# Rapid Detection and Suppression of Mining Equipment Cab Fires

*Maria I. De Rosa and Charles D. Litton, Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health, P.O. Box 18070, Pittsburgh, PA 15236, USA*

***Abstract.*** The National Institute for Occupational Safety and Health (NIOSH/PRL) conducted a series of large-scale experiments to evaluate the effectiveness of optical flame detectors, photoelectric smoke detectors, and combined ionization and photoelectric smoke detectors for rapidly detecting mining equipment cab fires. The detector alarm times were then used to trigger the discharge of a fire inerting system inside the cab to suppress cab material fires. This paper discusses the types of fire detectors tested, the experiments that were conducted, and the results that were obtained. Conclusions are that rapid detection of equipment cab fires can be achieved to trigger the discharge of a fire inerting system inside the cab to protect the operator in the cab.

**Keywords:** fires, equipment, detection, suppression, mining, inerting system

## 1. Introduction

### *1.1. Background*

Analyses of mining equipment fires for the 1990–1999 period showed that 171 of the 340 equipment fires were due to ruptured lines resulting in the spraying of hydraulic fluid or fuel onto the engine hot surfaces [1–3]. In at least 97 cases, these fires raged out of control resulting in loss of equipment and presenting significant risks to the cab operator. On 16 occasions, flammable vapors and mists penetrated the cab and ignited, forcing the operator to exit under hazardous conditions during the critical time needed to perform safe parking of the vehicle and engine shutoff. Findings also showed that on 10 occasions, fires originated in the cab due to electrical malfunctions that ignited combustible materials inside the cab.

In this study, optical flame detectors, photoelectric smoke detectors, and combined ionization and photoelectric smoke detectors were evaluated for their effectiveness in rapidly detecting cab fires. The detector alarm times were then used to trigger the discharge of a fire inerting system inside the cab to suppress cab fires. Of note is that during the inertization of the cab volume for the suppression of cab fires, the oxygen concentrations are reduced to levels that do not support combustion, yet are maintained sufficiently high to support life ($O_2$, ~12%) during the critical time needed for the operator to perform emergency tasks (safe parking of the vehicle and engine shutoff), and exit the cab.

Of note is that the NIOSH/PRL experiments, for the rapid detection and suppression of cab fires, are being conducted for the first time within the mining industry and other industries as part of extensive studies for the safety of equipment operators during fires.

The experiments were conducted in a large-scale mining equipment cab (1.8 m long $\times$ 1.5 m high $\times$ 0.9 m wide) (Figures 1–4), using various sized fire sources located within the cab, at various distances from the detector (Figures 1–4).

*1.1.1. Cab Fire Inerting System.* The cab fire inerting system [4] is a commercially available system consisting of an inert gas mixture concentration (Inergen, 45% mixture concentration: $N_2$, 50%; Ar, 42%; and $CO_2$, 8%), designed (1.45 $m^3$ of gas) for a cab volume of 2.43 $m^3$. The gas mixture is contained in a canister bolted to the cab rear wall and is discharged inside the cab through a muffled nozzle system at a discharge rate that maintains a breathable cab atmosphere [5, 6].

*1.1.2. Fire Detectors.* Four commercially available fire detectors were evaluated in this study for the specific intend to test their effectiveness in detecting incipient flaming and/or smoking fires in the cab for the early discharge of a fire inerting

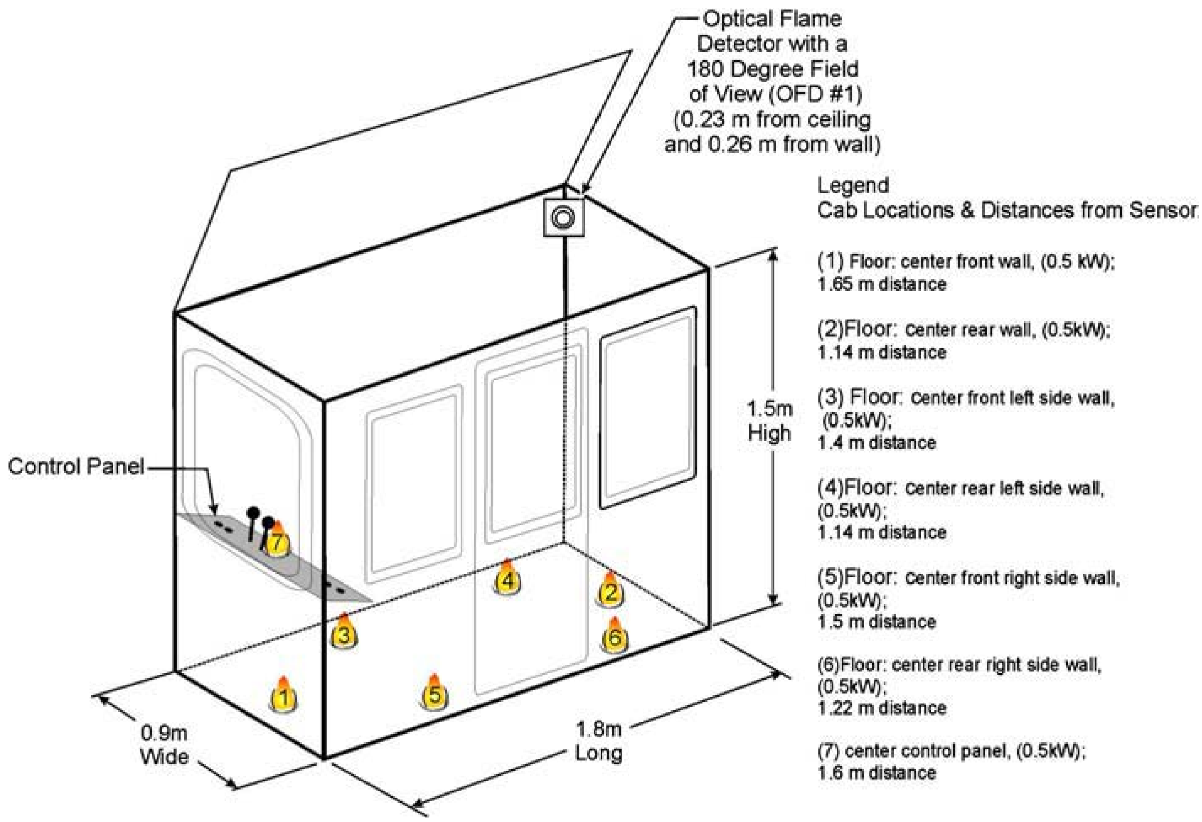


**Figure 1. Schematic of the cab with an optical flame detector (OFD #1) exposed to fire sources.**

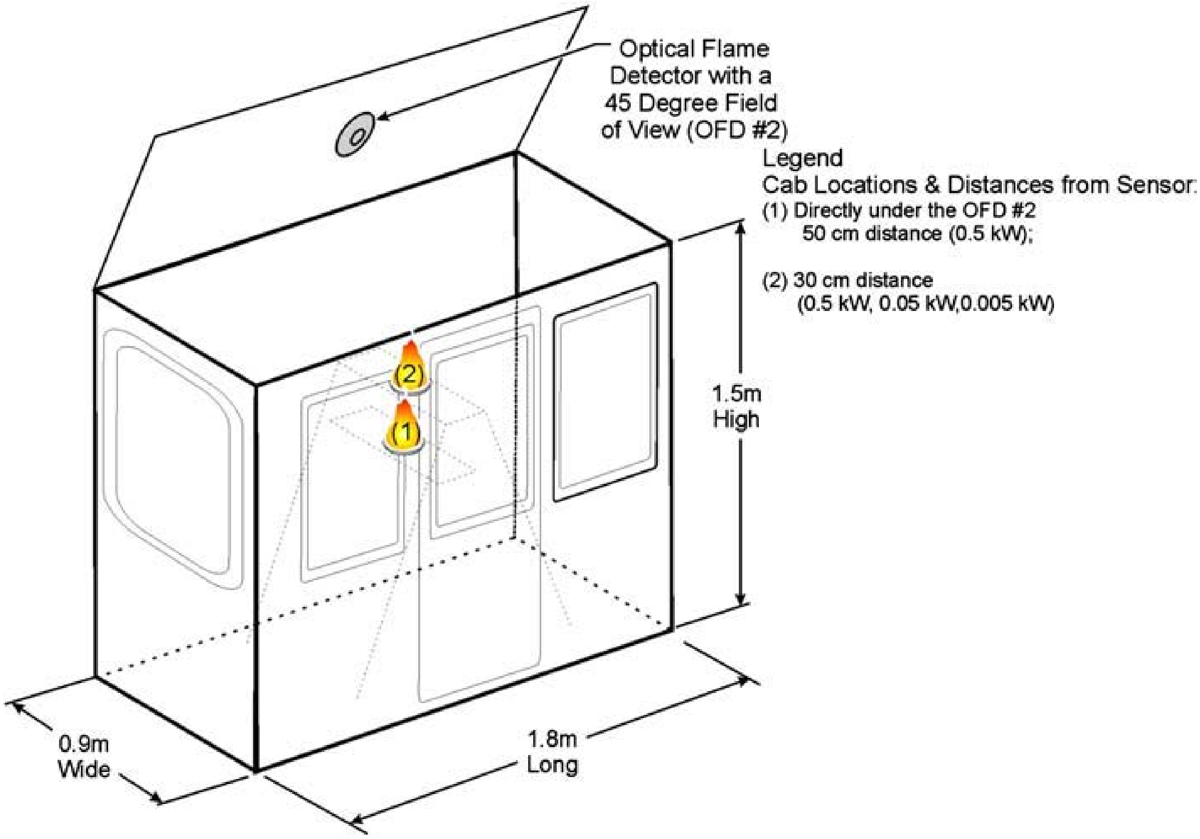


**Figure 2. Schematic of the cab with an optical flame detector (OFD #2) exposed to a fire source.**

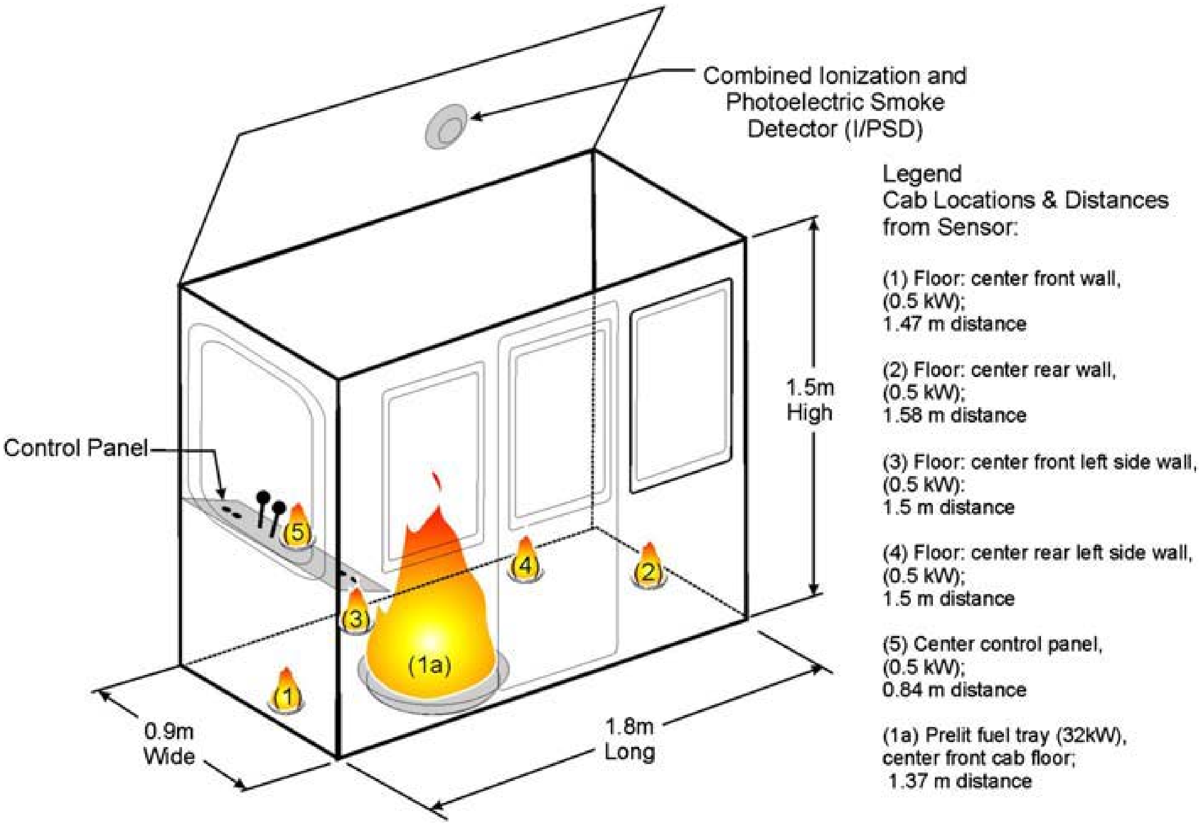


**Figure 3. Schematic of the cab with a smoke detector (I/PSD) exposed to fire sources.**

**Figure 4. Prelit fuel tray fires (32 kW: 250 ml diesel and 250 ml gasoline contained in a 23 cm dia fuel tray).**

system inside the cab. Two of the detectors were optical flame detectors, a third was a photoelectric smoke detector, and the fourth was a combined ionization and photoelectric smoke detector. The number of detectors was confined to four for experimental economic reasons. This study is not a survey and testing of commercially available fire detectors but a guide to the mining safety industry in the use of cab fire detectors.

The two optical flame sensors detect electromagnetic radiation produced by a flame. Both of these sensors respond to radiation produced in both the ultraviolet and infrared regions of the spectrum (UV and IR): ultraviolet sensors respond to energy emitted between 0.18 and 0.4 μm; while infrared sensors respond to energy between 0.75 and 20 μm [7–10]. The two sensors differ primarily by their respective field of view: one sensor, denoted as OFD (1, with a 180° field of view, was designed for wide-area coverage while the second, denoted as OFD (2, with a 45° narrow field of view, was designed as a line-of-sight detector for short distances ( < 50 cm). Both of these sensors have rapid response times in milliseconds, and may also be used as explosion detectors. For these experiments, the detectors response times were recorded in seconds due to software–hardware constraints.

The other two fire detectors that were evaluated were smoke detectors. One of the smoke sensors was a photoelectric smoke detector, denoted as PSD, which detects light scattered by smoke particles within a small chamber [11]. Photoelectric smoke detectors are generally more sensitive to the larger smoke particles produced from smoldering fires than to the much smaller particles produced from flaming fires. The other smoke sensor was a combined ionization and photoelectric smoke detector, denoted as I/PSD. This detector utilizes a small ionization chamber to generate an alarm to the smaller particles produced from flaming fires

[12] while the photoelectric component generates an alarm when larger smoke particles from smoldering fires are produced.

## 2. Experiments

A total of 47 experiments were conducted with the two optical flame detectors, the photoelectric smoke detector, and the combined ionization and photoelectric smoke detector, positioned within the equipment cab. For these experiments, various sized fire sources were used ($\sim$32, $\sim$0.5, $\sim$0.05 kW). In addition, a fourth fire source, a small candle, was also used with an estimated heat release rate of 0.005 kW. The fire sources were located at various cab locations and distances from the detector (Figures 1–4). Detector response times as a function of fire size, location and distance were recorded.

For the fire sources 32, 0.5, and 0.05 kW, a 50/50 mixture of No. 2 diesel fuel and gasoline were used with surface areas of 0.041, 0.002, and 0.00049 $m^2$, corresponding to diameters of 0.23, 0.05, and 0.025 m, respectively.

The fire heat release rate (kW), $Q_f$, was calculated from the standard formula [13]:

$$Q_f = (A_s)(H_c)(m_f'');$$

where $A_s$ is the surface area of the liquid fuel surface ($m^2$); $H_c$ is the average heat of combustion of the fuel mixture (approximately 40 kJ/g) and $m_f''$ is the mass flux of fuel from the surface given by the expression; $m_f'' = 55(1 - e^{2.1d})$; with $d$ equal to the fuel surface diameter, in m.

Combining these expressions yields heat release rates of 32, 0.5, and 0.05 kW for the three fuel surface areas defined above. The calculated heat release rate for the 32 kW fire sized source is reported in the following:

$$(0.041 \text{ fuel tray surface area})\text{m}^2(40 \text{ kJ/g})(19.5 \text{ g/m}^2 \times \text{s}) = 32\,\text{kW}.$$

### *2.1. Optical Flame Detector with a 180° Field of View*

Twenty-one experiments were conducted with the OFD (1, positioned at the upper left corner of the rear cab wall (0.23 m distance from ceiling and 0.26 m distance from wall; detector dimensions, 25 cm dia $\times$12 cm high) (Figure 1). For these experiments, three sized fire sources were used: 0.5 kW (5 ml of diesel and 5 ml of gasoline contained in a 5 cm dia tray), 0.05 kW (2.5 ml of diesel and 2.5 ml of gasoline contained in a 2.5 cm dia tray), and 0.005 kW (candle), located at various cab locations and distances from the detector (Figure 1). The cab floor locations, shown in Figure 1, were: (1) center of front wall (under the control panel, at 20 cm distance from the front wall; distance from the detector, 1.65 m); (2) center of rear wall (distance, 1.14 m); (3, 4) center of front and rear left side walls (distances, 1. 4 and 1.14 m, respectively); and, (5, 6) center of front and rear right side walls (1.5 m and 1.22 m, respectively). In addition, a flame source (7) was placed at the center of the control panel (distance, 1.6 m).

### 2.2. *Optical Flame Detector with a 45° Field of View*

Four experiments were conducted with the OFD (2, positioned at the center of the cab ceiling (detector dimensions, 7.5 cm dia ×5 cm high) using three sized fire sources (0.5, 0.05, and 0.005 kW) (Figure 2). For these experiments, the fuel sources (1) and (2) were located directly under the detector, at 50 cm (0.5 kW fire source) and 30 cm (0.5, 0.05, 0.005 kW fire sources) distances from the detector (Figure 2).

### 2.3. *Combined Ionization and Photoelectric Smoke Detector*

Eighteen experiments were conducted with the I/PSD, positioned at the center of cab ceiling (detector dimensions, 7.5 cm dia ×5 cm high), using four sized fire sources (32, 0.5, 0.05, and 0.005 kW), located at various cab locations and distances from the detector (Figure 3). The 32 kW fire source consisted of 250 ml of diesel and 250 ml of gasoline, contained in a fuel tray (23 cm dia) (Figure 4) equipped with electric matches for remote ignition at cab door closing.

The cab floor locations were: (1) center of front wall (under the control panel, at 20 cm distance from front wall; distance from the detector, 1.47 m); (1a) center front floor (distance, 1.37 m); (2) center of rear wall (distance, 1.58 m); and, (3, 4) center of front and rear side left walls (distances for each location, 1.5 m). In addition, one of the fire sources (5) was placed at the center of the control panel (distance, 0.84 m) (Figure 3). Additional experiments (two experiments) were conducted with the I/PSD exposed to smoldering fire sources (consisting of 10 pieces of electrical cord, 2.5 cm long, contained in a 13 cm dia tray), located at the center of the front and rear cab floor (distances, 1. 37 m and 1.4 m, respectively).

### 2.4. *Photoelectric Smoke Detector*

Two experiments were conducted with the PSD, positioned at the center of the cab ceiling (detector dimensions, 7.5 cm dia ×5 cm high), using smoldering fire sources similar to the sources used for the I/PSD, located at the center of the front and rear cab floor (distances from the detector, 1.37 and 1.4 m, respectively).

### 2.5. *Cab Fire Inerting System Experiments*

Two experiments were conducted with the cab fire inerting system for the suppression of cab fires. For these experiments, the discharge of the fire inerting system inside the cab was manually triggered 5 s after the 32 kW fuel tray was lit (Figure 5). The trays (1) and (2), equipped with electrical matches for remote ignition at cab door closing, were located at the center of the front and rear cab floor (distances from the detector, 1.37 and 1.4 m, respectively) (Figure 5).

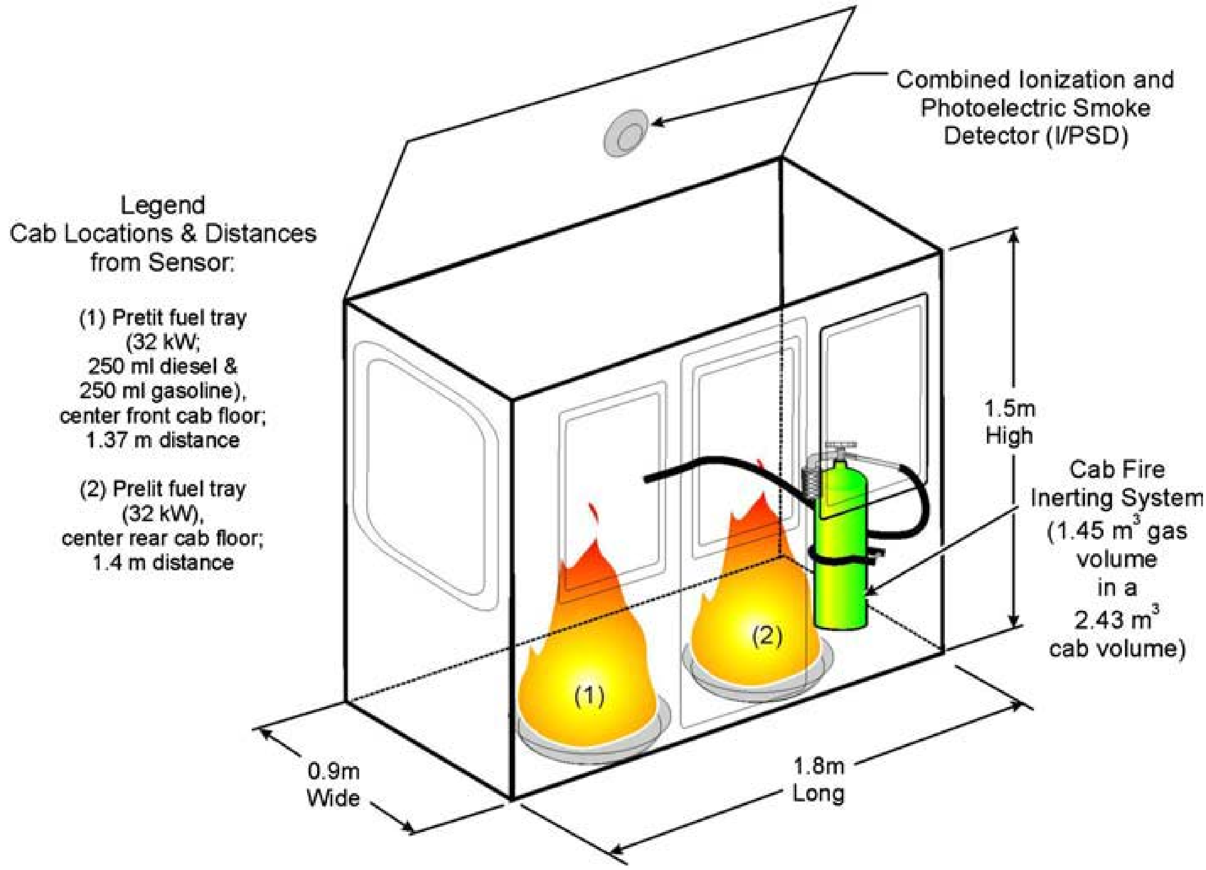


**Figure 5. Schematic of the cab with a cab fire inerting system.**

## 3. Results and Discussion

### *3.1. Detector Response Times*

Tables 1–3 and Figure 6 show the results for all the experiments. Figure 6 shows the response times (2 s) yielded by the optical flame detector with a 180° field of view (OFD (1), exposed to a 0.5 kW fire source located on the cab floor at the center of the front wall (distance from the detector, 1.65 m). The detector yielded similar response times for the 0.05 kW and 0.005 kW fire sources, located at all cab locations and distances (maximum distance, 1.65 m) (Table 1). Of note is that for these experiments, the detectors response times were recorded in ''seconds'' rather than in ''milliseconds'' due to software–hardware constraints.

For the OFD (2, similar response times of 2 s were obtained for all fire sources, located directly under the detector at 30 cm distance (Table 1). The detector failed to detect the 0.5 kW fire source (the only source tested) at a distance of 50 cm (Table 1).

For the combined ionization and photoelectric smoke detector (I/PSD), response times of 5 s were obtained for the 32 kW fire source, located at the center of the front cab floor (Table 2), at a distance from the detector of 1.37 m. For this type of detector, under these experimental conditions, the rapid response times are due to the fast rise of smoke particles within the flame by means of the buoyancy effect [14–17]. For the smaller fire sources (0.5 and 0.05 kW), the I/PSD

**Table 1**
**Optical Flame Detector Response Times for Various Sized Fire Sources, Cab Locations, and Distances from the Detector**

| Fire size | Response time | Distance from sensor | Cab location |
|---|---|---|---|
| OFD #1: positioned in the cab, at the upper left corner of rear wall | | | |
| | | | Cab Floor |
| 0.5 kW | 2 s | 1.65 and 1.14 m | Center front and rear walls |
| | 2 s | 1.4 and 1.14 m | Center front and rear left side walls |
| | 2 s | 1.5 and 1.22 m | Center front and rear right side walls |
| | 2 s | 1.6 m | Center control panel |
| 0.05 kW | 2 s | 1.65 and 1.14 m | Center front and rear walls |
| | 2 s | 1.4 and 1.14 m | Center front and rear left side walls |
| | 2 s | 1.5 and 1.22 m | Center front and rear right side walls |
| | 2 s | 1.6 | Center control panel |
| 0.005 kW (candle) | 2 s | 1.65 and 1.14 m | Center front and rear walls |
| | 2 s | 1.4 and 1.14 m | Center front and rear left side walls |
| | 2 s | 1.5 and 1.22 m | Center front and rear right side walls |
| | 2 s | 1.6 m | Center control panel |
| OFD #2: positioned in the cab, at the center of cab ceiling | | | |
| | | | Directly under the detector |
| 0.5 kW | No response | 50 cm | Vertical distance from detector |
| | 2 s | 30 cm | Vertical distance from detector |
| 0.05 kW | 2 s | 30 cm | Vertical distance from detector |
| 0.005 kW (candle) | 2 s | 30 cm | Vertical distance from detector |

**Table 2**
**Smoke Detector Response Times for Various Sized Fire Sources, Cab Locations, and Distances from the Detector**

| Fire size | Response time | Distance from sensor | Cab location |
|---|---|---|---|
| I/PSD; positioned in the cab, at the center of cab ceiling | | | |
| | | | Cab floor |
| 32 kW | 5 s | 1.37 m | Center front floor |
| 0.5 kW | 10 s | 1.47 and 1.58 m | Center front and rear walls |
| | 10 s | 1.5 and 1.5 m | Center front and rear left side walls |
| | 10 s | 0.84 m | Center control panel |
| 0.05 kW | 10 s | 1.47 and 1.58 m | Center front and rear walls |
| | 10 s | 1.5 and 1.5 m | Center front and rear left side walls |
| | 10 s | 0.84 m | Center control panel |
| 0.005 kW (candle) | No response[a] | 1.47 and 1.58 m | Center front and rear walls |
| | No response[a] | 1.5 and 1.5 m | Center front and rear left side walls |
| | No response[a] | 0.84 m | Center control panel |
| Smoldering fire source[b] | 60 s | 1.37 and 1.4 m | Center front and rear floor |
| PSD; positioned in the cab, at the center of cab ceiling | | | |
| | | | Cab floor |
| Smoldering fire source[c] | 60 s | 1.37 and 1.4 m | Center front and rear floor |

[a] Due to lack of smoke evolution.
[b] Consisting of 10 pieces of electrical cord, contained in a 13 cm dia tray; each piece, 2.5 cm long.
[c] Same as described for the combined ionization and photoelectric detector experiments.

**Table 3**
**Activation of a Fire Inerting System in the Cab, at Detector Fire Response time (5 s) for the Suppression of Fires Inside the Cab**

| Fire size | Fire suppression time | Distance from sensor | Cab location: cab floor |
|---|---|---|---|
| Prelit fuel trays[a] (32 kW) | 20th s[b] | 1.37 and 1.4 m | Center front and rear floor |

[a] 250 ml of diesel and 250 ml of gasoline, contained in a 23 cm dia tray.
[b] After the start of the discharge of the gas mixture ($O_2$, ~14%) (complete gas mixture discharge, 120th s).

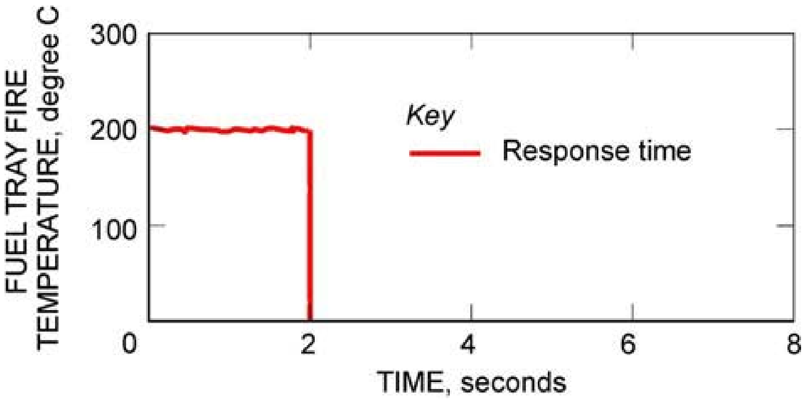


**Figure 6. OFD #1 response time, exposed to a 0.5 kW fire source in an equipment cab, at all cab locations and distances from the detector.**

yielded slower response times of 10 s at all cab locations and distances (maximum distance, 1.58 m) (Table 2). The I/PSD failed to detect the candle fire source (0.005 kW) due to lack of smoke particle evolution. The I/PSD was effective in detecting smoldering fire sources within 60 s, located at the center of the front and rear cab floor (distances, 1.37 and 1.4 m, respectively) (Table 2). Similar response times were obtained with the PSD, under similar experimental conditions (Table 2).

### *3.2. Activation of a Fire Inerting System in the Cab*

For the suppression of fires inside the cab, the I/PSD response times of 5 s were used to manually trigger the discharge of the fire inerting system in the cab (Table 3). The expectations were that the discharge of the gas mixture in the cab would be effective in suppressing the fires inside the cab by inerting the cab volume.

For these experiments, the cab fires (32 kW), located at the center of the front and rear cab floor, were suppressed within the first 20 s after the start of discharge of the gas mixture ($O_2$, ~14%) (Table 3). Of note is that the 32 kW fire source was mainly used to evaluate the effectiveness of the fire inerting system in suppressing large cab fires. In real situations, these fires might have been already detected at their smoldering or early flaming stage of combustion. However, it is important to stress that at fire detection time (conveyed by detector fire alarm and/or visual observations), the operator needs to rapidly perform safe parking of the vehicle and engine shutoff, and exit the cab, accompanied or preceded by the automatic or manual activation of the fire inerting system in the cab.

## 4. Conclusions

Results show that the optical flame detector with a 180° field of view (OFD (1) was effective in detecting within 2 s fires ranging from 0.5 to 0.005 kW, located at various cab locations and distances from the detector. Similar response times were obtained for the optical flame detector with a 45° field of view (OFD (2), exposed to similar sized fire sources located directly under the detector at 30 cm distance. At 50 cm distance, the OFD (2 failed to detect the fire.

For a combined ionization and photoelectric smoke detector (I/PSD), response times of 5 s were obtained for the 32 kW fire source. For much smaller fire sources (0.5 and 0.05 kW), the I/PSD yielded a slower response time of 10 s, at all cab locations and distances from the detector. The I/PSD failed to detect the 0.005 kW candle fire. The I/PSD and PSD were effective in detecting small smoldering fires within 60 s.

The I/PSD response time of 5 s was then used to manually trigger the discharge of the fire inerting system in the cab for the suppression of a 32 kW fire placed inside the cab. The cab fires were suppressed within the first 20 s after the start of the discharge of the gas mixture.

In conclusion, the data indicate that the OFD (1 flame detector and the I/PSD smoke detector, installed within the operator's cab, provide the operator with sufficiently early warning of early flaming fires (OFD (1 and I/PSD; 2 and 10 s, respectively) and smoldering fires (I/PSD; 60 s) to activate a cab fire suppression system, to perform safe parking of the vehicle and engine shutoff, and exit the cab. Of note is that the I/PSD detector offers additional qualities such as manageable size and cost effectiveness.

## References


[1] M. De Rosa, "Analyses of Mobile Equipment Fires for all U.S. Surface and Underground Coal and Metal/Nonmetal Mining Categories, 1990–1999," NIOSH IC 9467, 2004, 53 pp.

[2] M. De Rosa, "Analysis of Mine Fires for All U.S. Underground and Surface Coal Mining Categories, 1990–1999," NIOSH IC 9470, 2004, 36 pp.

[3] M. De Rosa, "Analysis of Mine Fires for All U.S. Metal/Nonmetal Mining Categories, 1990–1999," NIOSH IC 9476, 2004, 52 pp.

[4] M. De Rosa, "Effectiveness of Inert Gas Mixture Concentrations in Preventing and Suppressing Mining Equipment Cab Fires: Development of a Dual Cab Fire Inerting System," *Fire Technology Journal*, (in publication).

[5] G. Field, "The Physiological Effects on Human Exposure to Gas Mixtures of Air and Inergen," Dept. of Resp. Med., The Prince of Wales Hospital, Sidney, Australia, Report and Supplementary Report, 1992, 22 pp.

[6] C. Lambertsen, "Short Duration Inergen Exposures, Relation to Cardiovascular or Pulmonary Abnormalities," Env. Biom. Stress Data Center, Inst. Env. Med., Univ. of Pennsylvania Medical Center, College Park, PA, Report 2-1-93, 1993, 13 pp.

[7] C. Litton, "Fire Detectors in Underground Mines," U.S. Bureau of Mines IC 8786, 1979, 11 pp.

[8] D. Gottuk, M. Wright, J. Wong, H. Phan, and S. Rose-Pehrson, "Prototype Early Warning Fire Detection System," Naval Research Lab., Washington, DC, NRL/MR/6180-02-8602, 2002, 63 pp.

[9] S. Kulakov, O. Moskaletz, L. Preslenev, and A. Shabargin, "Materials and Devices for Photonic Circuits II," in *Proceedings of SPIE – International Society for Optical Engineering*, San Diego, CA, vol. 4453, 2001, pp. 157–161.

[10] B. Charumporn, M. Yoshioka, T. Fujinaka, and S. Omatu, "Early State Fire Detection Using Reliable Metal Oxide Gas Sensors and Artificial Neural Networks", *Proceedings of the International Joint Conference on Neural Networks*, vol. 4, 2003, pp. 3185–3188.

[11] R. Alpert, "Calculations of Response Time of Ceiling-Mounted Fire Detectors", *Fire Technology Journal*, vol. 8(3), 1972, pp. 181–195.

[12] R. Bukokowski, and J. Averill, "Methods for Predicting Smoke Detector Activation," in *Proceedings Fire Suppression and Detection Research. Application Symposium*, Orlando, FL, 1998. Nat. Fire Protection Research Foundation, Quincy, MA.

[13] *The SFPE Handbook of Fire Protection Engineering*, 1st Ed., *Vytenis Babrauskas "Burning Rates"* pp. 2-2 and 2-3, Society of Fire protection Engineers, Boston, MA, September, 1988.

[14] S. Lo, K. Yuen, W. Lu, and D. Chen, "A CFD Study of "Buoyancy" Effects on Smoke Spread in a Refuge Floor", *Journal of Fire Science*, vol. 20(6), 2002, pp. 439–463.

[15] F. Liu and J. Wen, "The Effect of Turbulence Modeling on the CFD Simulation of Buoyant Diffusion Flames", *Fire Safety Journal*, vol. 37(2), 2002, pp. 125–150.

[16] G. Heskestad, and T. Hamada, "Ceiling Flows of Strong Fire Plumes," FMRC Report OKOEI.RU, Factory Mutual research Corp., Norwood, MA, 1984, 43 pp.

[17] L. Cooper, "Ceiling Jet-driven Wall Flows in Compartment Fires," National Bureau of Standards, Interagency Report 87-3535, Gaithersburg, MD, 1987, 100 pp.