EVALUATION OF FIRE DETECTION TECHNOLOGY FOR SUITABILITY IN AIRCRAFT CARGO COMPARTMENTS

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ABSTRACT

NIST is assisting the FAA in its research to improve fire detection in Class C and D aircraft cargo compartments. Improved fire detection includes both fast (early) fire sensing and immunity to false alarms caused by environmental conditions. NIST conducted a survey of the scientific literature relating to existing and emerging fire detection technologies, and assessed the potential use of new fire detection strategies in cargo compartment areas. Current detector certification methods are not capable of evaluating the performance of multi-element detectors, nor detectors based on sensing unique fire signatures besides particulates. The Fire Emulator/Detector Evaluator (FE/DE) at NIST is an apparatus designed specifically to address these concerns. It is being upgraded to include phenomena found in aircraft cargo compartments, namely, temperature and moisture variations. This will allow for the assessment of detector performance and immunity to false alarm signatures found in cargo compartment environments.

INTRODUCTION

Current detection technology used in aircraft cargo compartments relies mostly on particulate sensing by light beam scattering or ionization type detectors. They may be utilized in an aspiration system or in a spot arrangement located on the compartment ceiling. In general, these systems perform their intended function of alarming at a particular smoke level and experiencing false alarm infrequently. Cargo compartment detectors are designed to alarm at smoke levels between 4% and 16% obscuration per 0.305m (1 ft.) (Blake, 1985). The detection threshold is set well above the typical particulate background levels and redundancy limits hardware faults. False alarms are still present with estimates of the ratio of false alarm to fire ranging upwards of 500:1 (Grosshandler, 1998). The frequency of false alarms is estimated as 44 per million departures (FAA NPRM 97-10, 1997). With the advent of Class D to Class C cargo compartment conversion, the absolute number of false alarms should increase in proportion to the increase in spaces protected. A false alarm requires unnecessary actions including delay, diversion, suppressant discharge and aircraft evacuation. Every false alarm also erodes confidence in the system; thus it is desirable to reduce them to a very low level.

The current aircraft regulation, FAR 25.858, requires that a system must detect a fire in the cargo compartment and provide visual indication to the crew within one minute. It may be possible to detect fires much smaller in size than one which would produce enough smoke necessary to make a current detection system alarm within the one minute time frame. Early reliable detection would allow for better control of the fire.

New technologies, including advances in signal processing and sensors, have the capability to greatly reduce nuisance alarms while simultaneously decreasing time to detection. The fire detection industry is moving in a direction to utilize advances in technology in order to increase the sensitivity of fire detectors and reduce false alarm rates. The hurdles to implementing new technologies in cargo fire detection include proving increased fire sensitivity and better immunity to false alarms, meeting the operation requirements of an onboard system, and certification from regulatory authorities. Current standards for fire detectors are not capable of evaluating a detector's immunity to false alarm stimuli, nor for evaluating detection systems that rely on new sensing technologies nor multi-sensor devices. The focus of this paper is to examine new technologies and their applicability to cargo compartment detection and to describe a methodology for evaluating technologies.

CARGO COMPARTMENT ENVIRONMENT

An aircraft cargo compartment is described below in generic terms encompassing a wide range of environments and configurations presently found in Class C and D compartments. Considering a passenger transport aircraft as a typical aircraft, the fuselage is cylindrical in shape and is separated into the main deck and the lower cargo compartments by the floor of the main deck. Cargo compartments are segmented with the volumetric size and ventilation air flow leading to the classification of the compartment. A Class C compartment has provisions for detection and suppression of fire and control of ventilation air flow. Typically, a ventilation control valve can be closed after the indication of fire. This functions to limit oxygen flow into the compartment and to decrease the loss of suppressant after discharge. Class C compartments can have ventilation air flows on the order of 0.24 m^3/s (500 cfm) or higher. Blake and Hill (1983) surveyed Class C compartment sizes and found a range of 20.8 m^3 - 176 m^3 (735 ft^3- 6200 ft^3.) Presently, the size range for domestic aircraft is 19.8 m^3- 85 m^3 (700 ft^3- 3000 ft^3) (FAA NPRM 10-97, 1997.)

All Class D compartments will be converted to Class C by the inclusion of detection and suppression systems or converted to Class E if the aircraft is dedicated to cargo transport (FAA NPRM 10-97, 1997). The rule for Class D compartment was that the sum of the volume in cubic feet and the air flow (ventilation or leakage) in cubic feet per hour be below 2000. The idea for this classification was that any fire would suffer oxygen starvation due the relatively small size and the limited air flow. That regulation was amended to reduce the space limitation to 28.3 m^3 (1000 ft^3) for new Class D compartments (FAA NPRM 10-97, 1997).

Cargo may be loaded in the compartments inside individual containers (containerized) or it may be directly loaded into the compartment such as passenger luggage (bulk loaded). Cargo may occupy nearly all of the compartment volume at times.

The environment in a cargo compartment may experience a range of temperatures and pressures under normal conditions. Most Class C and D compartments are located inside the pressurized portion of the aircraft, the exception being small Class D compartments located outside the pressurized portion of the cabin in some small aircraft (FAA NPRM, 1997). Typically, the temperature range would fall between ambient ground or cabin temperature and somewhat colder temperatures depending on the flight time and altitude and ventilation air flow. The pressure range would lie between ambient ground atmospheric pressure to approximately pressurization level at 3050 m (10,000 ft.). Airlines and airframers would have accurate temperature and pressure data for the aircraft they fly or build.

The standard for cargo compartment fire detection equipment used on aircraft states an operating temperature range of -30 °C to 60 °C, and an operating pressure range of 170 kPa to 51 kPa (SAE AS 8036, 1985). This range seems to include expected or possible depressurization at high altitude. Vibration is ubiquitous on an operating aircraft. A detector must be able to withstand mechanical vibration and SAE AS 8036 contains the vibration characteristics that must be met. Humidity and condensed moisture are one of the problems implicated in smoke detector false alarm in current aircraft (Nurcombe and Carver, 1997; Grosshandler, 1998). SAE AS 8036 specifies a detector operational range of between 0 and 95 % relative humidity.

Transportation of animals and perishable vegetables, fruits and flowers are sources of humidity and moisture. Dust may be kicked up during the loading and off-loading of cargo. Exhaust emissions from ground transport vehicles and other aircraft are present in the external environment while the aircraft is on the ground and may be picked up by the air intake. Measurements of background levels of particulates and combustion gases in cargo compartments have not been reported. Inside cargo compartments livestock may emit moisture, CO_2, CO, and CH_4 which could confuse chemical sensors designed to detect combustion gases. Treatment of vegetation by spray application after loading, just prior to compartment door closing may leave residual aerosol which can be sensed by detectors and cause a false alarm. The background concentration of particulates and gases must be known or estimated so that detector sensitivity is set above this level.

FIRE DETECTION TECHNOLOGY

Grosshandler (1992) has described a number of sensors and technologies for advanced fire detection. The fire detection problem covers a wide range of scenarios from smoldering to flaming combustion, large area protection in industrial settings to very localized detection in electrical cabinets, residential or commercial occupancies, etc. No single solution exists that covers this wide range; solutions are formulated based on likely scenarios for a particular space. Likewise, there are different types of fire detection technologies that have been developed or have been proposed for specific applications. There may be new technologies that could be useful in aircraft cargo compartment fire detection, so a review of fire research literature and recent patents relating to fire detection covering a range of sensors and signal processing algorithms was performed (Cleary *et al.*, 1998). Specific sensing technologies, their relative strengths and weaknesses, and their suitability in aircraft cargo compartments are described below. Improved sensor performance relies on appropriate signal processing in many cases. Auto-correlation, cross-correlation, neural networks, and fuzzy logic are some of the techniques that have been used in detector development. Multi-element detectors that rely on some type of empirically developed alarm criteria have been developed. A brief description of some applications of these techniques to fire detection reported in the literature is given below.

Smoke Detectors

Smoke detectors sense the aerosol produced from flaming or smoldering combustion. A detector may be located at the sensing location (spot detector) or it may be remote with the smoke pumped to the detector location. Both methods are used in aircraft cargo compartments. Two distinct types of smoke detectors are used in aircraft: ionization-type and photoelectric-type.

The principle of operation of an ionization detector is described as follows. Two opposing plates are held at a fixed voltage potential. Alpha particle radiation emanating from a source (specifically americum 241) interacts with air molecules creating charged ions. These ions flow to the oppositely charged plates generating a small current. Smoke particles flow between the plates and scavenge ions, decreasing the electrical current. If the current falls below a preset level the detector goes into alarm. A dual chamber design with a separate chamber that is not exposed to smoke allows for correction of the signal strength due to pressure and temperature effects. An ionization detector is particularly suited for detecting a flaming fire, which is accompanied by high concentration of small smoke particles.

The photoelectric detector operates on the principle of the attenuation (scattering and absorption) of electromagnetic waves by smoke particles. A light scattering detector operates in the following manner: a light source (typically a light emitting diode in the visible or IR spectrum) produces a collimated beam that extends across the sensing region. A photo-detector is located such that direct light from the source is blocked out. The photo-detector views the area the beam traverses at a fixed angle. Smoke particles that enter the detector scatter light, some of which is directed toward the photo-detector. The amount of light reaching the photo-detector, and thus its signal is proportional to the size of the particles scattering the light, their optical properties, and the number of particles in the sensing volume. A photoelectric light scattering detector is particularly suited for detecting a smoldering fire, which is accompanied by relatively large particles which scatter much more light than the small particles produced in flaming combustion. Photoelectric light extinction detectors measure the attenuation of light over the distance between the light source and the detector. Smoke particles scatter and absorb some of the light, reducing the signal strength.

Any aerosol (dust, vapor clouds, etc.) at a sufficient concentration can cause smoke detectors to alarm. Condensed water vapor on the alpha radiation source can block radiation in ionization detectors. Accumulations of dust, over time, will reduce the sensitivity of smoke detectors. A maintenance interval is required to periodically check the sensitivity or replace dirty units. Aerosol entrance characteristics for spot type detectors must allow for rapid sensing of the external environment.

Other types of particulate smoke detectors have been proposed. Schmidt-Ott *et al.* (1989) developed a smoke detector which senses the residual charge of combustion generated aerosols from either smoldering or flaming combustion. Tests show the device is more sensitive to flaming combustion than it is to smoldering combustion products. Non-fire aerosols would have a much lower net charge and could be discriminated from the fresh fire aerosol particles. Other techniques based on multiple scattering angle measurements have been proposed to discriminate smoke from other particulates. Loepfe *et al.* (1997) described a multiple scattering angle measurement technique which can discriminate between smoke, water vapor and other benign particles such as cooking oil aerosols. Meacham and Motevalli (1992) proposed using signals from multiple scattering angles to discriminate smoldering sources.

Chemical Sensors

Fire produces gaseous combustion byproducts which if they could be sensed might provide a basis for fire detection. Grosshandler (1995) has summarized fire signatures including chemical signatures, available for early fire detection. He identified chemical signatures including CO_2, H_2O, CO, H_2, total hydrocarbons, and gaseous fuel components. Chemical sensing can be achieved by optical spectrographic techniques, catalytic reaction, electrochemical reaction, and mechanico-chemical processes. Sensors based on these techniques are described below.

Optical spectrographic techniques such as Fourier transform infrared spectroscopy (FT-IR) and non-dispersive infrared absorption spectroscopy (NDIR) are possibilities for measuring combustion byproducts. Serio *et al.* (1995) have proposed an FT-IR based system for fire detection using a portable "low cost" FT-IR spectrometer. Either an open path or extractive system could be employed. Wong (1997) described a fire detector which combines a photoelectric smoke detector and a NDIR CO_2 gas detector that share a common light source.

Catalytic gas sensors use the heat of reaction of the chemical being sensed as it is oxidized catalytically to quantify concentration. Denney (1982) has provided a description of these devices. The pellistor type of detector consists of a refractory bead that has an imbedded platinum wire inside. The platinum wire is used to heat up the catalyst bead and is also used as a resistance thermometer. The power requirement necessary to sustain the catalyst temperature depends on the heat liberated from the exothermic reaction of oxidizing species. The platinum wire resistance is part of a wheatstone bridge circuit and the out of balance voltage from that circuit is proportional to the gas concentration. Depending on the operation temperature of the bead, and the make up of the catalyst, some chemical selectivity can be achieved. Hydrogen, carbon monoxide, and hydrocarbon gases can be sensed by catalytic detectors. These types of detectors have limited selectivity, and are susceptible to catalyst poisoning.

Semiconductor gas sensors respond to gas concentration by monitoring change in the electrical conductivity of a semiconductor metal oxide in the presence of the gas being sensed. A common formulation is a tin oxide Taguchi-type sensor. These detectors typically operate at temperatures in excess of 300 °C. Given a mixture of reducing gas and O_2, an equilibrium concentration of oxygen ions and reducing gas will be present on the metal oxide surface. Conductivity is a function of the gas phase concentration which produced the surface equilibrium concentration. Some selectivity is achieved through doping with noble metals and special preparations. Tournier *et al.* (1995) have described CO and CH_4 gas sensors using tin oxide doped with palladium. CO detection at near ambient temperatures is claimed. Harwood *et al.* (1991) described a platinum doped tin oxide sensor for CO that operates at low power consumption. Semancik and Whetstone (1994) have developed a planar array of thin film microsensors deposited on temperature controlled micro-hotplate. Power requirements of these sensors are lower than conventional semiconductor gas sensors.

Electrochemical sensors of various designs exist. Measurement of changes in current, voltage, or conductance due to electrochemical reactions with the gas species of interest is the basis of these sensors. Potentiometric solid-state electrochemical sensors have been constructed for O_2, H_2, H_2O, CO, and CO_2 (Grosshandler 1992.) Since gases must diffuse into the electrode, time lag on the order of minutes is common. The one minute sensing requirement in FAR 25.858 would be difficult to achieve.

Mechanico-chemical sensors consisting of organic thin films deposited on crystal surfaces could potentially sense fire gases (Grosshandler, 1992.) The frequency of surface acoustic waves (SAW) is affected by chemical species that diffuse through the organic membrane. Selectivity is achieved by tailoring the polymer coating. Hierlemann *et al.* (1995) have developed a 6 sensor array designed to detect organic vapors.

Thermal Detection

Fire can be detected by observing the change in the thermal environment. Spot heat detectors that respond to the fire plume temperature, alarming at a fixed temperature or rate of temperature rise has been used. Line detection with the use of devices such as temperature sensitive resistance wires or pneumatic tubes have been used in aircraft engine nacelles. Heat detectors have been used in aircraft cargo compartments with a fixed alarm temperature. Since thermal damage to the cargo liner and fire spread and structural damage to the aircraft is a primary concern, temperature detection provides an unambiguous indication of hazard. Relying solely on temperature would be precarious though since smoldering fires may produce low thermal output while growing to a size that would prove hard to control.

Radiation

Ultraviolet (UV), UV/IR, and dual IR band flame detectors are typically used to detect fires that may occur in open spaces. The radiation from the flame must not be obstructed from the detector. In cargo compartments, this criteria can not be assured, thus these types of detectors should not be considered as primary fire detectors. One device that does not need an unobstructed view is the near infrared fire detector described by Lloyd *et al.* (1998). Spectral radiation intensities at 900 nm and 1000 nm wavelengths incident on the detector are sampled at 500 Hz. By analyzing the time series data an algorithm that can discriminate fires through frequency and radiant power characteristics was proposed. It was demonstrated that the radiation could be reflected and fire still could be detected. Reflected radiation from smoldering fires was below the detection limit and a non-luminous alcohol fueled fire was not detected.

Multi-sensor Detectors

Multi-sensor detectors have been proposed and developed to increase the sensitivity to fires and reduce false alarms. Combinations of optical and ionization smoke detectors, temperature measurement, combustion gas measurements, and radiation measurements have been envisioned. The multi-sensor detectors considered here utilize some type of signal processing of the multiple outputs to make a decision whether a fire is present or not. Specific examples of multi-sensor detectors are described in the Signal Processing section below.

Signal Processing

Many of the detectors described above are of little or no use without proper signal processing of the sensor outputs. Likewise, multi-sensor detectors may significantly benefit from appropriate processing of the separate detector signals. A fixed signal threshold value for a sensor represents the simplest and most common use of sensor output. Automatic compensation for baseline drift or environmental effects can maintain a threshold level criterion for a detector. Use of time series data or combinations of sensor output can improve detector sensitivity and false alarm rate.

Klose and Siebel (1991) discussed the use of the auto-correlation function of a sensor signal or multi-sensor signals to reduce false alarms. The auto-correlation function is a higher order statistic of a sensor's time series output. For multi-sensor signal processing, assignment of weighting functions to individual signals was suggested as a means to tune detection to specific applications (most likely fire scenarios.)

Heskestad and Newman (1992) demonstrated the use of cross-correlation of time averaged sensor signals in fire detection. They examined the CO, CO_2, and total hydrocarbons concentration, ionization detector output, light scattering detector output, optical density measurements at different wavelengths and temperature signals measurements generated in a series of test fires. They tested a number of double and triple correlations. They found two complementary cross-correletions: CO concentration correlated with ionization detector output and CO_2 concentration correlated with temperature. These two cross correlations could detect all test fires used in the EN 54 part 9 (1982) much earlier than individual detector classification times.

Okayama (1991) described an odor sensor made from two tin oxide sensors with different response characteristics, utilizing an artificial neural network (neural net) trained to distinguish fire from environmental odors. The tin oxide (semiconductor-type) sensors respond to many different organic compounds to varying degrees. A neural net is a computational scheme that seeks to mimic the decision making process of the brain. The odor sensor must be trained by exposure to different sources, and the extent of training affects the performance of the neural net. Okayama *et al.* (1994) designed a neural net that used the odor sensor in combination with a smoke sensor. Ishii *et al.* (1994) designed a neural net that utilizes data from temperature, smoke, and CO gas (semiconductor type) sensors. Milke (1995) applied a neural net to sensor data gathered in full-scale tests. He demonstrated the feasibility of early fire detection, although he cautions that more research is needed.

Thuillard (1993) described fuzzy logic and its application to fire detection, and goes on to apply fuzzy logic to an ionization detector output. Fuzzy logic is particularly suited to combining two or more different signals in a decision algorithm. Fuzzy logic allows for more flexibility than classical logic; thus more complex phenomena can be analyzed. Hosokawa *et al.* (1992) developed a three sensor (smoke, heat, and CO) fire detector that uses fuzzy logic to discriminate fire from false alarm sources.

Detector manufacturers have developed individual detectors that include all of the signal processing on the circuit board of the detector itself. Each detector can include a central processing unit (CPU), software storage in read only memory (ROM), random access memory for time series data storage and analog to digital (A/D) converters. The detector can pass information to a central panel when it is polled or it senses a fire. Individual unit cost may be no more than traditional detectors. Manufacturers will tend to keep detection algorithms proprietary in order to protect their investment.

DETECTOR PERFORMANCE EVALUATION

The performance objective of fire detection in cargo compartments is to sense a burgeoning fire at a small enough size that designed intervention such as discharging suppressant, shutting off compartment ventilation, diversion and evacuation can effectively limit the fire damage and life safety hazard. The lower limit of the fire size is bounded by detection limits of fire sensors, their locations and the fire location. In addition, compartment flows and temperature gradients that must be overcome by plume buoyancy to transport the fire products to sensor locations if convected heat, gaseous chemicals or particulates are sensed. Full-scale cargo compartment fire tests performed in the past have established a fire size limit which was translated into the detection limit of one minute after the start of the fire.

Recent concerns involving transport of personal care products in pressurized aerosol containers utilizing flammable propellant gases led to full-scale testing at the FAA (Blake, 1989). Aerosol cans intimate to a fire source may rupture and the ensuing deflagration could damage cargo linings. It was found that a rupture after halon discharge did not result in a deflagration and no lining damage occurred. Early detection and suppressant discharge is desired to limit this particular hazard (Blake, 1989).

Current technology has an established history of false alarm frequency. New technologies must demonstrate immunity to false alarm that is as good as the current technology. Indeed, it should demonstrate improved immunity to false alarm.

The FAA and Navy conducted tests on seven different types of detectors using six fire scenarios (Blake, 1998). Ionization and photoelectric smoke detectors, temperature, humidity, CO and O_2 sensors and a flame detector were tested. These tests were representative of a wide range of fire conditions. The FAA is in the process of developing a standard test or tests for the evaluation of fire detectors in cargo compartments. Quantification of the production rates of smoke, combustion gases, and thermal energy (plume temperature) of the test fire(s) will allow a source term description to be used in simulation of specific aspects of the standard fire(s) in other compartment configurations, air flows and loading level. Experimental values or model simulations of smoke concentration, gas concentrations, temperature, and flow velocity could be reproduced in a laboratory setting to examine specific detector response over a wider range of conditions. The NIST Fire Emulator/Detector Evaluator was designed specifically for that task.

The Fire Emulator/Detector Evaluator (FE/DE) was first introduced by Grosshandler (1997). The concept of the FE/DE is to be able to simulate the conditions of fire and non-fire (nuisance) sources expected in the environment a detector will be placed such that the detector output can be characterized. It is a flow tunnel designed to reproduce the time-varying speed, temperature and concentration (gas and particulate) expected in the fire plume in the early stages of the fire (Figure 1.) The device has a test section 0.3 m high and 0.6 m wide (Figure 2); if an aspiration system is tested, it would draw from this location. The FE/DE employs a variable speed blower and resistance heaters to control velocity and temperature (ambient and higher) over ranges of 0.02 m/s to greater than 1 m/s and 20 °C to 80 °C, respectively. CO, CO_2, and hydrocarbon gases can be added to the flow in a controlled manner. Water vapor is added by evaporation of a mist spray at the outlet of the heater section. A propene diffusion burner smoke generator produces black smoke that may be injected into the tunnel. Smoke concentrations up to 40 %/m obscuration can be achieved. A dust nuisance source is simulated by aerosolized inorganic clay particles. Liquid aerosols can be introduced by a nebulizing aerosol generator originally designed for smoke detector testing (Lee, 1978.) Provisions are planned for an additional smoldering fire source, reduced air temperature operation and reduced detector temperature control.

Figures 3 and 4 show analog output signals from a multi-sensor fire detector exposed to smoke from the propene smoke generator and dust particles. Both the photoelectric scattering and ionization sensors detect the propene smoke; the ionization detector is more sensitive than the photoelectric detector as expected. The dust particles yield a strong response from the photoelectric sensor and almost no response from the ionization detector. Also plotted is the optical density across a 1.5 m path total length in the duct just forward of the detector location. The time shift between the optical density curve and the sensor output is due to the aerosol transport lag inside the detector.

The examples above are illustrative of the data that is obtained from the FE/DE. Specific fire and non-fire sources expected in different applications such as cargo compartments can be replicated in the FE/DE allowing for detector performance evaluation.

SUMMARY

New sensor technologies and signal processing techniques show promise in increasing cargo compartment detection system sensitivity while discriminating nuisance sources. Novel sensors and multi-sensor detectors with built-in intelligence need to be evaluated under conditions replicating those experienced in real fire and no-fire conditions. The NIST FE/DE is being modified to produce fire signatures and nuisance signatures characteristic of cargo compartment environments.

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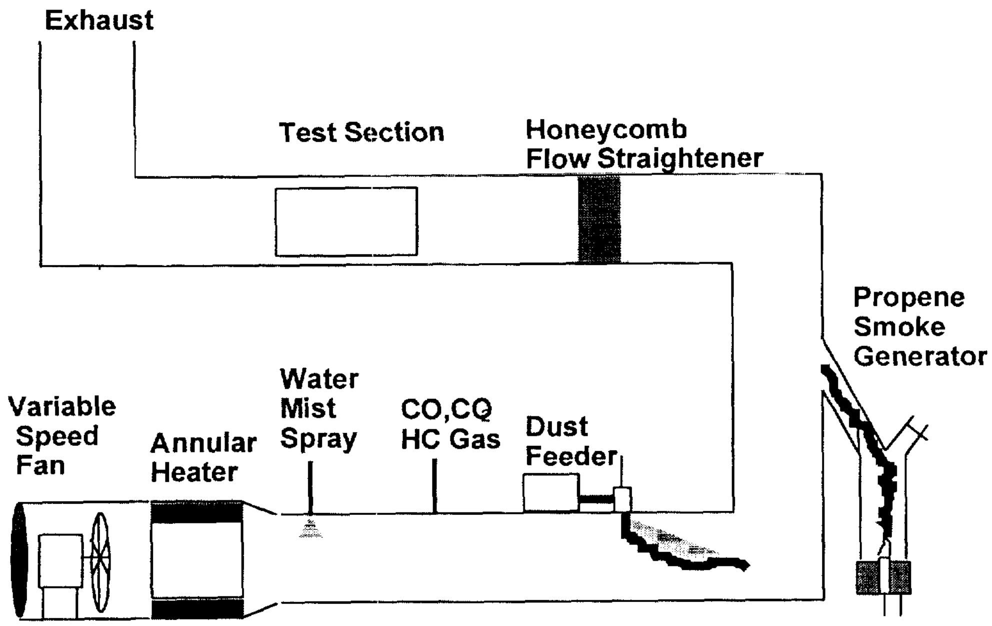

FIGURE 1. Schematic of the Fire Emulator/Detector Evaluator

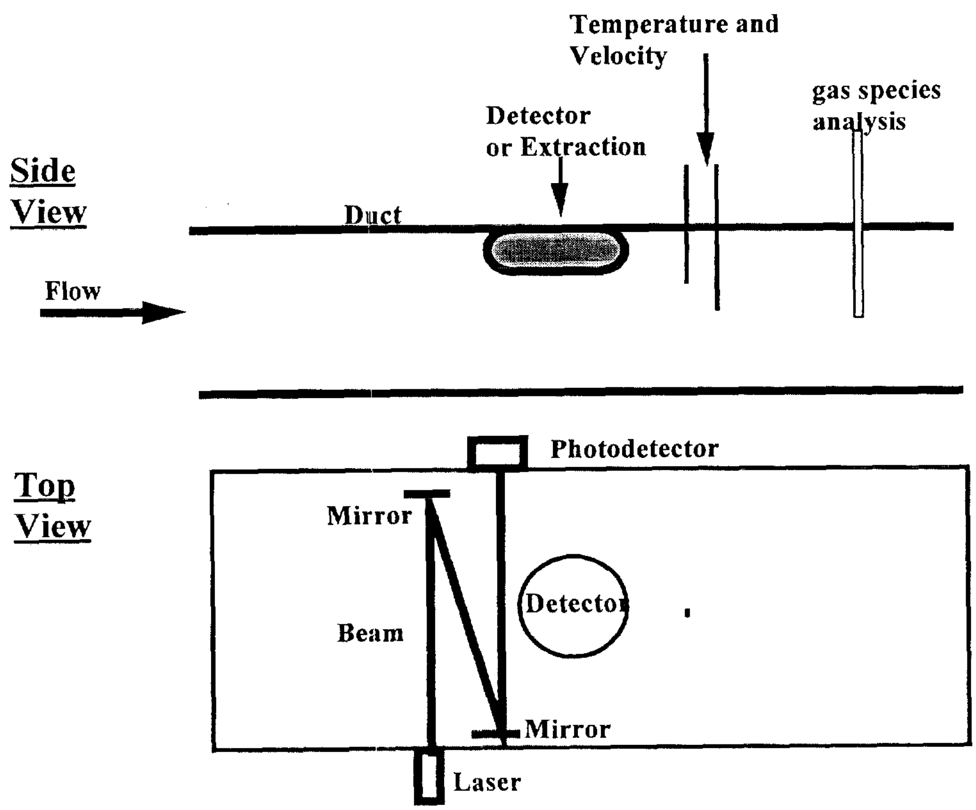

FIGURE 2. Test Section of FE/DE

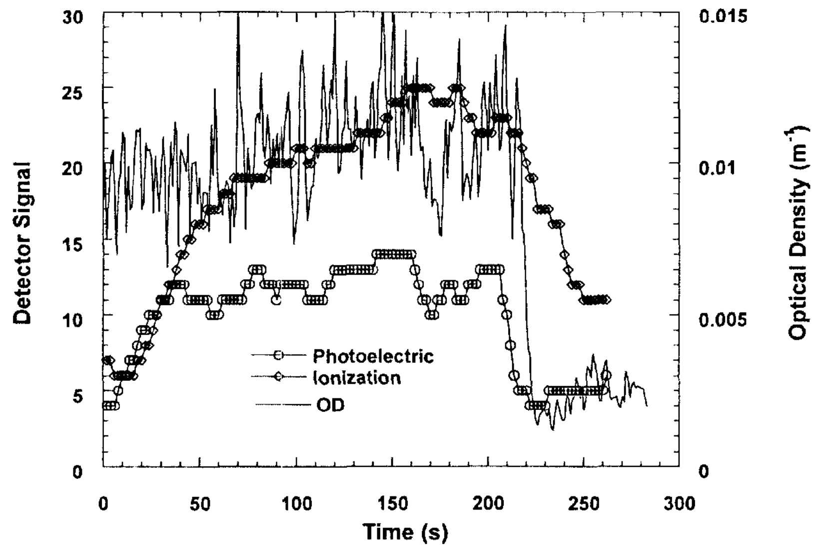

FIGURE 3. FE/DE test of multi-sensor detector response to propene smoke. Flow velocity, 0.15 m/s; temperature, 20 °C.

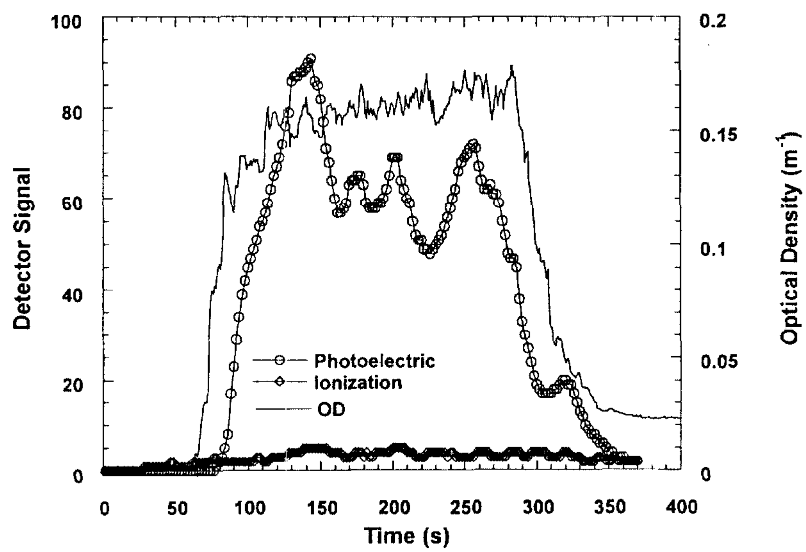

FIGURE 4. FE/DE test of multi-sensor detector response to dust aerosol. Flow velocity, 0.15 m/s; temperature, 20 °C.