# Fiber Optic Temperature Sensors for PEM Fuel Cells

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## Objectives

The objective of this research is to develop a low-cost, durable and fast-responding temperature sensor for proton exchange membrane (PEM) fuel cells. Temperature and temperature gradients within the fuel cell membrane electrode assembly (MEA) are a key indicator of the operational condition of the cell and its ability to respond to a required load. The thermal state of a fuel cell stack directly affects its ability to deliver energy on start-up or under adverse environmental conditions. Furthermore, localized hot spots within the MEA can lead to greatly reduced operational life and even catastrophic failure. Hence, realtime feedback of the thermal condition of a cell or stack can be utilized to control the stack, optimize performance, and monitor the condition of critical components and sub-components.

Currently, thermocouplers and thermistors are being used to monitor the thermal condition at a few locations in operating fuel cell stacks. After a few months effort and a review of our technology with fuel cell developers, the ability to measure temperature at many more locations, with a small, low-cost and electrical non-conductive sensor was considered of great interest. Additionally, the fiber optic sensors provide a safe way of making temperature measurements within the stack without the possibility of electrically shorting the stack to ground as may be the case with a conductive sensor like a thermocouple or thermistor. Finally, the ability to make many cost effective temperature measurements with a technology that is fast, durable and electrically insulating is of great interest to fuel cell developers.

## Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year R,D&D Plan:

- B. Sensors
- C. Thermal Management

## Approach

- Identify and characterize the optimum fluorescent medium (materials and possible binders and or matrices) for fast-responding, accurate and robust temperature measurement;
- Demonstrate material compatibility of the sensor with the fuel cell;
- Explore the most appropriate temperature measurement zones and arrays within the membrane and stack configuration;

- Explore alternate wave guide approaches to optimize sensor robustness, expand the range or density of measurements, and minimize cost of implementation;
- Develop and test probe concepts for cost effective implementation, functionality, durability, and performance;
- Develop a low-cost electronics package that readily integrates with fuel cell systems; and
- Study alternate probe configurations that may lead to sensing other critical parameters (e.g. humidity or flow measurements).

## Accomplishments

- Appropriate fluorescent transducer materials have been identified and characterized that will provide fast-responding (milliseconds) and accurate (<1% of range) temperature information from a fuel cell membrane electrode assembly;
- Low-cost probe designs have been tested in the lab that will provide temperature data from operating fuel cells;
- Initial field tests show that accurate and reliable temperature information can be gathered from operating fuel cells;
- New intellectual property (2 patent disclosures) has been developed in the areas of embedded wave guide sensors and spatially resolved temperature sensors that may lead to system designs that were previously unattainable; and
- Collaborative relationships are developing with several fuel cell designers and end users to gain perspective on designs and facilitate testing and implementation.

## Future Directions

- Probe designs will be evaluated in the lab and prepared for field tests;
- Measurement system design issues will be addressed (signal processing, packaging, etc.);
- Alternate probe concepts will be evaluated that could lead to previously unattainable functionality, performance, and cost targets;
- Field tests will be planned to evaluate system compatibility, durability and performance under real conditions; and
- Emerging possibilities to sense other important parameters or leverage to other related applications will be explored (e.g. humidity and flow, leverage to other fuel cell types, etc.).

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## Introduction

The need for an accurate, reliable and fast-responding temperature sensor has been identified as a critical need for advanced fuel cell designs. Temperature, thermal gradients, and thermal history play a key role in determining the health of a fuel cell and its ability to respond to instantaneous power demands. Furthermore, real-time thermal diagnostic sensors will allow designers to increase stack power density by reducing operating margins and quickly identifying the development of hot spots that could cause catastrophic failure.

This project is focused on the development of an optical fiber based temperature measurement probe that utilizes the unique fluorescence properties of certain materials to detect temperature. The persistence of light emitted (fluorescence) by these materials (thermographic phosphors) is proportional to their absolute temperature. Thus, one can measure the fluorescence lifetime as a means of accurately inferring the temperature of a material. The fluorescence lifetime, as a rule, gets shorter as temperature increases. Other related emission characteristics, such as the fluorescence amplitude or phase of a modulated fluorescence signal, can also be used to infer temperature. The technique can be applied over a wide range of temperatures (-270°C to >1700°C) and is potentially very accurate and durable.

In practice, one attaches, grows or dopes a length of fiber optic cable with the phosphor material included to the end of another fiber optic cable that is used to transmit the light signal to and from the measurement electronics. This impregnated length of fiber is inserted into the temperature measurement zone of interest. The impregnated fiber is excited by a light emitting diode (LED) or laser source, and the fluorescence signal is collected with a photodiode. The fluorescence signal is then analyzed, and a temperature is determined. Temperatures have been determined to better than 0.01°C accuracy in the laboratory.

Thus far, two similar materials (chromium doped yttrium aluminum garnet and ruby) have been identified that exhibit the appropriate characteristics for a fast, accurate and reliable temperature measurement over the range of -40°C to 150°C, the operating range for automotive fuel cells. Being developed now is the fiber optic probe to implement the measurement technique in operating fuel cells. The fiber optic probe can be very small in profile, low mass, low cost and rugged for real world applications. It is also electrically insulating, thus avoiding the possibility of shorting the fuel cell to ground. The measurement electronics can also be implemented in a very low-cost and robust manner, creating a temperature measurement system that is very attractive for commercial system diagnostics and control.

## Approach

The development process for this technology was initiated by an in-depth study of fuel cell designs and operating conditions. Once a clear picture of the measurement need and operating environment was gathered, exploratory research was performed to identify and characterize candidate fluorescent materials for the measurement. These candidate materials were studied in the laboratory, and optimum materials were selected. These optimum materials are now being implemented into various probe designs for further laboratory study. Favorable probe designs will then be installed in actual fuel cells to gather information about system compatibility, performance and durability.

Parallel to the exploratory work described above, alternate probe design and implementation strategies are being conducted with the goal of optimizing system performance, reliability and cost. During this process, two novel discoveries have been made in response to the challenge of creating a measurement technique that would be very low cost, reliable and yet scalable to many measurements distributed throughout the fuel cell. One concept involves the development of embedded wave guide sensors within the fuel cell, thus minimizing the need for intrusive probes inserted into the fuel cell. The other concept involves the development of a single fiber optic sensor that has the ability to measure temperature at a local region anywhere along the length of the fuel cell. This technique may facilitate many temperature measurements through a fuel cell stack with only a single measurement probe.

Considerable progress has been made on the development of initial prototype probes for field testing. Also, novel technologies have emerged that will potentially lead to highly useful and economically viable sensor technologies. Furthermore, our discoveries portend the possibility of other sensor modalities (humidity and flow) that would provide additional needed information about the internal performance and condition of operating and developmental fuel cells.

## Results

Several fluorescing materials were successfully tested which exhibited all the characteristics required and sufficient for an inexpensive temperature measurement system. These characteristics are:

1. Temperature dependence in the desired range;
2. The ability to be excited to emit using a light emitting diode or other low-cost source;
3. Sufficient excitation efficiency to be detected with an inexpensive photodiode or other low-cost detector; and

4. Adequate brightness for use with small diameter optical fiber.

Both powder (phosphor) and crystalline materials were tested. Figure 1 shows how the fluorescence decay time decreases as temperature is increased for one of the materials tested. At present, ruby spheres, items that are inexpensive and commercially available, appear to be the most appropriate as fluorescent transducers. YAG:Cr and $Gd_2O_2S$:Eu are potential alternatives.

Figure 2 shows a portion of the calibration curve for the ruby sphere in comparison with a competing material, YAG:Cr phosphor. Useable emission is expected up to at least 700°C, making it a candidate for current PEM fuel cells as well as future designs that potentially operate at higher temperatures. Figure 3 illustrates a small diameter fiber (50 micron core, 110 micron cladding) inserted into a demonstrator fuel cell. Shown with the fuel cell is a water electrolyzer that generates hydrogen and oxygen to power the fuel cell. The cell was operated at 200 mW power output, and its performance was monitored before and after the temperature sensor was inserted. The temperature measurement was performed as follows: 1) disassemble the cell and place a small spot of phosphor on the polymer membrane, 2) position the fiber adjacent to the phosphor spot, 3) reassemble the cell and operate, 4) transmit light into the cell via the fiber and collect the fluorescence signal back through the same fiber, and 5) process the fluorescence signal to determine temperature.

Temperature measurements were acquired without any noticeable change to the operation of the fuel cell. Viable fluorescence signal levels have also been achieved with an optical fiber pair with core diameters of 50 microns.

Figure 4 depicts various probe configurations that are under consideration. Laboratory tests are being conducted to optimize the signal-to-noise ratio of these probe designs.

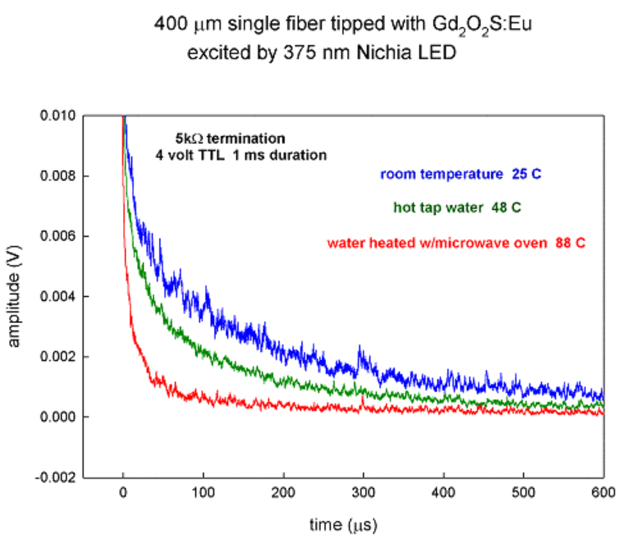


**Figure 1.** Example of How Temperature Affects Decay Time of a Phosphor (TTL = transistor-transistor logic)

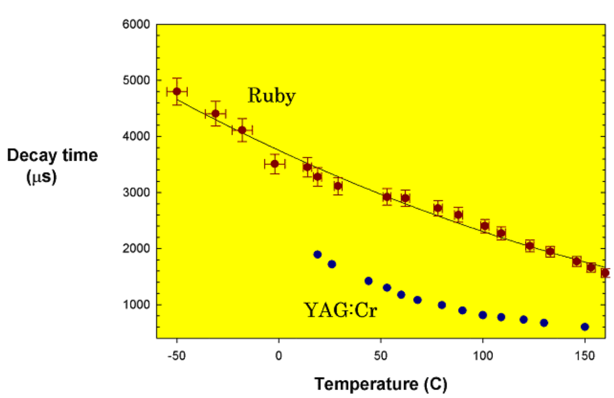


**Figure 2.** First Calibration Run for Ruby and YAG:Cr Phosphor

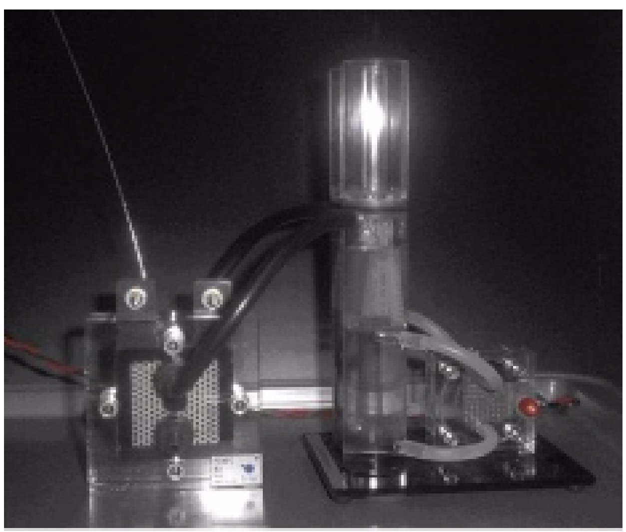

**Figure 3.** Example of Low Profile Fiber Temperature Sensor Inserted into Demonstrator Fuel Cell

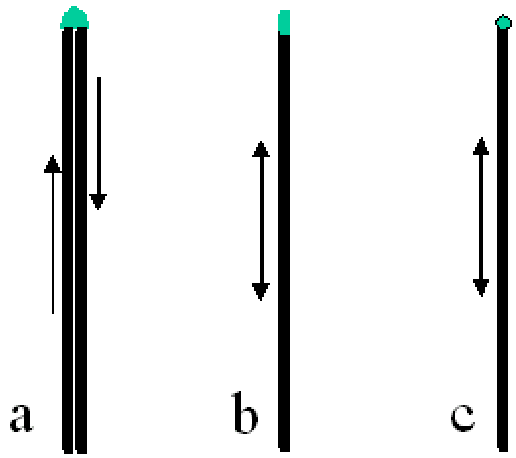


**Figure 3.** Three Probe Designs under Consideration: (a) Dual Fiber Probe with Phosphor Impregnated Matrix (glass or polymer) Tip; (b) Single Fiber Probe with Doped Fiber Sensing Element Grown to Tip; and (c) Single Fiber Probe with Doped Sphere Attached (cemented or epoxied) to Tip

## Conclusions

- Appropriate fluorescent transducer materials have been identified and characterized that will provide fast-responding and accurate temperature information from a fuel cell membrane electrode assembly.
- Low-cost probe designs have been studied in the lab that will provide temperature data from operating fuel cells.
- Initial field tests show that accurate and reliable temperature information can be gathered from operating fuel cells.
- Long term field testing is needed to verify material compatibility between the fuel cell and the sensor probes and to characterize probe durability.

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## FY 2003 Publications/Presentations

1. A poster on fluorescence thermometry was presented at the U.S. Department of Energy Hydrogen, Fuel Cells, and Infrastructure Technologies Program Review Meeting in Berkeley, CA, May 2003.
2. A description of progress is planned for the 2003 Fuel Cell Seminar to be held in Miami Beach, November 3-7, 2003.
3. A paper on spatially resolved temperature measurement and embedded wave guide sensors is being prepared for submission to Review of Scientific Instruments.

## Special Recognitions & Awards/Patents Issued

1. A patent disclosure has been filed on embedded wave guide sensors and their fabrication in polymer thin films.
2. A patent disclosure has been filed on spatially resolved fiber optic temperature measurement.