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FINAL SUMMARY OVERVIEW

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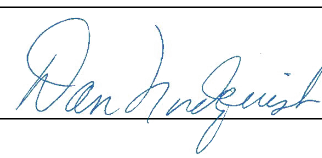
Signature of Submitting Official (signature shall be submitted in accordance with agency-specific instructions)	

Purpose

The purpose of this project is to provide fire and arson scene investigators with a new tool for more reliable temperature measurements during fire testing/modeling and during forensic investigations. Specifically, our goal is to demonstrate the feasibility of our temperature-duration (TD) sensors, embedded in wall paint, as a means to measure and record temperature during fire events. In order to accomplish our goal, we pursued the following objectives:

<u>Objective #1</u>: To develop and evaluate the means to securely embed our temperature sensors into paint and to subsequently recover and separate them from the paint. While the temperature sensors can simply be mixed into the paint like any other pigment, we need to verify that they are chemically stable over extended periods of time. Furthermore, we need to optimize the process for separating the paint from our temperature sensors for subsequent optical characterization.

<u>Objective #2</u>: To calibrate our paint-embedded sensors for temperatures between 400 K and 1400 K and heating durations between 1 min and 60 min. Reference measurements need to be performed over a range of temperatures and heating durations to determine the calibration curves for our temperature sensors. This will also include potential effects due to rapid cooling or oxygen deprivation due to fire-fighting means.

<u>Objective #3</u>: To compare experimentally-determined fire test results with modeling-determined fire test results, and to evaluate the performance of our temperature sensors. Fire tests will be performed at the ATF Fire Research Laboratory under well-defined conditions. Fires under these

same conditions will also be modeled using software such as CFAST (NIST) to simulate the fire's temperatures, including spatial gradients.

Project Design and Methods

To achieve objective #1, we performed ASTM-based aging experiments of temperature sensors embedded in paint. In addition, we developed a process to separate paint residue from our temperature sensors.

To achieve objective #2, we performed calibration measurements of our temperature sensors over a wide range of temperatures and heating durations. The sensors were heated under well-defined conditions to specific temperatures and for specific durations to map the relevant temperature-time space.

To achieve objective #3, we conducted multiple burn tests at the ATF Fire Research Laboratory (FRL) and then compared the results with those from fire modeling provided by the ATF FRL.

Data Analysis

For the data analysis, the test panels were analyzed for their specific photoluminescence (PL). Measurements of the samples were performed using a custom PL spectroscopy system. This system consists of a Continuum Panther OPO (pumped using a Continuum Powerlite Precision II Nd:YAG laser), focusing/collection optics, fiber-coupled Acton SpectraPro 2500 monochromator (0.5 m length, 1800 grooves/mm, 500 nm blaze), and a PI Max 4 1024i ICCD camera (Kodak KAI-1003 scientific grade interline CCD, HBf Gen III intensifier, P46 Phosphor). The use of an OPO allows for tunable excitation of our samples, with the two main wavelengths of interest being

355 nm and 527.8 nm. For each sample, multiple spectra were acquired, with each spectra consisting of 20 CCD accumulations. Once acquired, the spectra were smoothed using an adjacent-averaging algorithm to smooth out CCD noise. To further improve the sample analysis, we also assembled a scanning fluorescence microscope (SFM), which allows us to analyze the samples in a more efficient way.

Project Findings

Objective #1: We developed the means to embed our sensor particles into paint and to subsequently analyze them with and without extraction from the paint.

Objective #2: Based on the actual burn conditions at the ATF FRL, we performed calibration measurements for various temperatures and durations.

Objective #3: We conducted multiple burn tests at the ATF FRL, most recently in Oct/Nov of 2018. While the analysis for the most recent tests is still in progress, the results for a couple of earlier tests are shown below:

Test #1: Test panels containing paint with our temperature sensors were placed at different locations on the walls in the burn cell, see Figure 1.

Figure 1. Images of test panels located throughout the burn cell.

Figure 2 shows the thermocouple reference measurements at different locations within the burn cell, and Figure 3 shows how the results from our new sensors compare with the average and maximum temperatures measured by the thermocouples.

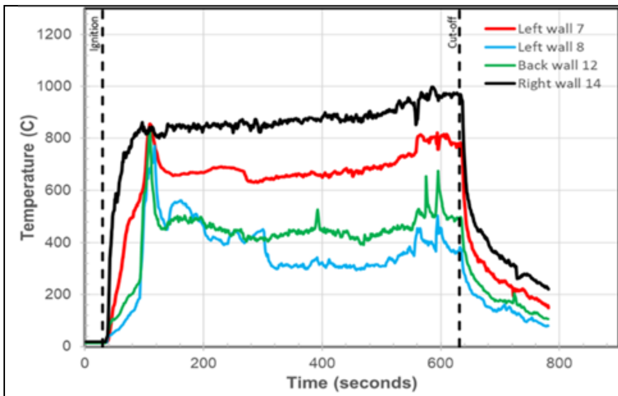


Figure 2. Thermocouple measurements of temperature at different locations during burn test.

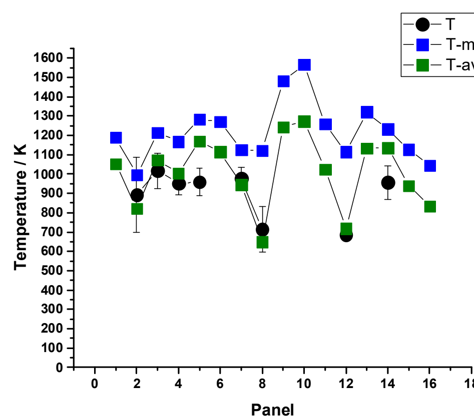


Figure 3. Comparison of temperature measurements from our sensors with the thermocouple reference measurements.

Test #2: Test panels containing paint with our temperature sensors were placed at different locations on the walls in the burn cell, see Figure 4.

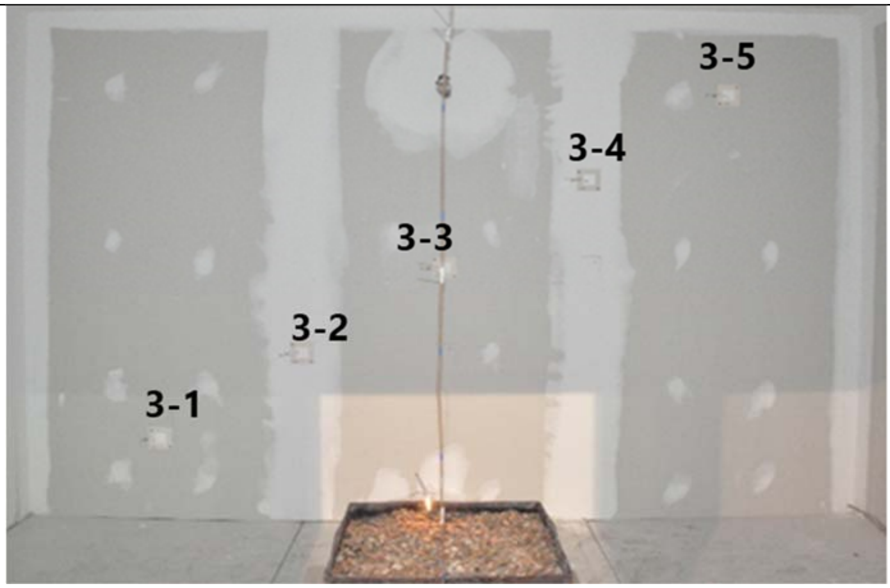


Figure 4. Image of test panels located throughout the burn cell.

Figure 5 shows the thermocouple reference measurements at different locations within the burn cell, and Figure 6 shows how the results from our new sensors compare with the average and maximum temperatures measured by the thermocouples.

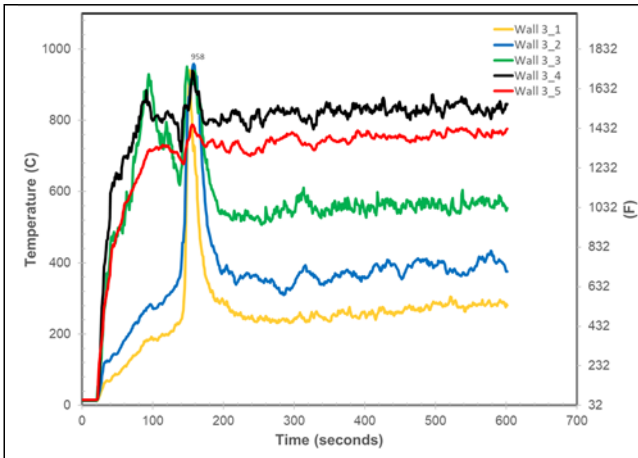


Figure 5. Thermocouple measurements of temperature at different locations during burn test.

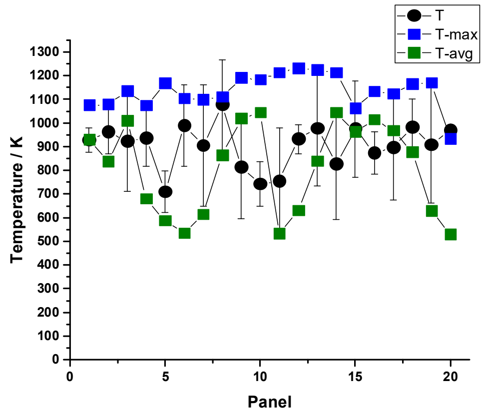


Figure 6. Comparison of temperature measurements from our sensors with the thermocouple reference measurements.

For both tests, the temperature measured by our new temperature sensors tracks well with the average temperatures measured by the reference thermocouples.

Implications

Originally, we envisioned that our sensors would be used in two applications: (1) widespread use in paint or other building materials, and (2) a tool to help in the training of fire investigators.

In the first application, the sensors could help with forensic investigation of fires. Many publications have summarized and highlighted the flaws and myths of fire investigations that have led to wrongful convictions and other erroneous judgments. A push toward using a more scientific approach resulted in the NFPA 921 publication in 1992. Newer editions of this publication continue to improve on the science behind fire investigations. Nevertheless, compared to other forensic sciences, the scientific footing of fire investigations still lags behind and there is plenty of room for improvements with the potential to more clearly identify the causes of a fire and avoid potential convictions based upon flawed evidence. In the second application, our research work would add a scientific tool, particle-based temperature sensors, for use by fire investigators studying fires in controlled environments such as the ATF Fire Research Laboratory.

During a recent discussion with about 15 members of the ATF FRL, it became clear that the widespread use of the sensor particles in paint or other building material is considered uneconomical as there are not enough fires. Instead, the most promising application for our temperature sensors is the use as a tool for fire investigators.

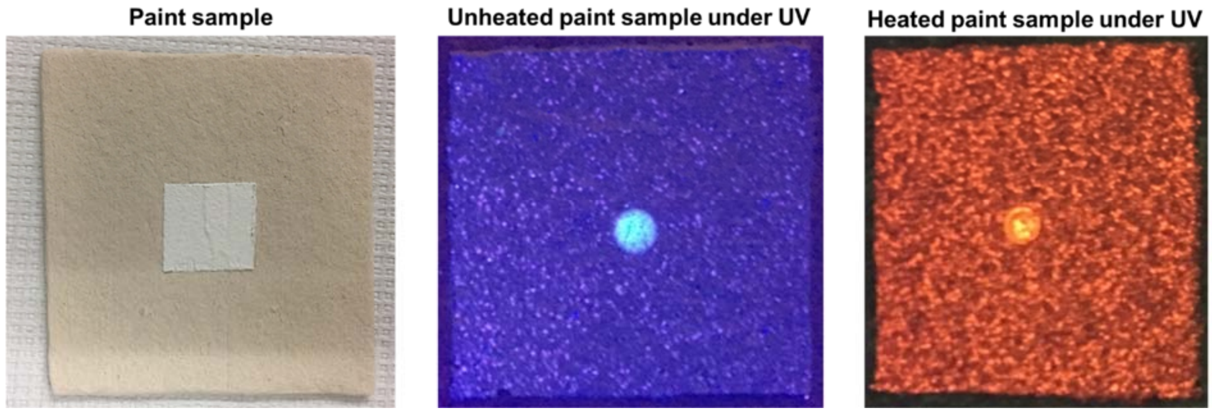


Figure 7. Images of unheated test panel under ambient light (left), unheated test panel under UV light (center), and heated test panel under UV light (right).

Since heated paint, containing our sensors, glows under UV illumination, see Figure 7, the ATF team suggested that this effect could be used during the training of fire investigators to correlate damage/conditions inside a structure with specific temperatures at that location. Such an application would require a portable instrument that can measure the fluorescence and calculate the temperature.

The specific next steps suggested by the ATF team are:

1. Arrange for a blind test of our sensor particles. We would be sending the ATF multiple test panels containing paint with our sensors. These panels would be placed within burn cells during tests and then returned to us for analysis. We would have no prior knowledge of the actual temperatures these panels were exposed to. We would analyze the sensors and provide the ATF with the results.
2. If the results are promising, the ATF would be interested in a portable instrument to analyze temperature sensors.

Our initial results demonstrate that our sensors are capable of passively measuring and recording temperature. We expect the outcome from the more recent tests to confirm this finding. While this capability could be used in various applications, the most likely initial application would be as a training tool for future fire investigators. In combination with a portable analysis instrument, these sensors could help investigators to more closely correlate specific fire damage/conditions with specific temperatures.

Publications and presentations:

- Hergen Eilers, Benjamin Anderson, Natalie Gese, Ray Gunawidjaja, “A new tool for fire/arson investigations,” invited presentation, PITTCON 2019, 19 March 2019, Philadelphia, PA.
- Benjamin R. Anderson, Natalie Gese, Ray Gunawidjaja, and Hergen Eilers, “Nanoscale Ex-Situ Thermal Impulse Sensors for Structural Fire Forensics,” App. Spec. 72, 1310–1321 (2018), doi.org/10.1177%2F0003702817734292
- Benjamin Anderson, Natalie Gese, Ray Gunawidjaja, and Hergen Eilers, “Demonstration of Paint-Embedded Ex-situ Thermal Impulse Sensors in a Burn Chamber Test,” submitted to Science & Justice.
- Ray Gunawidjaja, Benjamin R. Anderson, Natalie Gese, and Hergen Eilers, “Thermal Impulse Sensor Embedded in Paint for Recording the Thermal History of Fire,” In preparation for submission to the Journal of Fire Sciences.

- Benjamin R. Anderson, Natalie Gese, Ray Gunawidjaja, and Hergen Eilers, "Demonstration of Paint-Embedded Ex-situ Thermal Impulse Sensors in a Burn Chamber Test," under review in SN Applied Sciences
- Hergen Eilers, Ray Gunawidjaja, Benjamin R. Anderson, Natalie Gese, and Steven Livers, "Temperature Sensors for Forensic Fire/Arson Investigations," poster presented at PittCon 2018, 1 March 2018, Orlando, FL
- Benjamin R. Anderson, Ray Gunawidjaja, Natalie Gese, Gediminas Markevicius, Helena Diez-y-Riega, and Hergen Eilers, "Structural fire forensics: using optically active nanoparticles to determine a fires thermal impulse," in Frontiers in Optics 2016, OSA Technical Digest (online) (Optical Society of America, 2016), paper FF5B.4. doi.org/10.1364/FIO.2016.FF5B.4