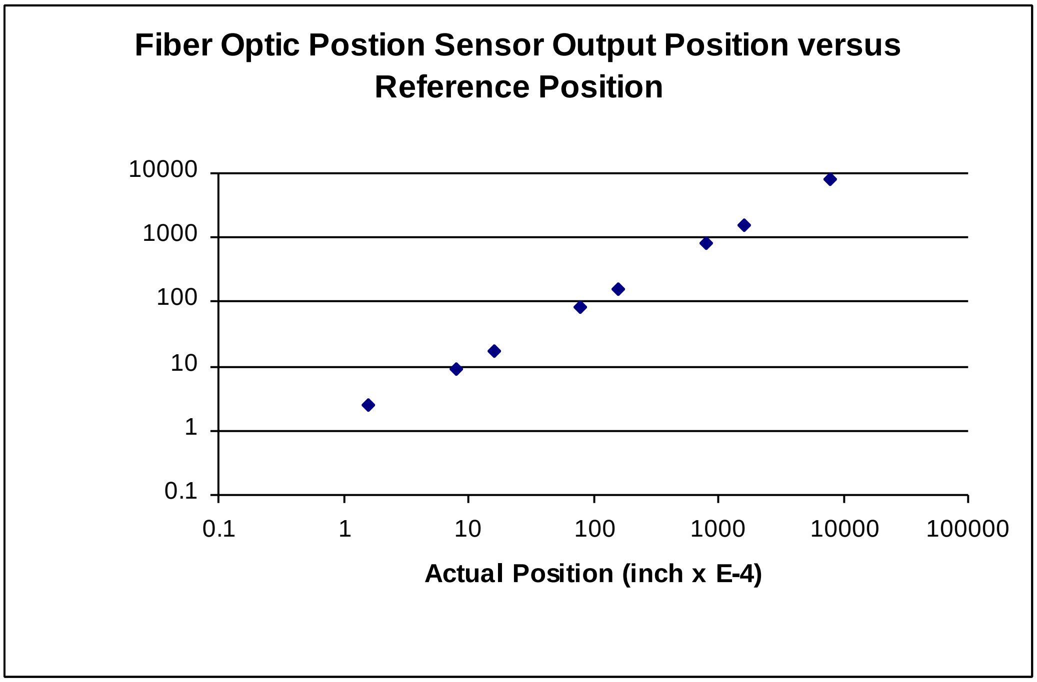

Fig. 5. Measured versus actual position from a fiber optic linear position sensor.

6. PRODUCTION TEMPERATURE SENSORS

In November, 2002, a thirty-two (32) channel fiber optic temperature measurement system was tested in a forty-two (42) foot high ethylene oxide (EO) tube reactor. The sensors provided point temperature measurements from the bottom to the top of the reactor. The temperature profile provides the reactor operator with vital information for the safe and efficient operation of the reactor including:

- Detection of hot spots that could compromise the integrity of the reactor

- Improved prediction of the end of life for the catalyst in the reactor.

Conventional multipoint thermocouple probes are considered unsatisfactory for use in temperature measurement of small diameter catalyst tubes for the following reasons:

1) The large cross-section of thermocouple probes adversely affects the flow and heat transfer dynamics of the catalyst reaction in the small diameter tubes.
2) Fewer than ten discrete measurement points can be included in a typical thermocouple probes.
3) The life of conventional thermocouple probes is often less than six months.

The multipoint fiber optic temperature sensing system tested in this application overcomes these shortcomings and can be applied to temperature profile measurement in tube reactors, along the length of furnace tubes, or in any application that requires a robust, high-resolution measurement with a very small cross-section.

Fiber optic temperature sensing probes can range in length from several inches to more than fifty (50) feet and can be packaged in sheaths smaller than 1/8" in diameter. The individual temperature sensors can be spaced as close as one inch apart. Laboratory experiments have shown that unsheathed fiber optic sensors respond to temperature changes in less than one second.

A rugged multipoint fiber optic connector was required by the customer as a part of the test hardware to enable quick and reliable connection of the sensor fibers to the signal conditioner. The signal conditioner can provided a seamless interface with existing control systems including 4-20mA, 0-5 volt, RS-485, Modbus, and Fieldbus and can be located safely hundreds of feet away from the hazardous process. In this first test, the signal conditioner was 100 feet from the sensor assembly and the signal conditioner output was 16 channels of 4-20mA signals sent to the customer’s data acquisition system.

6.1 System Description

The temperature measurement system consisted of a 46-foot long probe, a 100-foot long cable, and a thirty-two-channel signal conditioner. The probe was made of ¼” diameter 316 stainless steel. The probe contained thirty-seven (37) fiber optic temperature sensors spaced twelve inches apart beginning three feet from the end. Thirty-seven optical fibers exited the ¼” tube and were terminated in a multipoint fiber optic connector.

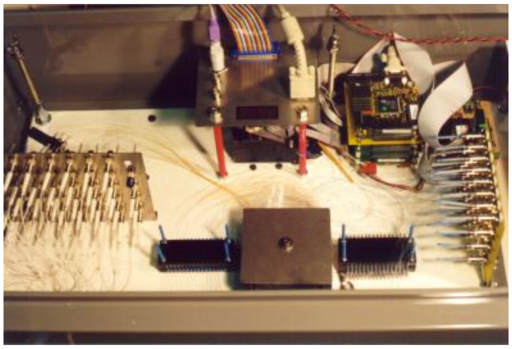
Fig. 6. 32 channel System

The multipoint connector enabled the probe to be easily and quickly connected and disconnected from a 100-foot armor sheathed cable which linked the thirty-seven (37) temperature sensors to the signal conditioner. The signal conditioner shown in Fig. 6 converted the optical signals to temperature readings and transmitted these readings to the process control computer via standard 4-20mA current loops. The system specifications are defined in Table 1 below.

System	Operating Range:	-100 to 550°F
	Operating Pressure:	300psi
	Accuracy:	± 3°F
	Upscale burnout:	Fail to maximum reading (20mA)
Probe	Sheath Material:	316 SS ¼” OD with 0.049 wall
	Sensors:	37 in one-foot increments beginning 3 feet from the end
	Cabling/Connectors:	100 feet of armored cable with a single 37-pin connector
Signal Conditioner	Channels:	Thirty-two (32) multiplexed channels
	Update Rate:	10 seconds
	4-20mA Scaling:	0 to 1000°F or 0 to 600°C
	Power Input:	24VDC; 1 Amp
	Enclosure:	NEMA 4

Table 1. Temperature measurement system specifications

6.2 Test Setup

The fiber optic sensor probe was centered in a catalyst tube that in turn was centered inside a 6” diameter reactor. The 2” annular space between the internal tube and reactor wall contained kerosene. At ambient temperatures, the kerosene level was 29 feet from the top of the reactor.

During the testing, the catalyst tube was filled with inert material and not actual catalyst. Nitrogen gas flowed through the inert catalyst and served as a heat transfer medium.

Only sixteen (16) 4-20mA lines were available to run from the control room to the signal conditioner and so only sixteen of the thirty-seven sensors in the probe were monitored. Five (5) reference thermocouples located in the annular space between the jacket and the catalyst tube were also monitored and used for comparison purposes. These thermocouples were located at elevations (measured from the top of the reactor) of 1, 5, 15, 29 and 39 feet. Sixteen fiber optic temperature sensors were selected from locations near the reference thermocouples to enable collection of comparative data.

The test plan specified operation of the reactor through the following temperature cycle ranging from ambient to approximately 500°F.

- Ramp the temperature to 500F and maintain the reactor at 500°F through the first day
- Shutdown the reactor at the end of the first day, allow it to cool passively overnight
- Ramp the temperature to 500F and maintain the reactor at 500°F through the second day
- Shutdown the reactor at the end of the second day, allow it to cool passively overnight
- Open the reactor and remove the probe on the third day.

The slow rate of passive cooling during the night provided a large amount of information and provided an excellent basis for evaluating the performance of the fiber optic sensing system.

6.3 Test Results

The first test demonstrated the signal conditioner survived shipping, handling, and installation. This test showed the seamless linkage between the fiber optic signal conditioner and the existing control system via the conventional 4-20mA-communication protocol. It also demonstrated the simultaneous communication to other computers via RS-232 serial digital protocol. A separate system monitor and calibrated sensor standards were used to provide a stable and immediate comparison between the readings displayed at the control system and the signal being sent from signal conditioner. The test demonstrated the following:

- Ruggedness of the system to survive shipping, handling, and installation.
- Communication via the 4-20mA was seamless.
- Readings on the control system were consistent with those at the signal conditioner.
- Communication via RS-232 digital interface was consistent with the 4-20mA readings.
- The upscale burnout reading was demonstrated.

The second test demonstrated the ease of installing and connecting the sensor probe to the signal conditioner. This involved positioning the forty-six (46) foot long temperature sensing probe into the reactor and completing the connection via the multipoint fiber optic connector. Once the system was installed and operational the functionality test began.

Fig. 7 shows the temperature versus time for the fiber optic temperature sensors at their respective elevations in the reactor along with the five thermocouple signals. In Fig. 7, the temperature axis for each sensor is offset in relation to its position within the reactor. Several observations from Fig. 7 are worth noting:

- The repeatability of the fiber optic sensors over the test period was very good and is especially apparent during the slow cool-down time periods.
- The temperature profile over time shows the delay in heating of the top of the reactor relative to the bottom.
- During the second heat-up cycle, it is obvious that an abrupt drop in temperature occurred near the top of the reactor.

- Near the end of the test, it is clear when the reactor was opened – the sensors near the bottom of the reactor show a step change to lower temperature and the sensors at the top of the reactor show a step change to higher temperature (chimney effect).
- Although all sixteen channels were operational and displayed on both the system monitor and the control system, due to a setup error, two of the sixteen channels were not stored in memory and thus are not displayed on the graph in Fig. 7.

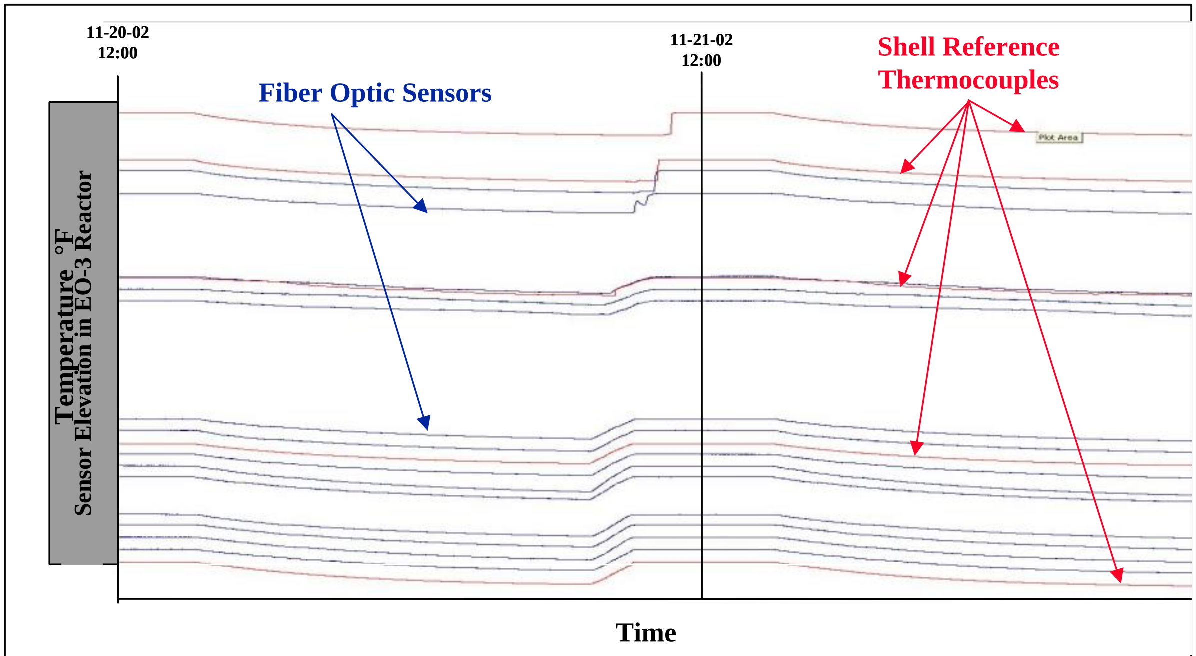

Fig. 7. Temperature profile summary

7. CONCLUSIONS

The advantages of fiber optics for industrial process control instrumentation are significant. The technology is mature; the infrastructure to support industrial fiber applications is in place; and the cost of critical components continues to fall while technical performance improves.

Fiber optic sensing systems have been designed and are being packaged to address the harsh environments of industrial process control. Sensors and signal conditioners have been tested under field conditions and have demonstrated seamless interface with existing distributed control systems. Integrated families of fiber optic sensors and signal conditioners are available to measure most physical parameters and systems are being used in refineries, chemical plants, power plants, and in oil and gas production facilities.

The beta test of the fiber optic temperature measurement system demonstrated the following:

- The capability of packaging thirty-seven (37) fiber optic temperature sensors in a probe with a ¼” OD.
- The durability of the cabling, probe, and instrumentation to survive shipping and handling during installation.
- A convenient connector/cable design that provided quick and reliable installation.
- A thirty-two channel, time-based multiplexing capability with an update rate of ten seconds per channel.

- A seamless and direct interface between the signal conditioner and the existing control system via standard 4-20mA current loop outputs.[1]
- The capability to provide the required scaling, readout in engineering units, and upscale burnout readings.
- The capability to communicate the measurement results to a remote host computer via standard serial communication channel (RS232, RS422, RS485).

ACKNOWLEDGEMENTS

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