AUBE '01

12TH INTERNATIONAL CONFERENCE ON AUTOMATIC FIRE DETECTION

March 25 - 28, 2001
National Institute Of' Standards arid Technology
Gaithersburg, Maryland U.S.A.

PROCEEDINGS

Editors: Kellie Beall, William Grosshandler and Ileinz Luck

NIST CENTENNIAL 1901-2001

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Thomas Cleary and Takashi Ono*
Building and Fire Research Laboratory, National Institute of Standards and Technology
Gaithersburg, MD, 20899 U.S.A.
*Department of Electrical Engineering, College of Science and Technology
Nihon University, Tokyo Japan

Enhanced Residential Fire Detection by Combining Smoke and CO Sensors

1. Introduction

The advantages of multi-sensor detection in general, and gas sensing in particular, suggest that a combined carbon monoxide-smoke fire detector could benefit the consumer by providing better fire detection through discrimination of some common nuisance sources, while warning of hazardous CO concentration in the living space. Heskestad and Newman [1] reported that the cross-correlation of CO concentration and measuring ionization chamber (MIC) measurements taken during room fire experiments was capable of detecting fires similar to EN 54 test fires with high sensitivity. Gottuk *et al.* [2] performed a number of fire and nuisance source room experiments, and showed that by combining CO and ionization signals, many nuisance sources were discriminated, while most fire source were detected. Ishii *et al.* [3] developed a detection algorithm using CO concentration, smoke concentration, and temperature measures in an artificial neural network. Here, three fire sources and four nuisance sources were emulated in the fire emulator/detector evaluator (FE/DE). Analog output photoelectric and ionization detector signals, along with an electrochemical CO cell's signal were gathered during the tests from sensors located in the FE/DE test section. The sensor signals from these tests were used to test a multi-parameter, de-based fuzzy logic detection algorithm.

2. Fuzzy Logic Detection Algorithm

Residential smoke detectors are typically ionization type or photoelectric type. There are dual sensor designs that contain both ionization and photoelectric sensors in the same housing, however, they function separately. The benefit of monitoring both photoelectric and ionization sensor outputs lies in their differing relative response to both fire smokes and nuisance aerosols. In combination with a CO measurement, potentially better fire detection and nuisance source discrimination is possible compared to a CO and ionization detector combination. Here, photoelectric, ionization and CO sensor signals were combined in a rule-based, *fuzzy* logic algorithm designed to discriminate between the emulated fire and nuisance source test results. The signal feature considered was the instantaneous value of the measured output. Hence, this algorithm is considered a static classification algorithm.

An overview of the fuzzy logic methodology and computations are described below. **A** more detailed treatment for the application of this methodology related to fire detection is given by Mueller [4]. Here, photoelectric, ionization, and CO signals were the input variables, and assigned to classes low, medium and **high** depending on their values. The state of alarm (fire) was the output variable, and assigned to class true or false. **A** rule base consisting of 27 rules of the form below was specified.

IF Photoelectric = (low, medium, or high) and Ionization = (low, medium, or high) and CO = (low, medium, or high) THEN fire = (TRUE or FALSE).

Each variable has a degree of membership in each class ranging from 0 to 1, given by defined membership functions. The membership functions for the variables photoelectric, ionization, and CO are shown in Figures 1-3. The final shape was obtained by an iterative process of testing the algorithm against the FE/DE test signals then adjusting membership functions. **A** commercial analog output photoelectric, ionization, and heat combination detector was used to obtain the photoelectric, and ionization sensor signals. The photoelectric and ionization sensor signals represent integer values from 0-255 spanning the sensor range; the membership function spans a portion of this range, where a zero-offset has been subtracted from the values. Figures **4-6** show the response of these sensors to steady concentrations of flaming soot, dust, and nebulized oil aerosol [5]. **A** linear fit through the data for each sensor is given along with the correlation coefficient. Error bars represent ± 1 standard deviation about the mean for each data point (an indication of aerosol source stability). The CO sensor signal was obtained from the voltage drop across a resistor attached to the terminals of an electrochemical CO cell. The voltage drop may be converted to CO volume fraction by multiplying it by **0.13** (volume fraction/volt).

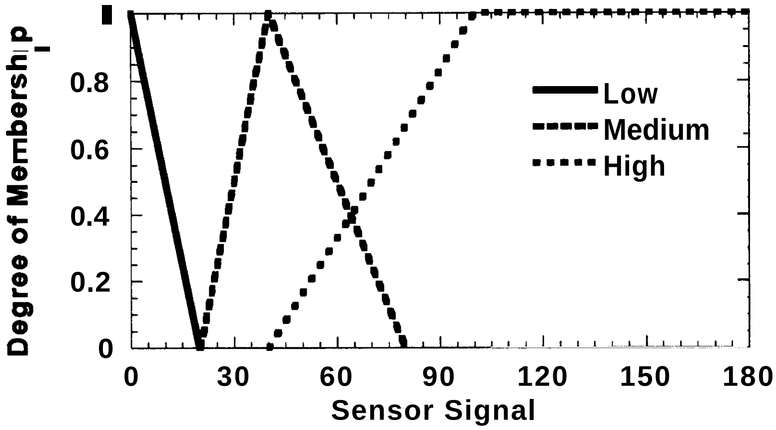

Figure 1. Membership functions for photoelectric sensor output.

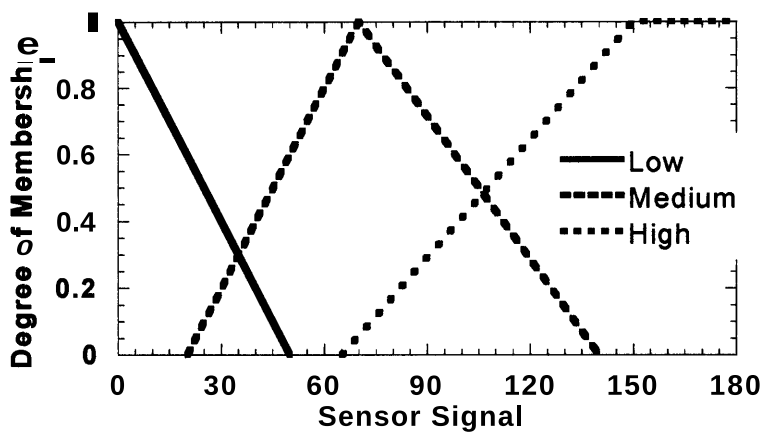

Figure 2. Membership functions for ionization sensor output.

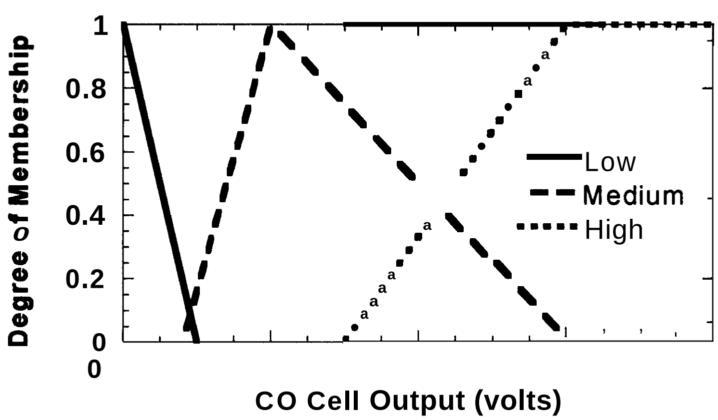

Figure 3. Membership functions for CO cell output.

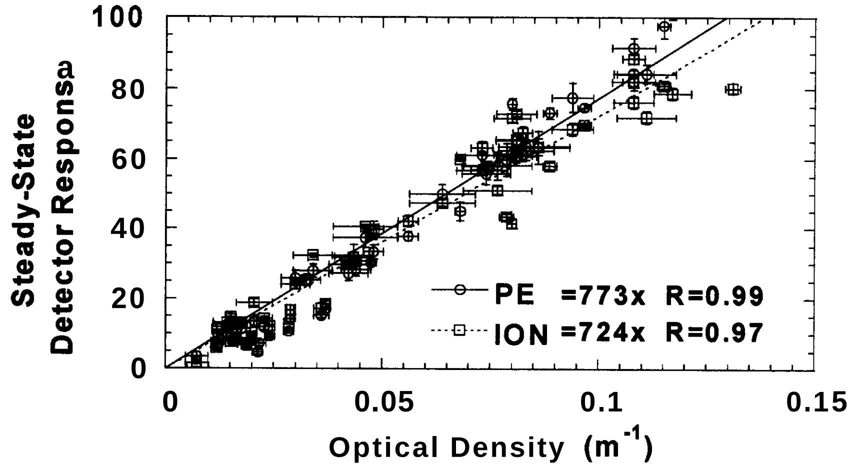

Figure 4. Photoelectric and ionization detector response to propene smoke.

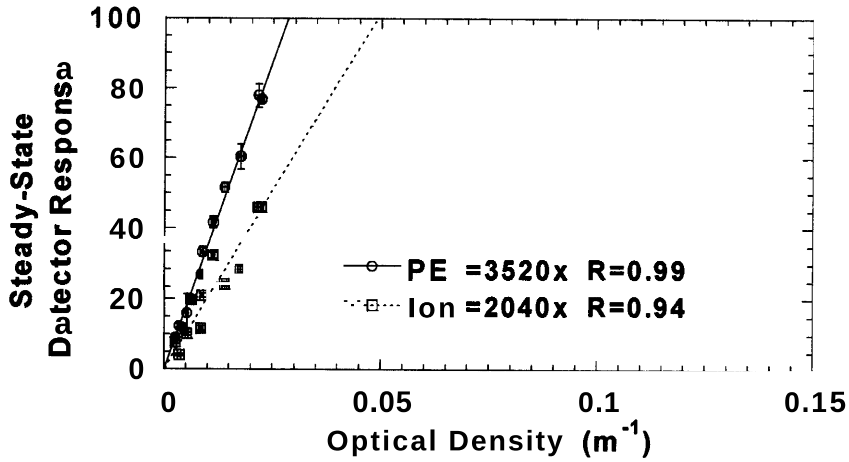

Figure *5*. Photoelectric and ionization detector response to nebulized oil.

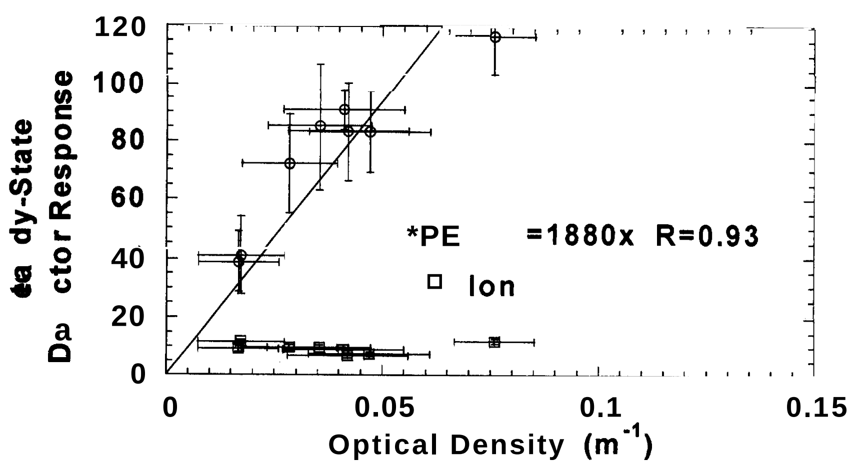

Figure *6*. Photoelectric and ionization detector response to Arizona test dust.

The degree of membership in each class for the input variables is used to evaluate the output variable's degree of membership. **A** weighted average of this set is used to determine if an alarm is reached by comparing it to a threshold value.

By computing the results over the entire range of photoelectric, ionization and CO sensor outputs, a surface plot reflecting the boundary between no alarm, and alarm conditions was constructed. In Figure **7,** all space on and above the surface reflects computed alarm conditions, while the space below reflects the computed no alarm conditions. At an ionization signal of about **70** and higher and a photoelectric signal of **80** and higher, no ***CO*** concentration was required for alarm. At lower ionization and photoelectric signal values, CO cell voltage must be above zero to indicate alarm. No alarm was indicated when ionization signal fell below **34.** No single sensor value was sufficient to cause alarm by itself over the range considered.

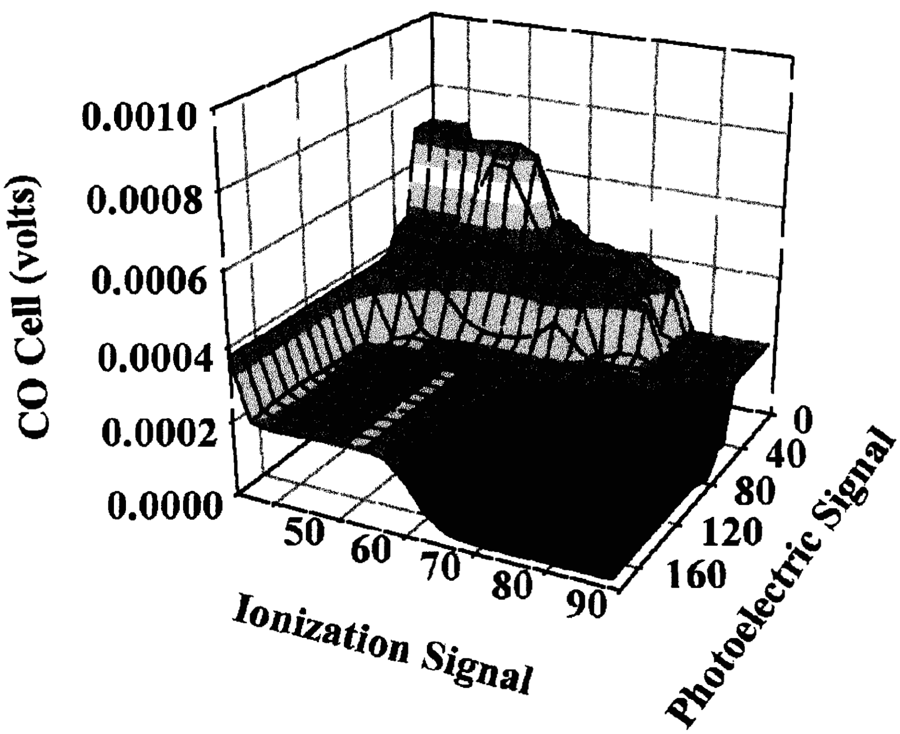

Figure **7.** Boundary surface between alarm and no-alarm conditions.

3. Fire and Nuisance Source Signals and Algorithm Output

Three fire smokes (flaming fire, smoldering cotton, and pyrolyzing wood blocks) and **4** nuisance sources (Arizona test dust, toasting bread, heated cooking oil, and cigarette smoke) were produced in the FE/DE, and sensor data for the analog output detector and CO electrochemical cell were gathered (see other papers by Cleary ***et** al.* in this proceedings for details on the FE/DE). Residential photoelectric and ionization detectors were placed on the ceiling of the FE/DE test section just down stream from the analog output detector and CO cell. Alarm times for these detectors were recorded during the tests. Each source is described below, along with the photoelectric, ionization, and CO sensor outputs and the alarm algorithm computations over the length of the test.

The flarning fire source was produced by heating the air, ramping the fan speed, and increasing soot from the propene smoke generator to emulate conditions from a burgeoning pool fire. Figure **8** shows the photoelectric, ionization, and CO sensor signals along with residential detector alarm points and the computed fuzzy alarm algorithm. The photoelectric, ionization, and CO signals all begin to rise at about **280 s.** The residential ionization detector alarms first, followed by the algorithm computation (indicated by the transition from an arbitrarily low computed value to a high value), then the residential photoelectric detector.

Cotton smolder smoke was generated by igniting 10 cotton wicks inside the FE/DE at the bottom of the vertical riser with the fan speed set at **5** Hz (corresponding to a mean flow velocity of 0.05 m/s). Figure **9** shows the sensor signals and alarm algorithm computation. The photoelectric signal climbs more steeply than the ionization signal and peaks at a higher value. For this source, the algorithm computation alarms first, followed by the residential photoelectric detector, then the residential ionization detector less than 10 **s** later.

Smoldering wood smoke was generated by heating **8** blocks of wood on an electric hotplate placed in the FEDE at the bottom of the vertical riser (this source was a scaled down version of EN 54 test fire **2)** with a fan speed of **7** Hz. Figure 10 show the sensor signals and alarm algorithm computation. While all signals begin to rise between **600 s** to **700 s,** the photoelectric signal rises much more steeply and reaches its maximum value. The

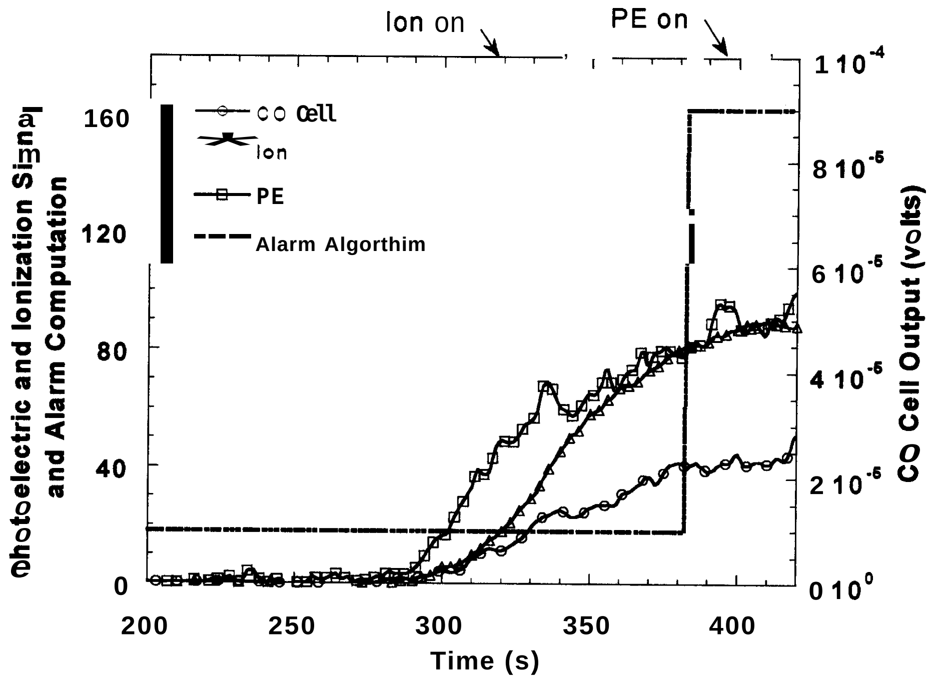

Figure **8.** Sensor signals and algorithm computation for flaming fire scenario.

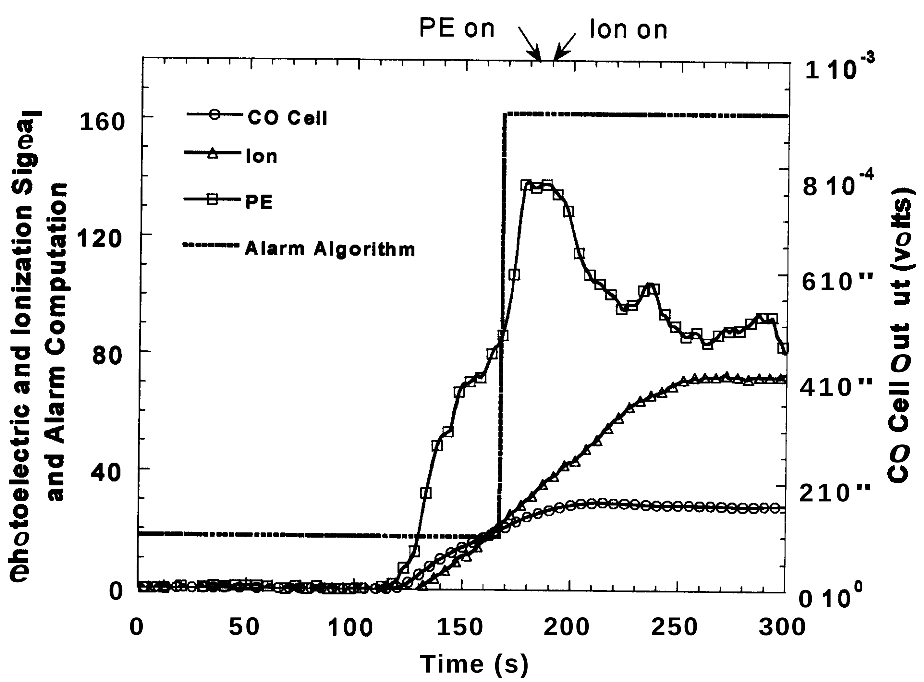

Figure **9.** Sensor signals and algorithm computation for smoldering cotton source.

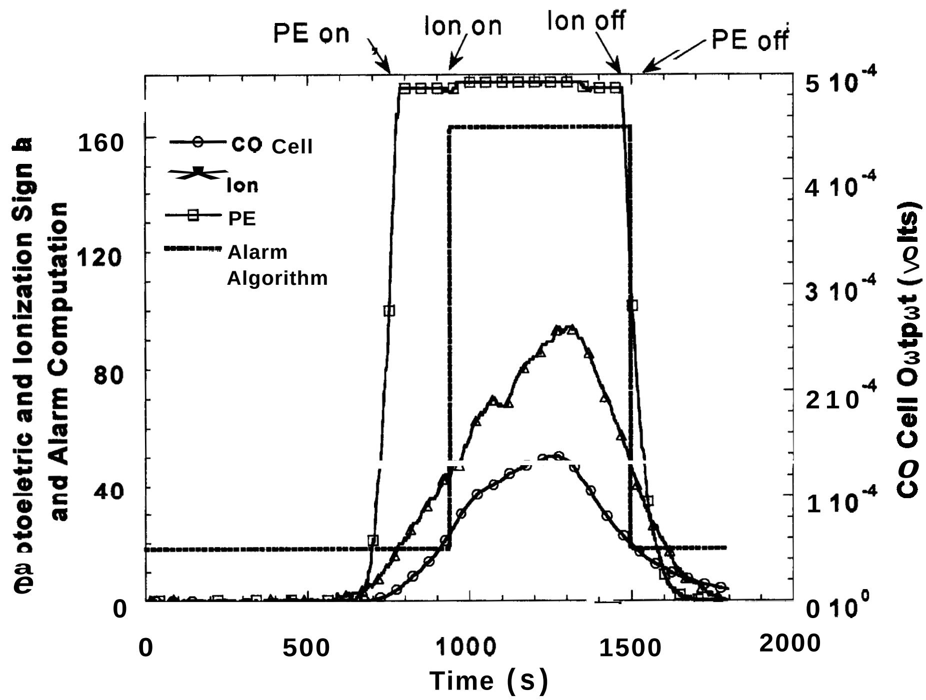

Figure 10. Sensor signals and algorithm computation for pyrolyzing wood source.

residential photoelectric detector was the first to alarm, followed about 200 s later by the residential ionization detector and the algorithm computation.

The dust exposure was produced by introducing Arizona test dust into the FEDE duct by a powder-delivery feeder at a constant rate, with a fan speed setting of 10 Hz. Figure 11 shows the sensor signals and the alarm computation. The photoelectric and ionization signal began to rise at **80** s with the photoelectric signal reaching its maximum value less than 10 s later. The ionization signal reached a much lower steady maximum 30 s to 40 s after beginning to rise. No appreciable rise in CO cell voltage was observed. The residential photoelectric detector was the only one to alarm. The algorithm computation stayed low throughout the test.

Cigarette smoke **was** produced by igniting a single unfiltered cigarette that had its unlit end attached to an air ejector (designed for this test to provide a continuous draw on the cigarette) placed at the bottom of the vertical riser. Smoke emitted directly from the burning coal, and drawn through the cigarette by the air ejector was blown to the test