Evaluating Multi-Sensor Fire Detectors In The Fire Emulator/Detector Evaluator*

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ABSTRACT

NIST has developed the Fire Emulator/Detector Evaluator (FE/DE) for the purpose of testing detectors in a controlled environment. The FE/DE is a flow tunnel where fire or nuisance source characteristics can be controlled so that a detector placed in the FE/DE is exposed to the same stimuli it could experience in its end-use location. Multi-sensor detectors with three distinct sensing elements (photo-electric light scattering, ionization, and thermal) were tested in the FE/DE. The exposure scenario implemented in the FE/DE was based on the TF 4 scenario in EN 54 Part 9. Large Eddy Simulation modeling was used to obtain velocity and temperature profiles at the detector location in the EN 54 test room. Literature values of smoke obscuration were used. The smoke injected into the tunnel was not quite sufficient to achieve the peak obscuration values measured in full-scale TF 4 tests. The emulated scenario was repeatable as indicated by a narrow spread in detector alarm values, smoke obscuration and temperature profiles for replicated tests.

INTRODUCTION

The advantages of multi-sensor detectors have been described in detail in recent experimental research[1-4]. Earlier detection and enhanced discrimination of nuisance sources have been demonstrated through the use of signal processing algorithms that combine individual sensor outputs. Such algorithms are not limited to signal threshold values as alarm criteria. Multiple criteria algorithms that consider combinations of threshold values, rate of rise of signals, and statistical characteristics of signals may be employed in algorithms based on fuzzy logic, expert systems, artificial neural networks, or ad hoc implementations. Examples of such multi-sensor, multi-criteria spot-type detectors have begun to appear as commercial products in recent years. Typically, these detectors are certified ("listed") via the standard test protocols developed for single-sensor detectors which include full-scale room fire tests in EN 54 part 9[5], and UL 268[6]. The full-scale room fire tests consist of a standard fire source placed in a fixed location of the room with ceiling-mounted detectors placed at a fixed radial distance from the projected center of the fire source on the ceiling. These tests establish comparative results for different types of detectors exposed to the standard fires. The enhanced benefits of multi-sensor, multi-criteria detectors over single-sensor detectors are not completely established by such tests. For example, a multi-sensor, multi-criteria detector may meet the detection time limits for most or all test fires in EN 54 part 9, implying that such a detector is appropriate for various applications. However, the detector could utilize complex and proprietary algorithms that would make estimation of detector performance in

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other scenarios difficult. In addition, individual sensor response to nuisance sources combined with algorithm processing may enhance or degrade false alarm susceptibility.

The fire emulator/detector evaluator (FE/DE), first introduced by Grosshandler[7], is being developed at NIST in part to address issues concerning multi-sensor, multi-criteria detectors. The objective of this research program is to provide a well-controlled environment where detectors can be exposed to fire signatures and nuisance sources. Fire signatures include: the temperature rise, induced flow velocity, particulate and chemical species concentrations realized at the detector location. (Electromagnetic radiation in the UV, visible and IR spectrums produced from fires are not emulated in this implementation; hence detectors that sense such phenomena would not be tested in the FE/DE.) Nuisance sources include: dusts, water vapor, and any number of location-specific sources such as cooking aerosols in residential settings.

Fire signatures to be emulated in the FE/DE could come from full-scale experiments where the environment at the detector location is characterized. An alternative approach is to simulate the smoke, gas, and heat transport from a fire to detector locations with a suitable computational fluid dynamics model. The fire is characterized by experimental measurements in terms of heat release, smoke, and chemical species production rates which then are used as model inputs. The model output is used to define the environment the detector is exposed to in the FE/DE. This approach is not limited to a fixed test room size allowing one to examine more realistic and complex configurations by simulating them. Davis *et al.*[8] discuss how numerical modeling of fire plumes can be used to develop detector siting rules in spaces with complex geometry. In that study detectors were assumed to alarm after a fixed local temperature rise. More realistic detector response could be obtained with the FE/DE. In this paper, time varying velocity, temperature, and smoke concentration tests were performed in the FE/DE to demonstrate that a test fire exposure can be emulated in a repeatable manner, and that a multi-sensor, multi-criteria detector's response can be evaluated.

EXPERIMENTAL FACILITY

The FE/DE is a flow tunnel designed to reproduce the time-varying air velocity, temperature, and concentration (gas and particulate) expected at a detector during the early stages of a fire. The device is shown schematically in Figure 1. It has a variable speed fan and heater for air stream velocity and temperature control over ranges from 0.02 m/s to greater than 1 m/s and 20 °C to 80 °C, respectively. Water vapor, CO, CO_2, and hydrocarbon gases can be metered into the air stream. A honeycomb flow straightener is located upstream from the test section to condition the flow before it enters the test section. The cross-section of the duct at the test section is 0.30 m high by 0.60 m wide. The duct has a top-hat mean velocity profile at velocities up to 0.3 m/s, then starts to develop a more pronounced parabolic profile at higher flow velocities. Velocity is measured with a thermo-anemometer calibrated from 0.05 m/s to 5 m/s with measurement uncertainty estimated at ± 10 %. Measurements of flow velocities less than 0.05 m/s were obtained from neutrally-buoyant soap bubble trajectories and punk smoke visualization. The fan speed is equated to flow velocity from 0.02 m/s to 0.05 m/s with measurement uncertainty estimated at ± 25 %. Air temperature is measured with a 0.4 mm diameter bare-bead type-K thermocouple. Laser light extinction is measured across the duct at the height of the detector inlet, slightly forward of the detector placement, and at the mid-height of the duct as shown in Figure 2. Each laser beam traversing the duct is reflected twice by mirrors inside the duct to extend the path length to 1.50 m. A He-Ne laser at 633 nm wavelength is used as the light source. Silicon photo-diode detectors described by Pitts *et al.*[9] were used to record laser light intensity. The output of the signal is proportional to the laser intensity reaching the detector. With the use of a laser intensity stabilizer (Thorlabs Inc. Model

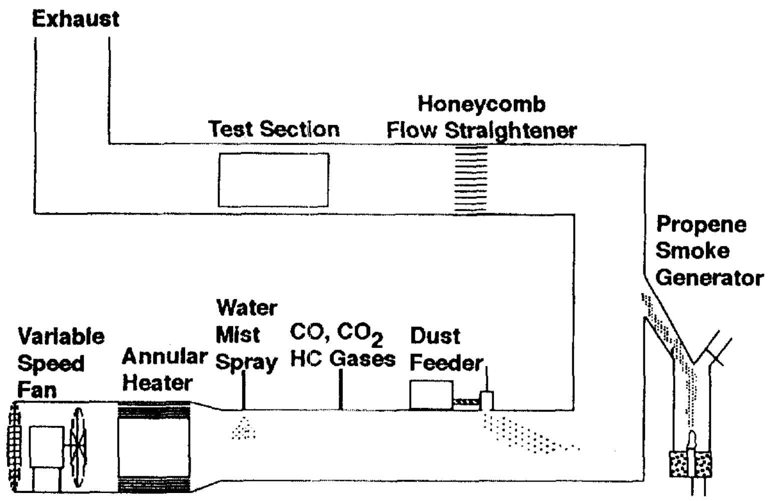

Figure 1. Schematic of the Fire Emulator/Detector Evaluator (FE/DE).

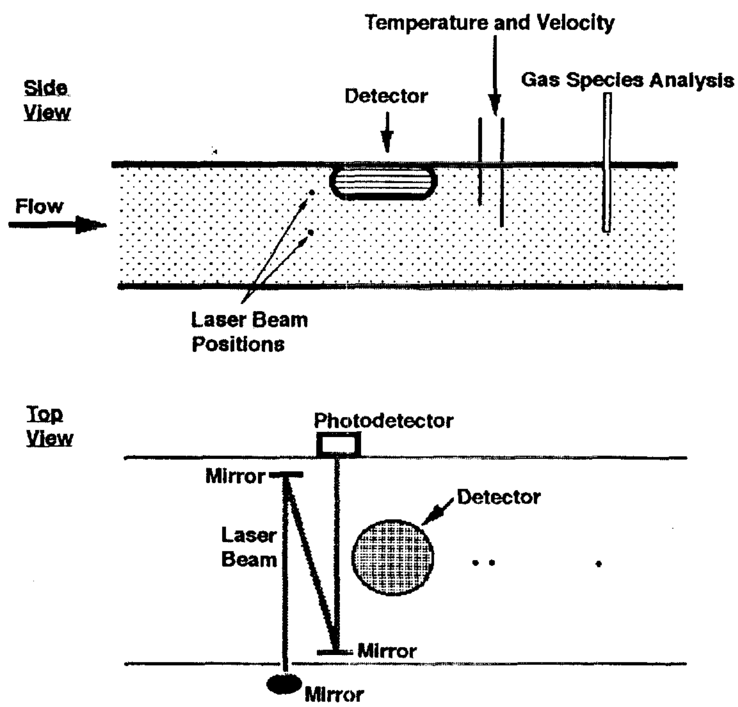

Figure 2. Schematic of FE/DE test section.

CR200-A)** the signal-to-noise ratio is such that an intensity variation of 0.01 % is resolved. The detector signal is normalized by the pre-test signal level and recorded as a intensity ratio at 1 s intervals.

A propene diffusion burner provides the black smoke exposure. Control of the amount of smoke introduced into the duct is provided by the propene and burner air flows and the position of a bypass damper. Laser light extinction is used to indicate the amount of smoke flowing past the detector in the test section. The extinction coefficient (k) in units of (m^{-1}) is given by Equation 1.

$$I/I_o = e^{-kL} \qquad [1]$$

Where I/I_O is the intensity ratio and L is the path length in meters. The intensity ratio and the extinction coefficient from which it is derived are a function of the wavelength of the light source. The extinction coefficient is related to the smoke mass concentration (C_S; g/m^3) through a constant of proportionality termed the specific extinction (σ; m^2/g), Equation 2.

$$k = \sigma C_s \qquad [2]$$

The specific extinction is a function of the wavelength of light (λ), smoke aerosol size distribution, structural properties, and optical properties; it is an intrinsic property and nominally constant for flaming hydrocarbon and polymeric fuels with a value of 8.5 m^2/g $\pm$ 1.5 m^2/g at a wavelength of 633 nm covering most fuels measured[10].

Recently, the FE/DE was used to evaluate the smoke entry lag effects of detectors at low (0.02 m/s) to moderate (0.3 m/s) flow velocities[11]. Analog output detectors (detectors that can provide a continuous output signal to a computer) were exposed to square wave changes in smoke concentration at various fixed velocities and fixed ambient temperature. A two parameter model was developed to capture the time lag which was observed to be very substantial at low flow velocities. Development of nuisance aerosol exposures has begun, and preliminary research was presented recently[12].

TEST FIRE SCENARIO

A challenging test fire to emulate is one that produces rapid changes in temperature, smoke concentration, and flow velocity at the detector location. Such a test fire is TF 4 from EN54 part 9. It is a polyurethane foam fire consisting of three mats (50 cm by 50 cm by 2 cm thick stacked on top of one another) that exhibits a peak heat release rate of approximately 50 kW and produces a large amount of smoke[13]. As mentioned above, there are two approaches to obtaining the temperature, velocity and smoke levels at the detector location: experimental measurement or simulation. While smoke and temperature values at the detector location were reported in the literature, velocity measurements were not available[13,14]. Therefore, computational fluid dynamics calculations of the

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** Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

TF 4 fire in the EN 54 test room were conducted to produce the velocity profile at the detector location. The model calculations are described below.

LES CALCULATIONS

The Large Eddy Simulation (LES) model[15] was used to simulate conditions within a compartment specified by EN 54 part 9. The physical dimensions of the compartment matched experiments reported by Ahonen and Sysiö[14] which were 9.5 m by 6.3 m by 4.0 m high. The fire was located at the geometric center of the room and the detector was located on the ceiling at a 3 m radius extending from the room center and orthogonal to the long wall/ceiling interface. The computational grid was composed of 768,000 cells (120 x 64 x 100), yielding physical resolution of between 4 cm and 10 cm. The heat release rate of the fire was the result of multiplying the mass loss rate reported in the literature[14] with a heat of combustion estimated for the fuel. The heat of combustion of this particular foam material is unknown, therefore two estimated heats of combustion representing the convected heat release were used in two bounding model solutions to incorporate this uncertainty. Heats of combustion of 11 kJ/g and 7 kJ/g were specified. Again, these values represent the convected heat released per gram consumed. Assuming a radiated fraction of 0.3 and a combustion efficiency of 0.95, the chemical heat of combustion values would be 17 kJ/g and 11 kJ/g respectively. The ambient temperature was 21 °C and the total simulation time was 200 s. The thermal boundary conditions were assumed to be adiabatic, and a vent measuring 0.25 m^2 at the floor of the wall opposite the detector location simulates leakage in the test chamber.

Experimental temperatures reported by Ahonen and Sysiö[14] were compared to the model bounding solutions. Figure 3 shows the experimental and LES temperatures at the detector location. The upper and lower bounds are two model results representing the uncertainty in the convective heat release rate of the fire. Near the end of the test, the experimental temperature starts to fall, while the simulated values reach a plateau. The plateau is most likely due to the adiabatic condition imposed on the simulation. The experimental measure reflects the thermocouple heat losses as soon as the peak heat release rate occurs. There is reasonable agreement between model upper bound and the experiment. Having determined that the temperature field was reasonably accurate, confidence was gained that the velocity vectors for the upper bound should reasonably match experimental values. Figure 4 shows the magnitude of the upper and lower velocity bounds in the principal direction (along the long axis of the compartment).

The model calculations provide the temperature and velocity profiles at the detector location, while smoke concentration values were obtained from test data. Ahonen and Sysiö[14] reported experimental light extinction values at the detector location. The light source produced a narrow-band peaking in intensity at λ = 950 nm. The profile is shown in Figure 5 where the extinction measurement is presented as an optical density which is equal to the extinction coefficient divided by ln(10) (~2.303). Figures 3-5 present the time varying temperature, velocity, and smoke extinction profiles that were emulated in the FE/DE.

MULTI-SENSOR DETECTORS

The detectors used in this study contain individual photo-electric light scattering, ionization, and heat sensors. Detector output signals for each sensor are transmitted about every 2 s and recorded by a computer. Both the ionization and photo-electric sensor outputs were found to be

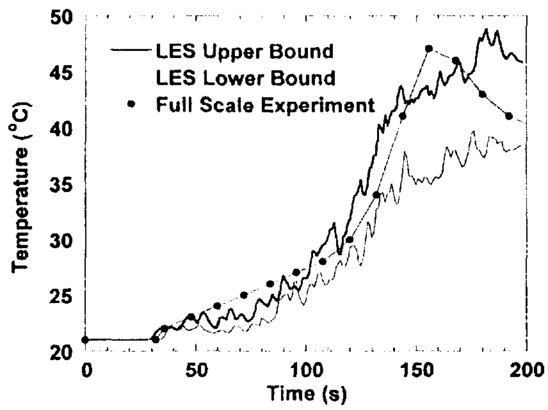

Figure 3. LES and experimental temperature; LES values are the average of 3 vertically spaced grid cells (grid height = 4 cm), and experimental values were recorded 5 cm below the ceiling.

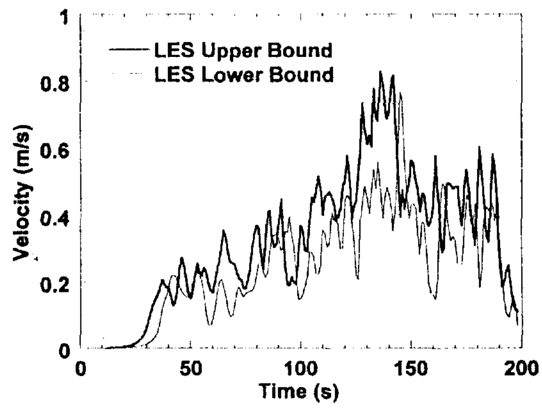

Figure 4. LES velocity profiles; the velocity along the principle axis averaged over 3 vertically spaced grid cells (grid height = 4 cm).

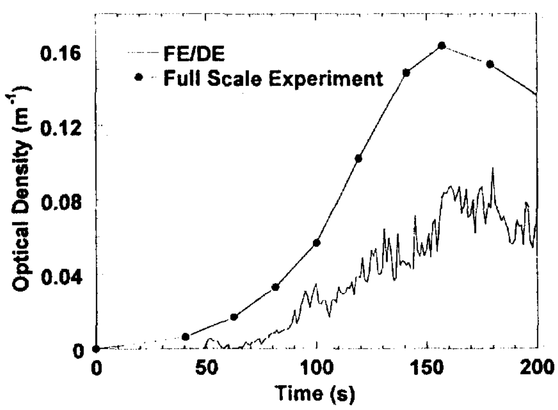

Figure 5. Optical density; measures from a FE/DE test (λ = 633 nm) compared to experimental test fire data (λ = 950 nm).

linear functions of optical density for smoke produced by the propene diffusion burner, suggesting that the detector electronics linearize the output with respect to optical density. Figure 6 shows optical density versus steady-state detector output over a range of constant optical densities. The heat sensor output was found to be proportional to the temperature in the test section.

RESULTS AND ANALYSIS

Velocity, temperature, and smoke concentration values were reproduced in the FE/DE by a combination of computer and manual control. Typical profiles are compared to simulated and experimental results in Figures 5,7, and 8. Figure 7 shows the simulated velocity profile and the duct velocity in the FE/DE. In order to maintain an increasing smoke concentration, the peak duct velocity was intentionally reduced in order to lower the smoke dilution factor. Figure 8 shows the simulated temperature profile, the experimental profile, and the profile reproduced in the FE/DE. The reproduced value compares favorably with the simulated and experimental values. Near the end of the test, the experimental temperature starts to fall as the fire dies out, whereas the temperature profile reproduced in the FE/DE does not fall because of the slow cool down of the heating elements. Figure 5 shows experimental extinction measurements compared to values produced in the FE/DE. The most notable aspect of this comparison is that the values produced in the FE/DE are approximately a factor of 2 lower than the experimental values. Most of this discrepancy is accounted for in the difference between extinction for the two distinct light source wavelengths. Dobbins *et al.*[16] reported specific extinction measurements of crude oil pool fire smoke at 3 discrete wavelengths: 450 nm, 630 nm, and 1000 nm. The mean specific extinction was found to be 7.8 m^2/g at $\lambda = 630$ nm and 5.1 m^2/g at $\lambda = 1000$nm, a 35 % decrease from the lower wavelength measure to the higher wavelength. Applying this scaling factor to the results in Figure 5 (nearly identical wavelengths) would drive the curves much closer together, i.e., the difference in the peaks would only be 30 %. However, the FE/DE optical density is at its maximum value for the peak duct velocity. This reflects a limitation on the smoke injection rate into the duct from the propene diffusion burner. A redesign of the burner damper controls should allow for higher smoke concentrations at the test section in the future.

Three detectors were exposed to the emulated TF 4 fire conditions in the FE/DE, and a total of six tests were conducted. Figures 9-11, representing 3 replicate tests (T1, T2, T3) with the same detector, show the detector output along with the extinction or temperature values recorded at the test section plotted as a function of time. The results are similar for each test. The photo-electric and ionization sensor outputs closely follow the optical density measured outside the detector. At low flow velocities, a pronounced time shift in the detector signal would be noticeable; however in this scenario the velocity profile quickly rises to over 0.2 m/s where little smoke entry lag is expected. The magnitude of the photo-electric sensor and the ionization sensor output is the same which is expected given the steady-state results shown in Figure 6. There is a noticeable time lag associated with the heat sensor compared to the thermocouple measurement which is most likely associated with the thermal time constant of the thermistor used as the heat sensor.

Figure 12 shows the test section temperature versus time for each of the six tests. The temperature profile is very repeatable as indicated by the spread among the curves. Figure 13 shows smoothed optical density (15 point running average) versus time for each test. There is some run-to-run variation in the optical density. An improved smoke control strategy should decrease this variation. This detector model uses a proprietary algorithm to combine the signals from the individual sensors with an alarm threshold based on multiple criteria. The time-to-alarm values are an indication of the

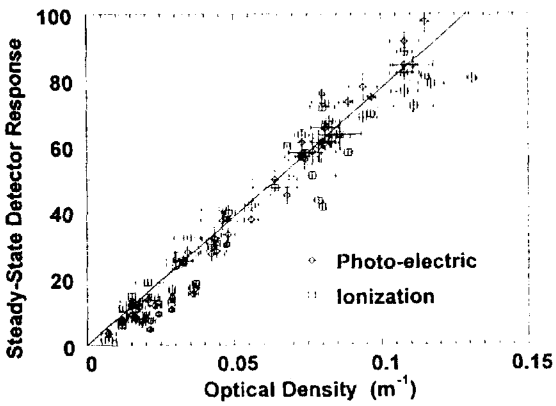

Figure 6. Steady-state response of photo-electric and ionization sensors exposed to propene smoke.

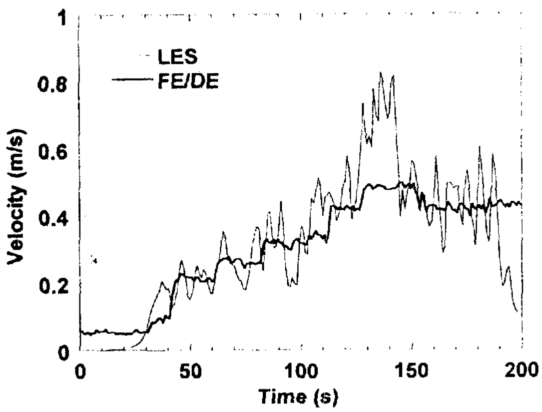

Figure 7. Velocity profiles; FE/DE compared to LES upper bound velocity.

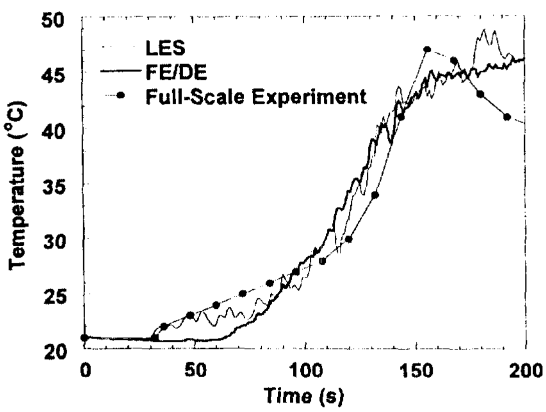

Figure 8. Temperature profiles; comparison of FE/DE, LES, and full-scale experimental test data.

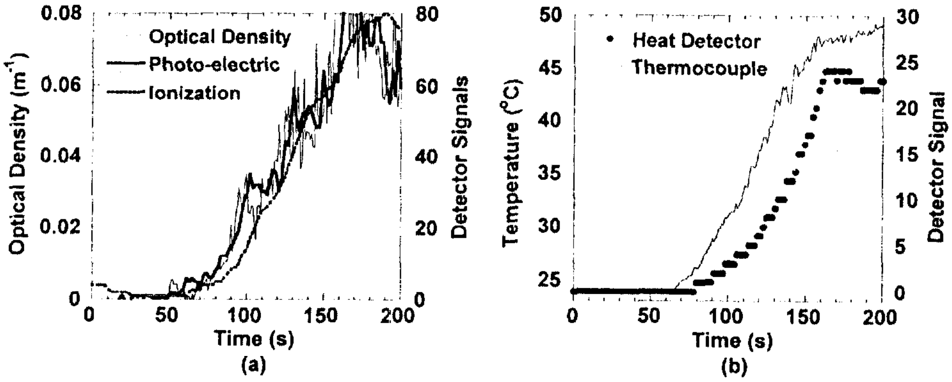

Figure 9. Detector response to emulated TF 4 conditions; test T1 results.

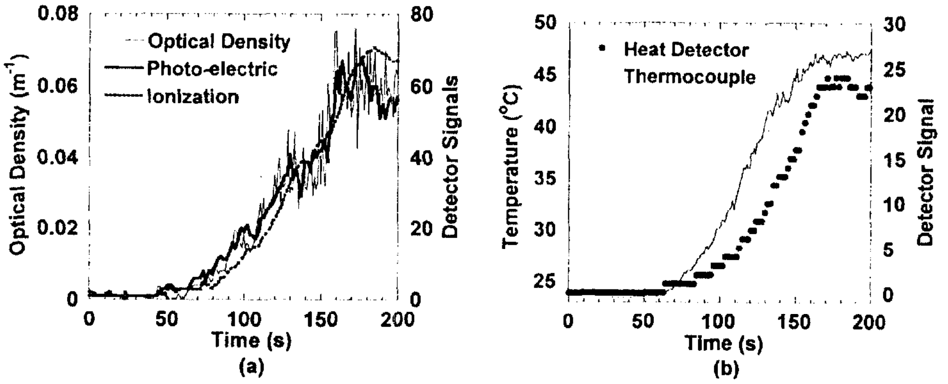

Figure 10. Detector response to emulated TF 4 conditions; test T2 results.

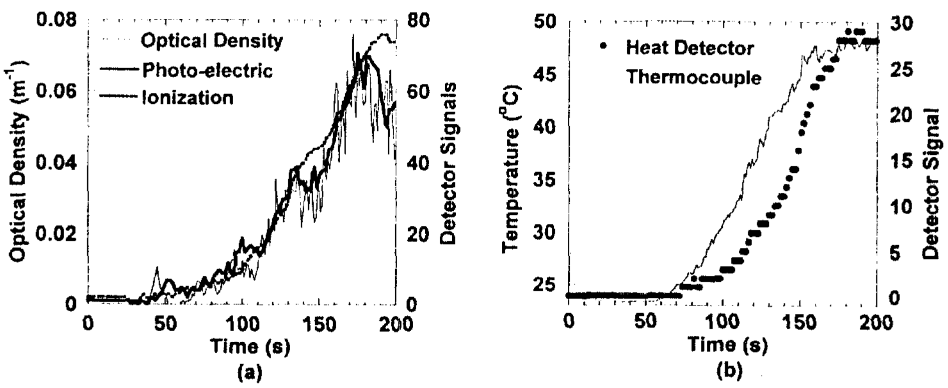

Figure 11. Detector response to emulated TF 4 conditions; test T3 results.

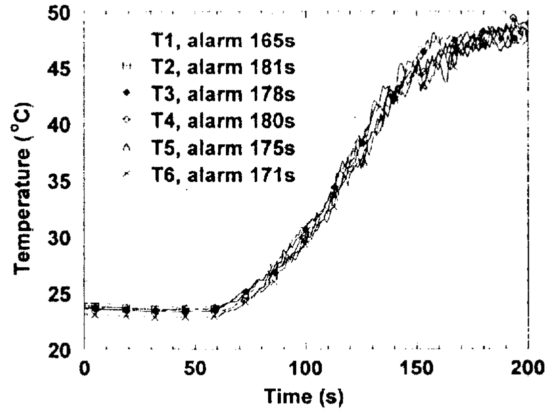

Figure 12. Temperature vs. time for FE/DE test series.

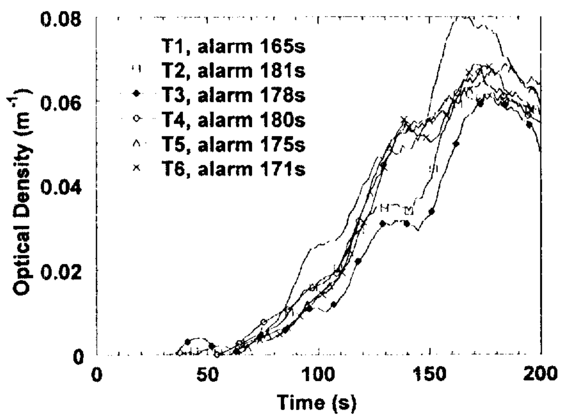

Figure 13. Optical density vs. time for FE/DE test series.

repeatability of the conditions produced in the FE/DE and the variation among different detectors. The time-to-alarm ranged from 165 s to 181 s with a mean value of 175 s. This narrow distribution indicates the test conditions are repeatable. Comparison of temperature, velocity, and smoke concentration curves between the individual tests also indicates the conditions are repeatable.

SUMMARY AND CONCLUSIONS

A detector fire exposure based on TF 4 from EN 54 part 9, a flaming polyurethane foam fire, was modeled to provide velocity and temperature inputs to the FE/DE along with experimental smoke extinction values for that fire test scenario. Multi-sensor, multi-criteria detectors were tested in the FE/DE by exposing the detectors to the temperature, velocity and smoke extinction profiles. From this study, we conclude the following:

1. LES modeling of the TF 4 fire scenario produced temperature profiles consistent with experimental values suggesting that the convective heat of combustion chosen for the upper bounding simulation was reasonable, and lending confidence that the velocity profile at the detector location is a reasonable reproduction of the test conditions.

2. The smoke injection into the duct is not quite sufficient to emulate the high velocity, high extinction conditions expected after the peak heat release rate is experienced. A re-design of the bypass damper should allow for higher smoke concentrations.

3. Detector output from the photo-electric and ionization sensors are of the same order of magnitude, and linear with the smoke optical density. The heat sensor output is also with temperature.

4. The velocity, smoke, and temperature conditions emulated in the FE/DE are repeatable.

5. The FE/DE can be used to evaluate multi-sensor, multi-criteria spot-type detectors.

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REFERENCES

1. Heskestad, G., and Newman, J. S., "Fire Detection Using Cross-Correlations of Sensor Signals," *Fire Safety Journal*, Vol. 18, No. 4, 355-374, 1992.
2. Milke, J.A., and McAvoy, T.J., "Analysis of Signature Patterns for Discriminating fire Detection With Multiple Sensors," *Fire Tech.*, Vol 31, No.2, May/June, 1995.
3. Pfister, G., "Multisensor/Multicriteria Fire Detection: A New Trend Rapidly Becomes State of the Art," *Fire Tech.*, Vol. 33, No. 2, May/June, 1997.
4. Gottuk, D.T., Peatross, M.J., Roby, R.J., and Beyler, C.L., "Advanced Fire Detection Using Multi-signature Alarm Algorithms," *International Conference on Automatic Fire Detection "AUBE '99", 11th*, March 16-18, 1999, Gerhard Mercator University, Duisburg, Germany, Luck, H., Editor, pp. 237-246, 1999.

5. *EN 54: Components of Automatic Fire Detection Systems*, European Committee for Standardization, Part 9, 10 p., July 1982.
6. UL 268, "Smoke Detectors for Fire Protective Signaling Systems," Fourth Edition, Underwriters Laboratories, Inc., Northbrook, IL, Dec. 30, 1996.
7. Grosshandler, W., "Towards the Development of a Universal Fire Emulator-Detector Evaluator," *Fire Safety Journal* Vol. 29, pp. 113-128, 1997.
8. Davis, W., Forney, G., Bukowski, R., "Developing Detector Siting Rules from Computational Experiments in Spaces with Complex Geometries," *Fire Safety Journal*, Vol. 29, pp129-139, 1997.
9. Pitts, W., Yang, J., Gmurczyk, G., Cooper, L., Grosshandler, W., Cleveland, W., and Presser, C., "Fluid Dynamics of Agent Discharge," Section 3 in *Evaluation of Alternative In-Fight Fire Suppressants for Full-Scale Testing in Simulated Aircraft Engine Nacelles and Dry Bays*, Grosshandler, W., Gann, R., and Pitts, W., editors, NIST Special Publication SP 861, National Institute of Standards and Technology, U.S. Dept. of Commerce, Gaithersburg, MD, 1994.
10. Mulholland, G.W., "The Emission and Optical Properties of Smoke," Recent Advances in Flame Retardancy of Polymeric Materials, Vol. III, Proceedings of the Conference, M. Lewin Editor, Business Communications Company, Inc., 1992.
11. Cleary, T., Chernovsky, A., Grosshandler, W., and Anderson, M., "Particulate Entry Lag in Spot-Type Smoke Detectors," Fire Safety Science Proceedings, 6th International Symposium, Poitiers, France, July 5-9, 1999.
12. Cleary, T., Grosshandler, W., and Chernovsky, A., "Smoke Detector Response to Nuisance Aerosols," *International Conference on Automatic Fire Detection "AUBE '99", 11th*, March 16-18, 1999, Gerhard Mercator University, Duisburg, Germany, Luck, H., Editor, pp. 32-41, 1999.
13. Andersson, P., and Holmstedt, G., "CFD-Modelling Applied to Fire Detection – Validation Studies and Influence of Background Heating," *International Conference on Automatic Fire Detection "AUBE '95", 10th*, April 4-6, 1995, Gerhard Mercator University, Duisburg, Germany, Luck, H., Editor, pp. 429-438, 1995.
14. Ahonen, A., and Sysiö, P., "A Run-In Test Series of a Smoke Test Room," Technical Research Center of Finland, Research Report 139, Espoo, Finland, 1983.
15. McGrattan, K.B., Baum, H.R., and Rehm, R.G., "Large Eddy Simulations of Smoke Movement," *Fire Safety Journal*, Vol. 30, pp.161-178, 1998.
16. Dobbins, R.A., Mulholland, G.W., and Bryner, N.P., "Comparison of a Fractal Smoke Optics Model with Light Extinction Measurements," *Atmospheric Environment*, Vol. 28, No. 5, pp. 889-897, 1994.