SMOKE DETECTOR RESPONSE TO NUISANCE AEROSOLS

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Abstract

The worth of a fire detector is determined as much by its ability not to respond to stimuli that are generated from non-threatening sources as to respond in a timely manner to an actual fire. Photo-electric and ionization smoke detectors react to a greater or lesser degree to all particles that enter the sensing chamber, and, by themselves, the detectors can not distinguish smoke from a nuisance aerosol. The fire-emulator/detector-evaluator (FE/DE) is used to produce smoke and nuisance aerosols representative of what could be present immediately adjacent to an installed detector, and provides a test bed to determine the response of spot-type detectors to physical products (temperature, gases, and smoke) formed in simulated fires, as well as the response to stimuli not associated with a fire threat. The analog output of a multi-sensor detector is measured as a function of aerosol type (peanut oil and clay dust), concentration, and air flow, and is compared to the response of the detector to a flaming fire, and to the extinction of laser light in the FE/DE test section at optical densities up to 0.12 m^{-1}.

Introduction

The ability of a detector to satsifactorily sense the presence of a fire is determined in a series of tests performed by Underwriters Laboratory in reduced and full-scale. UL 217 [1] and UL 268 [2] utilize a 1.7 m long, 0.5 m wide and 0.5 m high test chamber into which "gray" smoke from a cotton lamp wick and "black" smoke from a kerosene lamp are introduced. The detector is mounted at the top of the chamber and a fan causes the smoke-laden air to flow past the detector at about 0.16 m/s. The concentration of smoke is controlled to produce an optical density between 0.003 m^{-1} and 0.2 m^{-1}. A wind tunnel is used for UL 268A [3] to simulate flow through a 0.3 m square duct at speeds between 0.1 m/s and 1.7 m/s. Smoke is created by heating wood sticks on a hot plate and by

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burning a small pool of heptane. Factory Mutual has a smoke detector standard [4] that uses smoldering cotton rope as the smoke source. The requirement is that the detector must activate before the obscuration reaches 12%/m.

CEN Technical Committee TC72, the Committee for Fire Detection and Fire Alarm Systems, is revising the current standard, EN 54 [5], that directs how smoke detectors are to be tested in the European Community. According to Northey [6], the fire sensitivity tests previously contained in Part 9 of EN 54 are to be integrated into Part 7, which deals specifically with point detectors using scattered light, transmitted light, or ionizing radiation.

A difficult problem for sensors designed to detect smoke is to discriminate between non-threatening air-borne aerosols and particles originating from an unwanted fire. Road dust entering with the wind through an open door, oil mists generated by moving machinery, soot from an operating Diesel engine, aerosols emitted during cooking, and steam from a shower or clothes dryer are examples of aerosols that may trigger a nuisance response from traditional photo-electric and ionization sensors.

Only one test method deals specifically with air-borne particulates formed from other than flaming or smoldering fires. UL 217 [1] checks the sensitivity to typical aerosols emitted during cooking by exposing the detector to the emissions from animal fat, vegetable oil and beef gravy vaporizing on a hot plate. The smoke detector is not to activate in this situation. At a recent workshop [7], nuisance sources that impact fire detection in telecommunication systems and aircraft cargo areas were discussed, along with possible means to quantify and evaluate detectors exposed to non-fire aerosols. The current paper describes how the NIST fire-emulator/detector-evaluator (FE/DE), first discussed by Grosshandler [8], can be used to examine the response of smoke detectors to different aerosols, including dust, oil, and water, as well as to smoke.

Experimental Facility and Operation

The FE/DE is a flow tunnel designed to reproduce the time-varying speed, temperature and concentration (gas and particulate) expected in the plume above the early stages of a fire. This device, shown schematically in Fig. 1, has a test section 0.3 m high and 0.6 m wide. It has a variable speed fan and heater for velocity and temperature control over ranges of 0.02 m/s to greater than 1 m/s and 20 ^{o}C to 80 ^{o}C, respectively. A honeycomb flow straightener is placed in the tunnel before the test section.

At the test section, air temperature and velocity are measured. The tunnel has a top-hat mean velocity profile at speeds up to 0.3 m/s, and starts to develop a parabolic profile at higher flows. At the location of the detector opening (20 to 30 mm below the ceiling of the tunnel) the vertical velocity gradient is small. Velocity was measured with a hot-wire anemometer calibrated from 0.05 m/s to 5 m/s. Measurements of flow velocities less than 0.05 m/s are obtained from neutrally buoyant soap bubble trajectories and punk smoke visualization. Measurement uncertainty is estimated at ± 10 % of the value for velocities greater than 0.05 m/s using the hot-wire anemometer, and ± 25 % for velocities below 0.05 m/s.

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 Fig. 2. The laser is reflected off two mirrors inside the tunnel to extend the path length to 1.50 m. A He-Ne laser at 633 nm wavelength is used to measure extinction. The signal-to-noise ratio is approximately 10^4:1 with no aerosol present. The signal is normalized by the pre-test signal level and recorded as a relative intensity ratio at 1 s intervals.

The smoke extinction coefficient (m^{-1}) is 1/e times the optical density, and is related to smoke mass concentration through a constant of proportionality equal to the specific extinction coefficient (m^2/kg). The specific extinction coefficient is a function of the smoke aerosol size distribution and optical properties; it is an intrinsic property and nominally a constant for a given fuel and combustion mode [9]. In the current study, propene/air diffusion burner provides a black smoke source. A portion of the flow from the smoke generator is injected into the air stream ahead of the test section to achieve the desired smoke loading. Step changes in smoke concentration yielding an optical density of up to 0.20 m^{-1} can be achieved. The burner output is stable for at least 30 minutes.

Oil-based aerosols are produced using the NBS aerosol generator [10] and injected into the FE/DE. This generator was designed to simulate a smoke from a smoldering source in terms of the aerosol size and optical properties. Peanut oil is used for the aerosol in the current tests to simulate a nuisance cooking source. Small clay particles (7 :m nominal diameter), representative of a nuisance dust, are added to the air flow using a variable speed screw-feeder fit with a vibrator. A small air jet is passed by

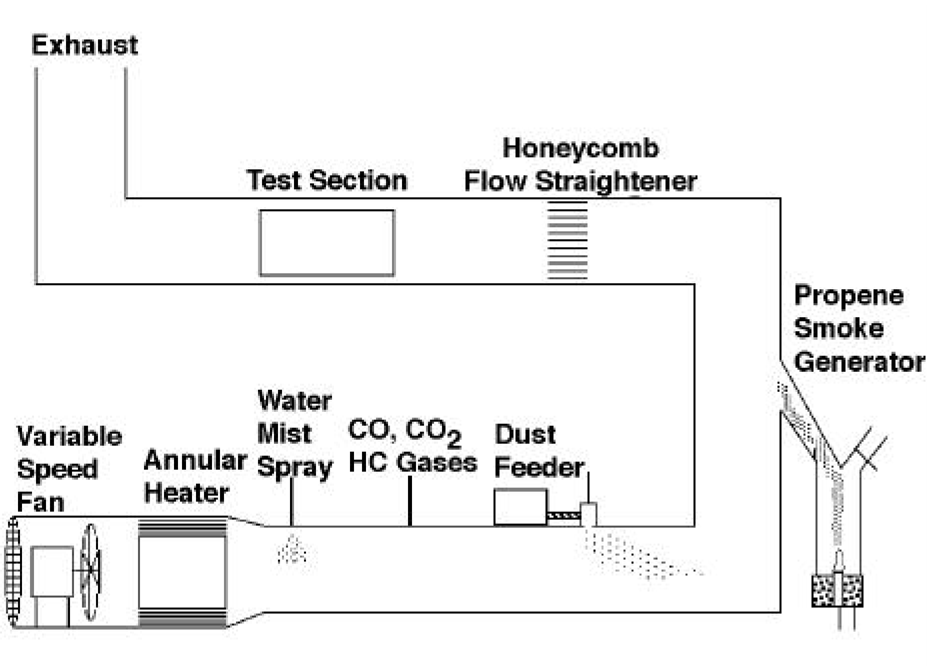

Figure 1. Schematic of fire-emulator/detector-evaluator.

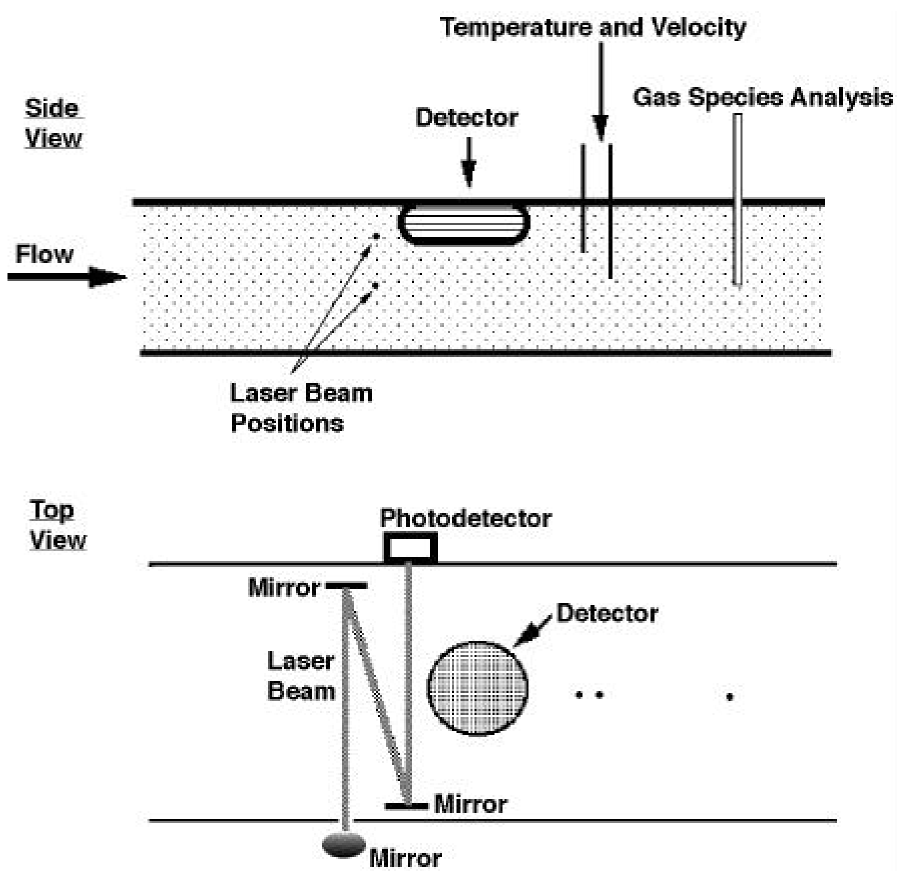

Figure 2. Schematic of FE/DE test section.

the entrance tube to ensure distribution of the dust across the duct. Details of the FE/DE can be found in ref. [11].

The detectors examined in the present study contain photo-electric and ionization sensors and a thermistor. Detector output signals are transmitted about every 3 s as 8 bit binary numbers allowing for a resolution of 1 in 256. Three quarters of the scale (1-192) is used for the output range, with the remaining reserved for zero-drift compensation. The detectors were mounted at the center of the flow tunnel ceiling in the test section. Both ionization and photo-electric detector output were found to be linear functions of optical density for smoke produced by the propene diffusion burner, suggesting that the detector electronics were linearized internally by the manufacturer with respect to optical density.

An experiment in the FE/DE begins by recording for 30 seconds the background signal from the smoke detector and from the laser system with clean air flowing through the test section at the predetermined temperature and velocity. Depending upon the particulate matter desired, either the flow from the smoke generator, the dust feeder, or oil mist generator are initiated. The data are recorded every three seconds during the initial build up of aerosol concentration and for a 60 s steady-state condition. The aerosol flow is then terminated and measurements continued until the reference laser experiences close to full transmission and the detector signals fall to zero.

Results and Analysis

Data were collected in the FE/DE at ambient pressure (100 kPa ± 2 kPa) and temperature (20 °C ± 2 °C), for a range of air speeds between 0.02 m/s and 0.35 m/s. The optical density measured by the attenuation of the reference laser was varied between 0.003 m^{-1} and 0.12 m^{-1} by a combination of increasing the mass loading of the aerosol and decreasing the total air flow.

Figure 3a shows a typical run with smoke from the propene/air diffusion flame for air flowing at 0.20 m/s. The optical density measured with the reference laser is plotted as the solid line (no symbols) on the right-hand vertical axis, versus time on the horizontal axis. The flow of smoke to the wind tunnel begins at 30 s, and can be seen to attenuate the laser light starting 10 s later. By 60 s, the optical density reaches a peak and then oscillates around a mean value of 0.075 m^{-1} for the next 170 s. The flow of smoke is terminated, followed by a rapid drop in optical density back to the initial state. The output from the detector head is plotted on the left-hand vertical axis. The photo-electric sensor responds first, about 15 s after the smoke is present in large particles are more effective scattering centers. This description is consistent with the very low ionization sensor output, which, for a fixed mass loading, is much the air stream flowing past the detector body. The magnitude of this delay was found previously by Cleary et al. [12] to be a strong function of the air velocity. The internal geometry of the detector also influences the response time of the detector, which can be seen by the significantly longer delay required before the ionization sensor responds. Both particle sensors produce similar output signals at the steady state. The heat sensor is able to track the small increase in temperature (0.5 °C) associated with the smoke.

Figure 3b shows the response of the photo-electric and ionization sensors to the peanut oil aerosol in an air flow of 0.04 m/s. No change in temperature was measured. The general shape of each curve is the same as the corresponding curve in Fig. 3a. The steady-state optical density is less than 1/6 the value measured with smoke, but the detector signals are between 60 % and 75 % as large. The much higher response of the detector sensors to the peanut oil aerosol is hypothesized to be attributable to a higher albedo and smaller size of oil droplets relative to smoke. The photo-electric sensor responds preferentially to light scattering, while the reference laser is sensitive to light absorption. The ionization sensor responds to the total particle number density, which is
dominated by smaller particles, but the reference laser is more influenced by the larger end of the size distribution.

The response of the detector sensors to a nuisance dust represented by a clay particle cloud in a stream of air traveling at a speed of 0.35 m/s is plotted in Fig. 3c. There are significant qualitative features different in this figure when compared to Fig. 3a, although the mean value of the optical density measured with the reference laser is of the same order in the two experiments. First, the oscillations of the laser signal occur at a fixed frequency, and the peak-to-peak values are greater than the mean value of the signal. This behavior can be traced to the slowly rotating screw-feeder, which drops a fixed portion of clay dust every 360 degrees. The photo-electric sensor is able to follow these fluctuations, and yields an average signal which is greater than that produced by an equivalent amount of laser light attenuation measured from the smoke in Fig. 3a. The clay particles would be expected to have a higher albedo than the smoke, and while the primary particle size is small, the screw-feeder causes the clay to agglomerate, and the

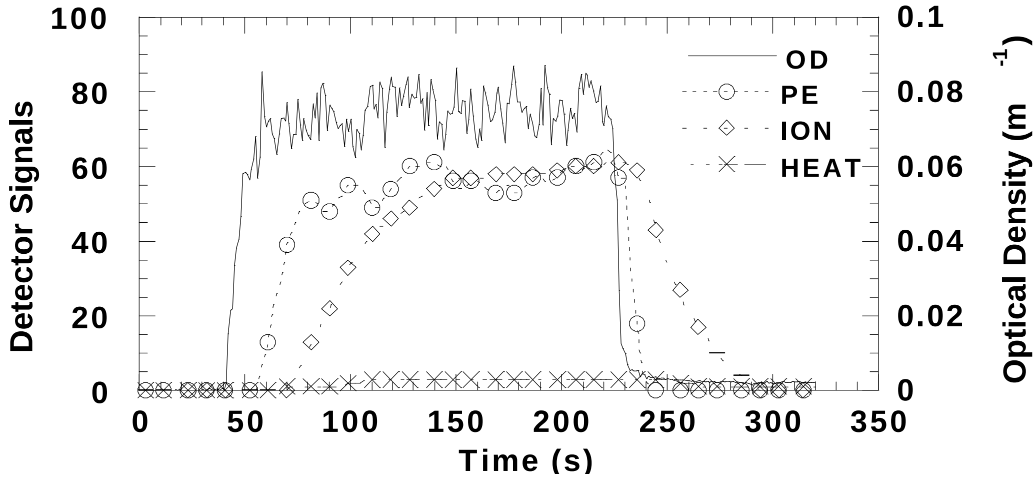

Figure 3a. Detector response to propene smoke ; flow velocity is 0.20 m/s.

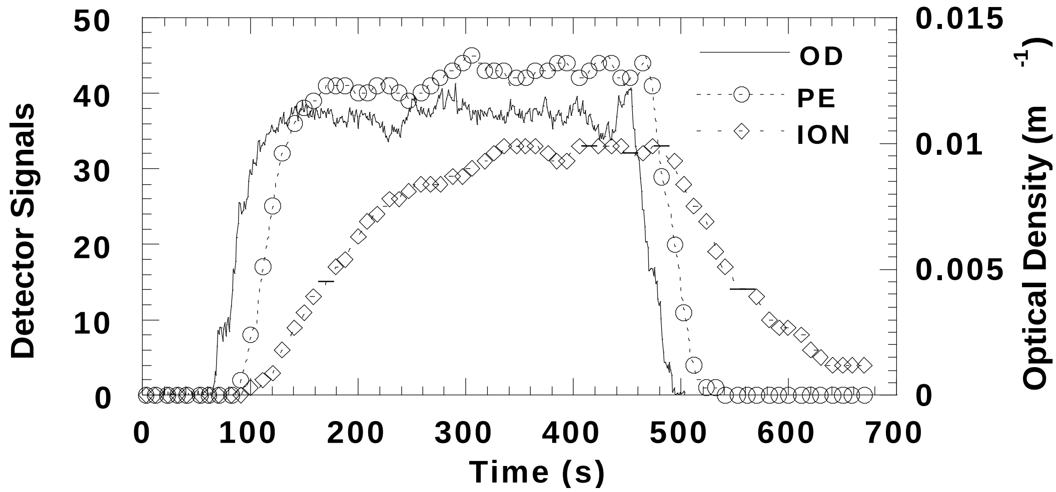

Figure 3b. Detector response to oil aerosol ; flow velocity is 0.04 m/s.

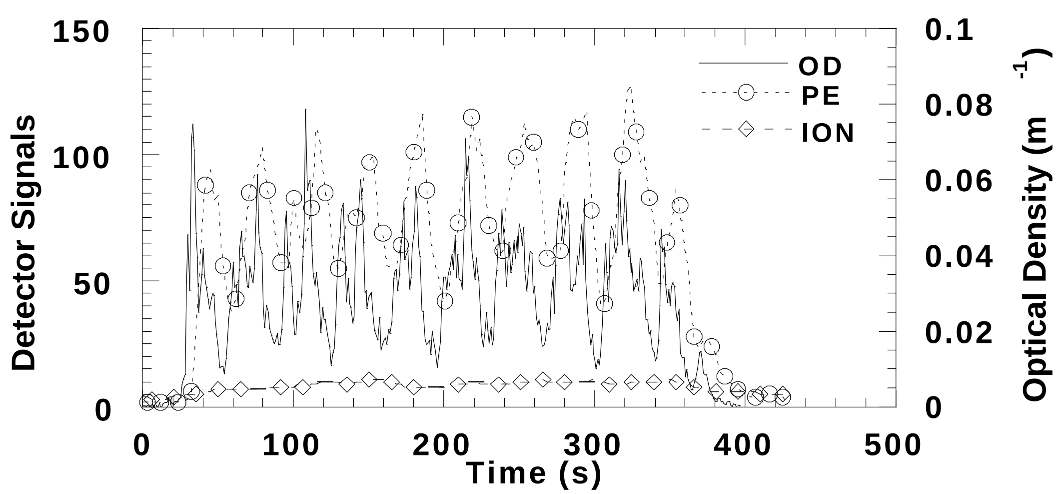

Figure 3c. Detector response to dust aerosol; flow velocity is 0.35 m/s

more sensitive to a large number of small particles than to a small number of large particles.

The steady-state detector signals are plotted in Figs. 4a, 4b, and 4c over the range of optical densities measured by the reference laser. Error bars represent ± one standard deviation. The maximum sensitivity for the detector is stated to be 3.70 % obscuration per 0.305m (1.00 ft). The response from the smoke generator, plotted in Fig. 4a, is linear and about the same for both detectors, with correlation coefficients greater than 0.96. A linear fit also correlates the peanut oil aerosol well, as demonstrated in Fig. 4b. In this case, the slope of the output signal from the photo-electric sensor is almost twice as steep as that from the ionization sensor. Both sensors show a higher sensitivity to the optical density created by the peanut oil than to the propene smoke.

In spite of the large oscillations in clay dust concentration created by the screw feeder, the signal from the photo-electric sensor, Fig. 4c, correlates to the mean optical density with a correlation coefficient of 0.93. The slope of the curve is greater than 2 times steeper than the corresponding curve for smoke. The ionization sensor shows no correlation with the clay dust, and is totally insensitive to the mass loading of the aerosol.

Summary and Conclusions

A modern multi-sensor fire detector was used in this study to demonstrate the utility of the FE/DE for evaluating sensor response to fire and non-fire aerosols. In addition to smoke formed from flaming hydrocarbon combustion, the detector was exposed to clouds of peanut oil and clay dust in air flowing at speeds between 0.03 m/s and 0.20 m/s. This work was illustrative of two types of nuisance aerosols. Future studies will focus on producing steadier and better controlled particle loading in the test section of the FE/DE, expanding the number of nuisance aerosol materials, and characterizing the aerosol size distribution, number density, and optical properties.

Acknowledgements

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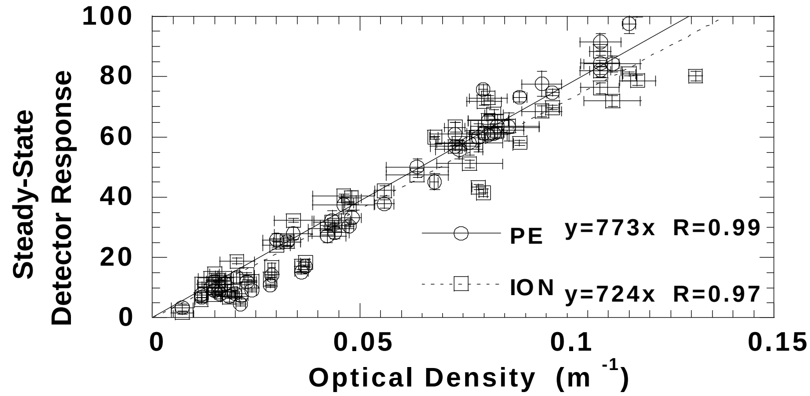

Figure 4a. Steady-state detector response to propene smoke. Equations for best-fit lines through data are given along with correlation coefficients (R).

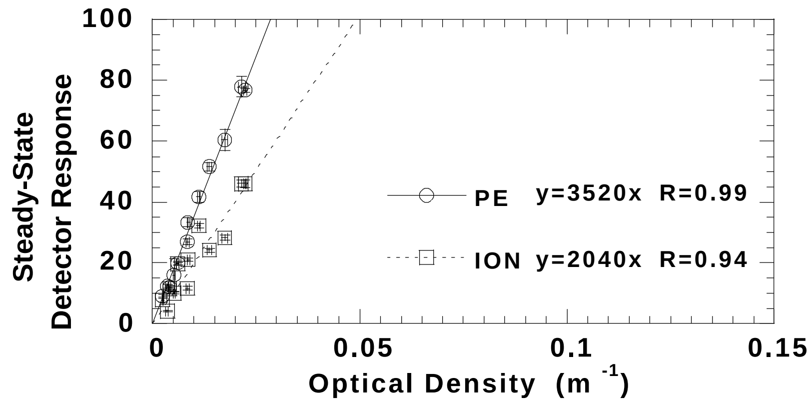

Figure 4b. Steady-state detector response to peanut oil aerosol. Equations for best fit lines through data are given along with correlation coefficients (R).

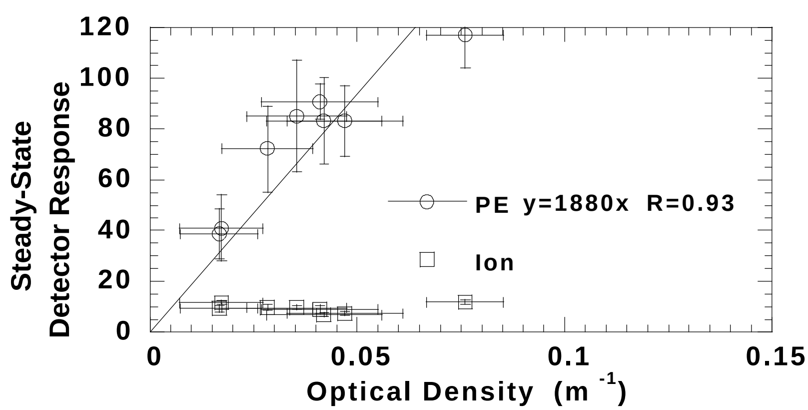

Figure 4c. Steady-state detector response to dust aerosol. Equation for best fit line through photo-electric detector data is given along with correlation coefficient (R).

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