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Early fire detection for underground diesel fuel storage areas

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Abstract

With the increased use of mobile diesel-powered equipment in underground mines, the fire risk posed by underground diesel fuel storage areas is a concern. To reduce the risk associated with the storage and transfer of large quantities of diesel fuel in permanent underground mine storage areas, an experimental study was conducted to investigate the responses of different sensors for early detection of diesel fuel fires in a storage area. Fire sensors tested in this study were four carbon monoxide (CO) sensors, two smoke sensors, and one flame sensor. A series of fire tests were conducted in the NIOSH Safety Research Coal Mine, Bruceton, PA, using various fire sizes at different ventilation airflow velocities and fire locations. Response times for different sensors were analyzed, and the results suggest that the flame sensor and smoke sensors resulted in shorter response times in most tests compared to the CO sensors. Based on the test results, the appropriate sensor locations for early fire detection in a diesel fuel storage area were identified. The results of this study can help mining companies to select appropriate fire sensors for underground diesel fuel storage areas and improve the deployment of these sensors to ensure the safety of underground miners.

Keywords

Fire detection; Diesel fuel storage; Carbon monoxide sensor; Smoke sensors; Flame sensor; Ventilation

1. Introduction

Diesel-powered equipment is commonly used in underground coal mines across the United States. Diesel equipment in underground coal mines poses a risk of fire or explosion, as a result of the introduction of an ignition source (the diesel engine) into an environment that may contain methane gas. Improper fuel handling and fuel transfer procedures underground present significant fire hazards. Because of the methane gas and coal dust present in the underground coal mining environment, any fire presents a significant risk of loss of life.

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The U.S. Code of Federal Regulations, Title 30, Part 75.1903 requires that a permanent underground diesel fuel storage area facility be constructed of noncombustible materials and ventilated with intake air. The regulations state that the area must be equipped with an automatic fire suppression system. 30 CFR Part 75.1912 sets forth the requirements for automatic fire detection using fire sensors to activate an automatic fire suppression system for permanent underground fuel storage areas. However, the regulations do not specify what kind of fire sensors should be used nor where the fire sensors should be installed in the area. This information is critical for effective early detection and extinguishing of the fire and to prevent a small diesel fuel fire incident from causing a major explosion.

A considerable amount of research has been done on the hazard characterization of diesel fuel pool fires in other structures and facilities. Wang et al. (2009) studied diesel oil pool fire characteristic under natural ventilation conditions in tunnels with roof openings. Li et al. (2010) researched the ignition of the leaked diesel on a heated horizontal surface. Sahu et al. (2017) conducted full-scale experimental and numerical studies on the effect of ventilation in an enclosure diesel pool fire. Yuan and Lazzara (2004) investigated the effects of ventilation and preburn time on water mist extinguishing of diesel pool fires in underground diesel fuel storage areas. De Rosa and Litton (2010) studied the rapid detection and suppression of mining equipment cab fires with diesel fuel as the fire source. However, no research has been conducted on the early detection of fires in an underground diesel fuel storage area, which poses specialized fire prevention challenges. In these areas, the diesel fuel may be spilled on the floor or may leak on to the floor during the fuel handling and transfer process. The spilled or leaked fuel may become ignited by a heat source such as a hot engine exhaust pipe or engine surface.

Early fire detection is vital to reducing both the damage and injury the fire may cause. Carbon monoxide (CO) sensors have been commonly used in underground coal mines for fire detection in conveyor belt entries, diesel fuel storage areas, and battery charging stations (Smith and Litton, 2015). Appropriate smoke sensors, if and when they become available, could be used in parallel with the CO sensors or as replacements because of their early warning capability (Perera and Litton, 2012). Edwards and Friel (1996) conducted an in-mine evaluation of CO and smoke sensors in a mine entry. They recommended that smoke sensors be used whenever possible as part of a mine atmospheric monitoring system as they would give greater flexibility for setting alarm values for fire detection at low smoke levels. Litton and Perera (2015) evaluated different fire sensors for mine fire detection in a mine entry using an atmospheric monitoring system, but with mixed results. In the current study, to further add to this body of research and develop guidelines for placement of sensors for early fire detection, a series of experiments were conducted in the NIOSH Safety Research Coal Mine (SRCM) using various diesel fuel fire sizes at different ventilation airflow velocities to evaluate the responses of CO sensors, smoke sensors, and a flame sensor for early fire detection in a diesel fuel storage area. A novel approach was used in this study to make comprehensive comparisons of sensor response between CO sensors and smoke sensors, between CO sensors and a flame sensor, and between CO sensors and a fire suppression system detector for the early detection of diesel fuel fires. To authors’ knowledge, no such research has been done before. The results of this study provide unique and practical solutions on optimizing fire detection systems for the diesel fuel storage areas.

These results are not available before and can greatly improve the effectiveness of fire detection systems to ensure the safety of workers.

2. Experimental

A diesel fuel fire test chamber simulating a diesel fuel storage area was constructed in the SRCM. The test chamber was located in a crosscut in the mine with dimensions of 153 in long, 87 in wide, and 70 in high, as shown in Fig. 1. A regulator with dimensions of 24 in by 24 in was located in the rear of the chamber with a door in the front of the chamber. Four CO sensors and two smoke sensors were installed under the roof of the chamber along the centerline parallel to the regulator. One flame detector was installed on the roof near the front door per manufacturer instructions.

Diesel fuel pool fires were used as the fire source and were located on the floor of the chamber, as shown in Fig. 2. Two round fire pans with diameters of 6 in and 4 in were utilized to generate a large fire and a small fire, respectively.

Before each test, all CO sensors were calibrated using standard calibration gas, and the smoke sensors and flame sensor were calibrated based on the manufacturers' recommendations. The airflow rate was adjusted using brattices and a desired air velocity was achieved at the regulator. During each test, diesel fuel in the fire pan was ignited using a propane torch, and the signal outputs from all sensors and airflow velocities at the regulator were collected using a data acquisition system. The duration of diesel fuel burning was also recorded to estimate the heat release rate of the fire. In the tests, the diesel fuel fire was placed at three locations—the center of the chamber, two feet from the front door, and two feet from the regulator—to examine the effect of the fire location on the sensor responses. In each location, the fire pan was placed along the centerline perpendicular to the regulator. To determine the appropriate placement of CO sensors, ten fire tests were conducted with only one CO sensor installed at different locations as detailed in the Results and Discussion.

The sensors tested in this study were four CO sensors from different manufacturers: Rel-Tek, AMR, Conspec, Pyott-Boone (designated as PB); two smoke sensors—Conspec and Rel-Tek; and one flame sensor—Honeywell. All CO sensors have their alarm levels set at 10 ppm. The Conspec smoke sensor has on/off alarm at a preset smoke density level, while the Rel-Tek smoke sensor responds to optical obscuration of air due to smoke particles with a linear output over the 0%–10% optical density range. The alarm was set at 1% per meter obscuration level. The Honeywell flame sensor is the multi-spectrum triple infrared fire and flame detector and has the fire detection performance combined with optimal false alarm rejection. All the CO sensors and smoke sensors are approved by the Mine Safety and Health Administration (MSHA) for use in underground coal mines, while the flame sensor is not MSHA-approved.

3. Results and discussion

A total of 27 tests were conducted to examine the responses of different sensors to the diesel fuel fires. Because the focus of this study is on early fire detection, during which time the heat release rate of the fire is usually small, the diesel fires generated from two fire pans proved to be sufficient for the sensor response tests. Fig. 3 shows the typical responses of CO sensors to both large and small diesel fires. For the large fire, the Rel-Tek and PB CO sensors had a maximum CO reading of 60 ppm, and the maximum CO readings for the AMR and Conspec were over 80 and 90 ppm, respectively. Because a 10-ppm CO concentration is commonly used as the threshold value for alarming in mine fire detection systems, this value was used as the criterion for determining the sensor response time.

The Rel-Tek sensor had the longest response time and the AMR sensor the shortest. For the small diesel fire, all CO sensors had much lower maximum readings compared to the large fire. However, the time order of responses for the CO sensors was the same for both fires, indicating that the CO sensors exhibited a similar response pattern for the different fire sizes.

3.1 Effect of airflow velocity on CO sensor responses

Fresh ventilation airflow is required by federal regulations to ventilate the diesel fuel storage area. However, the presence of this airflow can affect the response of fire detection sensors. Therefore, in this study, tests were conducted to evaluate the sensor responses at different ventilation air velocities at the regulator.

Fig. 4 shows the sensor responses with different airflow velocities using the Conspec CO sensor for the large diesel fuel fire. As the air velocity increased from 125 feet per minute (fpm) to 240 fpm, then to 400 fpm, the maximum CO value and the time to reach the maximum value both decreased significantly, and the time to clear the CO also reduced. The sensor response times at 10 ppm decreased from 126 s (at 125 fpm) to 121 s (at 240 fpm) to 112 s (at 400 fpm), indicating a decrease of 14 s in response time with an increase of 275 fpm in airflow velocity.

3.2 Effect of fire location on CO sensor responses

Tests were conducted to examine the effect of fire location on the CO sensor responses. The diesel fuel fire was positioned at three locations—center; two feet from the regulator; two feet from the front wall—along the centerline perpendicular to the regulator. As shown in Fig. 5 with the Conspec CO sensor, the center location resulted in the shortest response time (91 s), while the location two feet from the regulator had the longest response time (126 s). Because the sensor was installed under the roof at the centerline, with the fire located two feet from the regulator, the smoke first rose to the roof and spread against the ventilation towards the center to reach the CO sensor, resulting in the longest response time and the lowest maximum CO reading.

3.3. Effect of heat release rate of fire

The heat release rate of the fire played a major role in the sensor response. In this study, the heat release rate of each fire was estimated using the amount of diesel fuel burnt and the duration of the burning. In addition to the small and large fires in 4 in and 6 in diameter pans, tests were also conducted using a round pan of 8 in and a square pan of 2 ft by 2 ft. Fig. 6 shows the readings for the Conspec CO sensor responding to the diesel fuel fires with different heat release rates. For the small and large diesel fires, the estimated heat release rate was 4.5 kW and 15 kW, respectively, while the heat release rate was 25 kW and 182 kW, respectively, for the 8-in pan fire and 2-ft by 2-ft pan fire. For the tests with the heat release rates of 25 kW and 182 kW, the CO sensors became saturated quickly. With the heat release rate of 4.5 kW, the CO reading increased to 10 ppm in 115 s, while it took only 25 s for the CO reading to reach 10 ppm with the heat release rate of 182 kW, indicating the significant effect of the heat release rate on the CO sensor response.

3.4. Optimum CO sensor location

In practice, it is important to install sensors in an appropriate location so that a rapid detection of a fire can be achieved. In this study, additional tests were conducted to investigate the optimum sensor location for the CO sensors. Five possible sensor locations were examined in the tests: location #1: center; location #2: one ft from the front wall; location #3: one ft from the rear wall; location #4: outside of the chamber and 3 ft from the regulator; location #5: center and 2 feet below the roof. Except for locations #4 and #5, the sensor was installed immediately below the roof.

Fig. 7 shows readings for the Conspec CO sensor at five locations with the small diesel fuel fire located at the center. With this fire, sensor readings at locations #3 and #4 never reached 10 ppm. The sensor at location #1 had a response time of 102 s, while those at locations #2 and #5 had response times of 199 s and 325 s, respectively.

The same tests were also conducted with the large diesel fire located at the center. Fig. 8 shows the readings for the Conspec CO sensor at the five locations. The test results were consistent with those from the small diesel fire. Sensor location #1 produced the shortest response time (62 s), followed by longer response times at location #2 (91 s) and location #5 (102 s). Locations #3 and #4 produced the longest response times—114 s and 113s, respectively.

Notably, location #2 produced shorter response time than locations #3, #4, and #5. It was observed that CO sensors in some coal mines are installed at locations corresponding to locations #3 and #5. Test results in this study indicate that the optimum CO sensor locations are at the center or at the front side of the storage area.

3.5. Comparison between CO sensors and smoke sensors

CO sensors are often installed in underground diesel fuel storage areas for the purpose of early fire detection. However, in practice, CO sensors may not produce the shortest response time for diesel fuel fires. Therefore, in this study, two smoke sensors (Conspec and Rel-Tek) were also examined in the diesel fuel fire tests.

The Conspec smoke sensor does not record the real value of smoke density—instead its output value changes from 0 to 1 when the smoke density reaches a preset point. The Rel-Tek smoke sensor registers the percentile between 0% and 10% obscuration caused by smoke. Because the 1% value was arbitrarily used as the threshold value for determining the sensor response time for the Rel-Tek smoke sensors, the sensor response results from these sensors are not discussed in the paper.

Fig. 9 shows the comparison between response times of the Conspec smoke sensor and the four CO sensors. The solid line indicates the equal response time values between the smoke sensor and CO sensors. In most diesel fire tests, the smoke sensor had a shorter response time compared to the CO sensors. Out of 100 data points, only 11 points are below the solid line, indicating that the smoke sensor performed better in 89% of tests. It should be noted that for those 11 points below the solid line, they were all from the large fire tests with the response time at or below 65 s. For the small fire tests with the response time above the 65 s, the smoke sensor always resulted in the shorter response times.

3.6. Comparison between CO sensors and flame sensor

Because the diesel fuel fire is a flaming fire, a Honeywell flame sensor was also used in the fire tests in this study. Fig. 10 shows the repose times for the flame sensor, the Conspec smoke sensor, and four CO sensors with the large fire located at three different locations. The flame sensor always resulted in the shortest response time, and the performance was not affected by the fire location. The flame sensor response time was 13 s, while the maximum response times for the CO sensor and the smoke sensor were 148 s and 43 s, respectively.

For the small fire tests, the average response times for the different sensors are shown in Fig. 11. The flame sensor again produced the shortest response times, and the performance was not affected by the fire location. The flame sensor response time was 13 s, while the maximum response times for the CO sensor and the smoke sensor were 770 s and 126 s, respectively. For both large and small fires, the CO sensors and the smoke sensor were significantly affected by the fire location.

It can be seen that the small fire located at the front position was the most difficult one to detect for the CO sensors. It took over 11 min for the Conspec and PB CO sensors to detect the fire, and over 2 min for the Conspec smoke sensor to detect it. However, it only took 13 s for the flame sensor to detect the fire. In this study, the flame sensor demonstrates a clear advantage over the CO sensors and smoke sensor in the early fire detection. This flame sensor, however, is not approved by MSHA for using in underground mines.

3.7. Comparison between CO sensors and fire suppression system detector

As required by federal regulations, an underground diesel fuel storage area is usually equipped with an automatic fire suppression system. The fire suppression system is often actuated by a thermal detector. One of the commonly installed fire suppression systems has an activation temperature of 356 °F (180 °C) for a linear thermal detector. In this study, an effort was made to compare the CO sensor response times with the thermal detector actuation time for the fire suppression time. In the tests, thermocouples were placed near the CO sensors to measure the gas temperatures. For the tests reported above for both the small and large diesel fuel fires and the 8-in pan diesel fire, the heat release rates were below 50 kW and the measured gas temperatures were always below 100 °C. Only the test using the 2-ft by 2-ft square pan with the heat release rate of 182 kW registered the gas temperature over 200 °C, as shown in Fig. 12.

The gas temperature measurements from two smaller fires—22.2kW and 31.6 kW—were also plotted in Fig. 12 as a comparison. In the fire test with the heat release rate of 182 kW, the gas temperature increased quickly and reached 180 °C in 109 s. The response time was 14 s on average for the CO sensors, 7 s for the smoke sensor, and 4 s for the flame sensor. These test results indicate that even for a much larger diesel fuel fire, the smoke and CO sensors detect the fire in a shorter amount of time.

4. Conclusions

This work is part of NIOSH’s continual efforts to develop workplace solutions for detection of hazardous conditions in underground mining operations. In this study, experiments were conducted in the fire test chamber in the NIOSH Safety Research Coal Mine, Bruceton, PA, to study the responses of different fire sensors for the early detection of fire in an underground diesel fuel storage area. Four CO sensors, two smoke sensors, and one flame sensor were examined in the tests using different-sized diesel fuel fires. The test results demonstrate that:

(1) The smoke sensor responded in a shorter time compared to the CO sensors in 89% of all tests. The smoke sensors always had shorter response times for the small fires (around 4.5 kW) in this study.

(2) The flame sensor produced the shortest response times in all tests compared to the CO sensors and the smoke sensors. The flame sensor performance was not affected by the fire location.

(3) For a larger diesel fire with the heat release rate of 181 kW, the CO sensors, smoke sensors, and flame sensor all detect the fire in shorter times than the thermal detector used for actuation of the fire suppression system.

(4) The appropriate locations for the CO sensors were the center and the front locations of the chamber. The rear location, the location far below the roof, and the outside location all produced longer response times.

(5) The airflow velocity had an insignificant effect on the CO sensor response except for reducing the maximum CO readings.

(6) The fire location and the heat release rate of the fire affected the responses of the CO sensors and the smoke sensors.

Although the focus of this study was on the early fire detection for underground diesel fuel storage areas in the mining industry, the results of this study are also relevant to any other industries involving diesel fuel storage and transportation.

Acknowledgement

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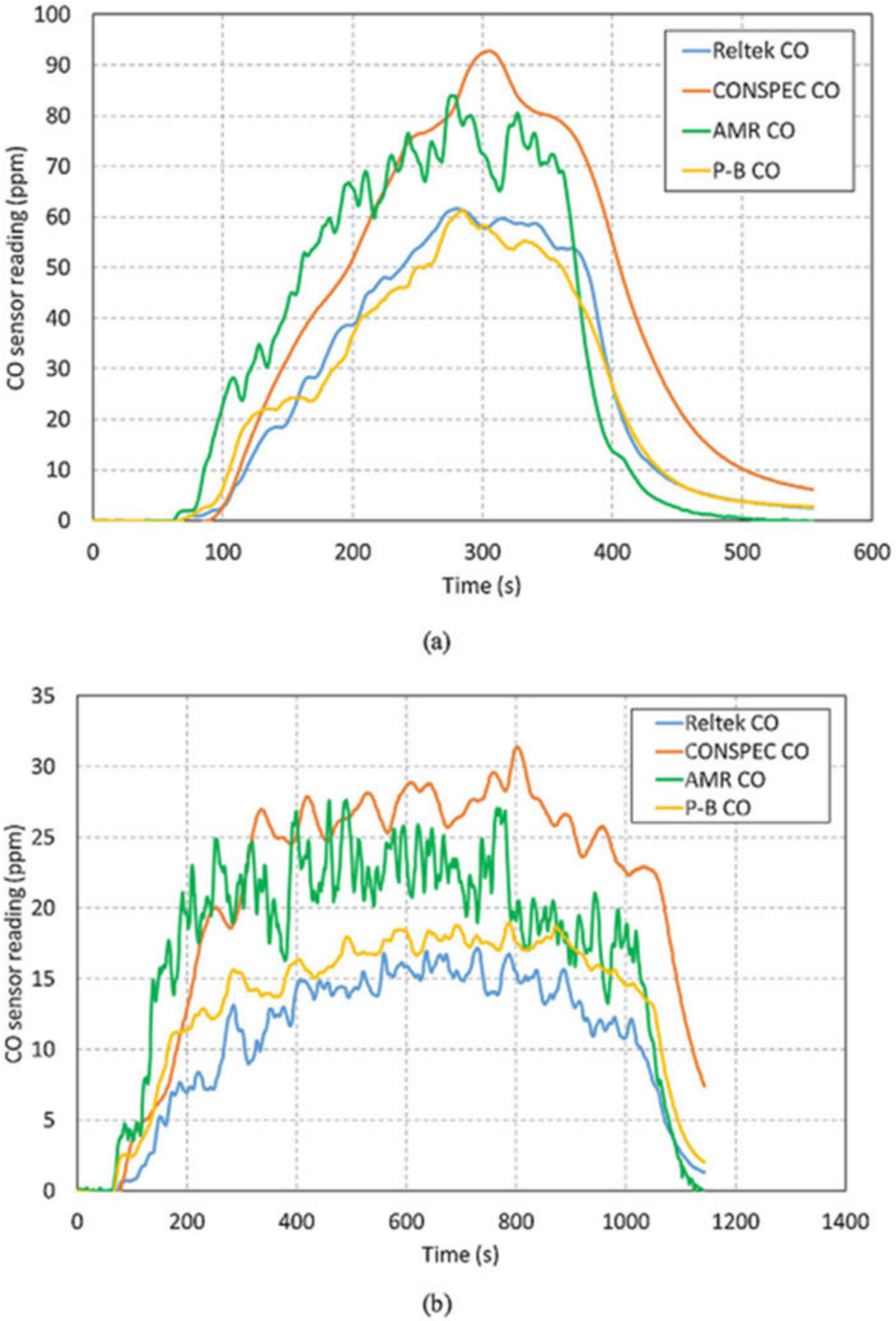
Fig. 1.

Fire test chamber in the NIOSH Safety Research Coal Mine.

Fig. 2.

Diesel fuel fire test setup.



(a)

(b)

Fig. 3.

Typical CO sensor responses. (a) large fire; (b) small fire.

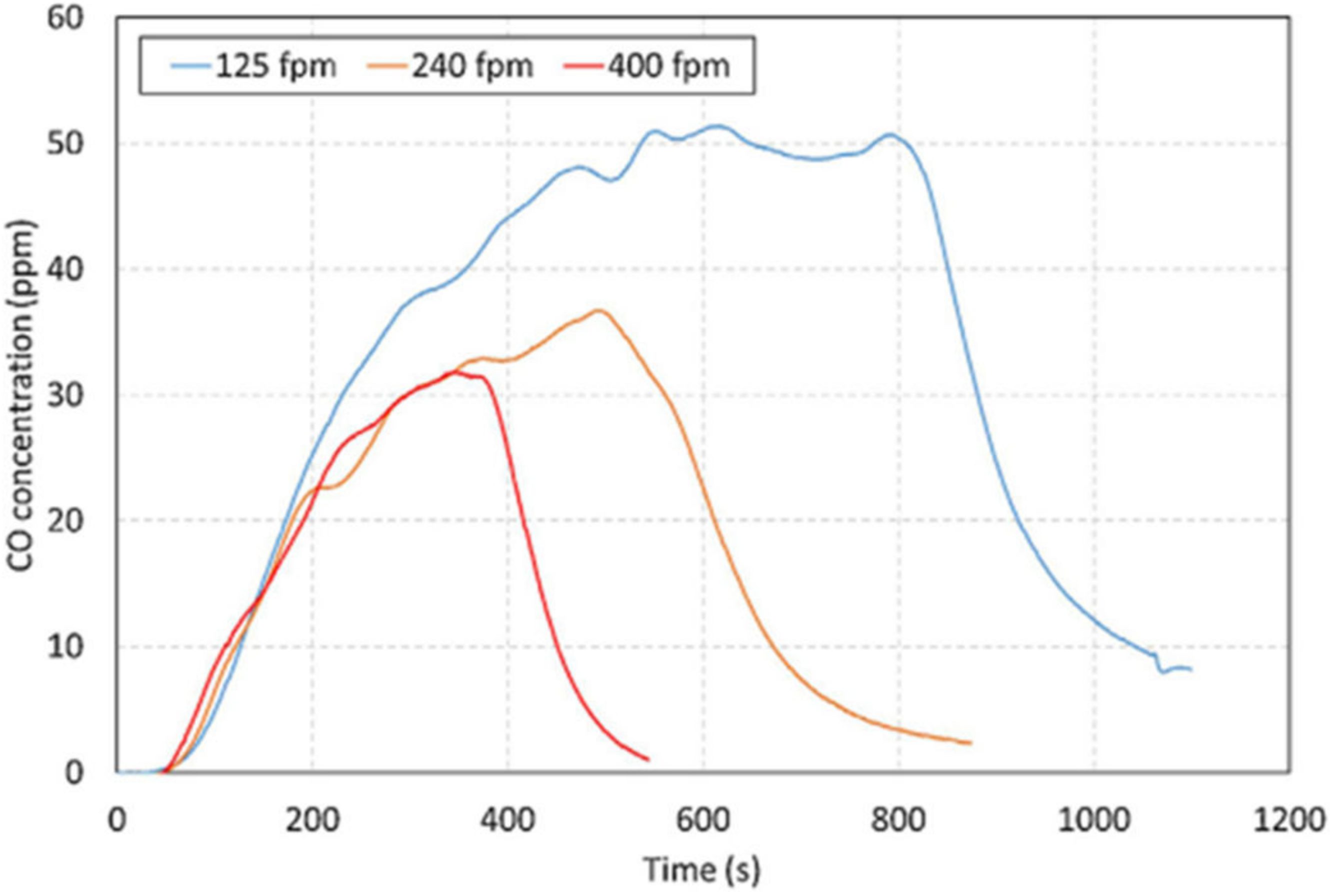


Fig. 4.
CO concentrations with different airflow velocities.

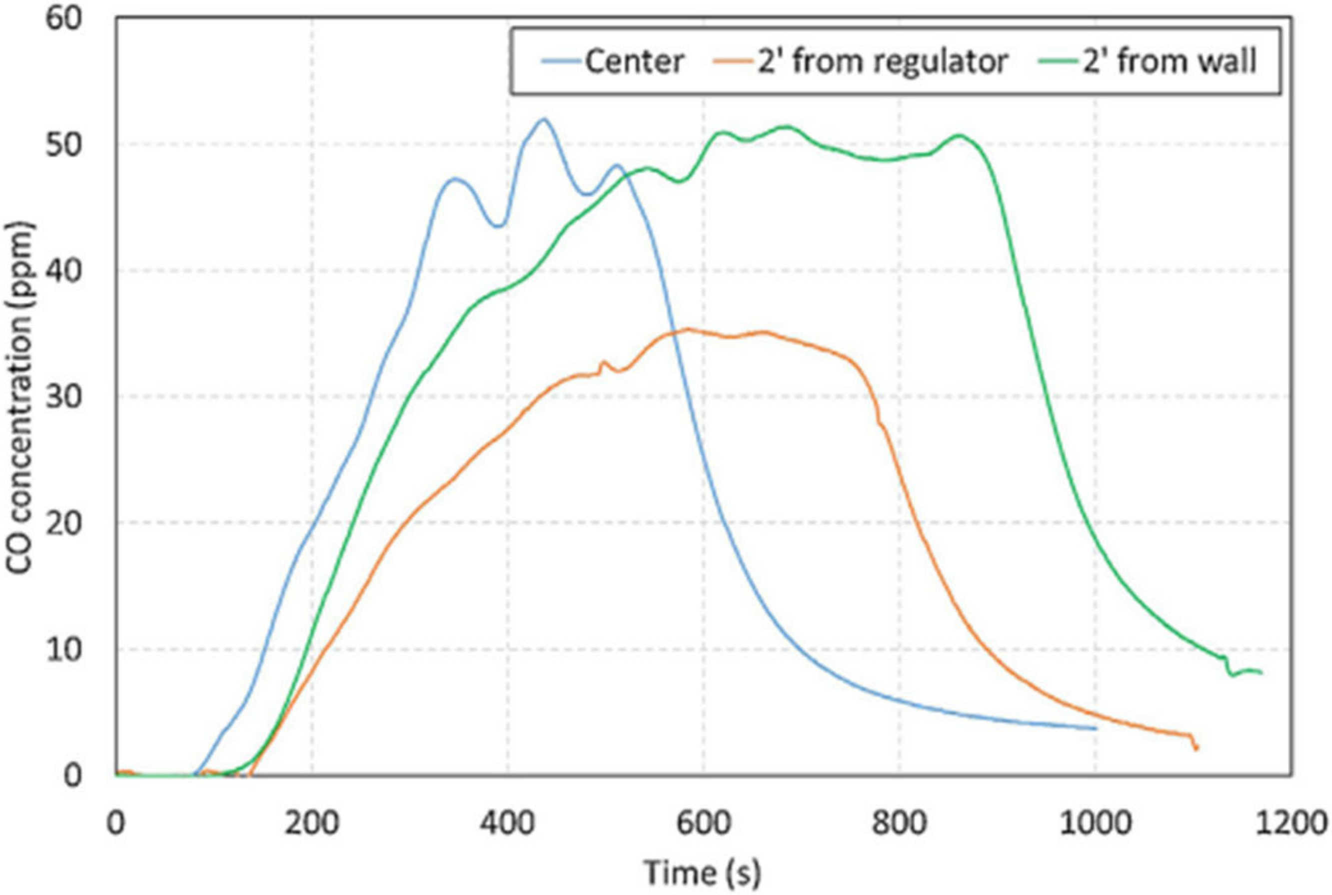


Fig. 5.
CO concentrations with different fire locations.

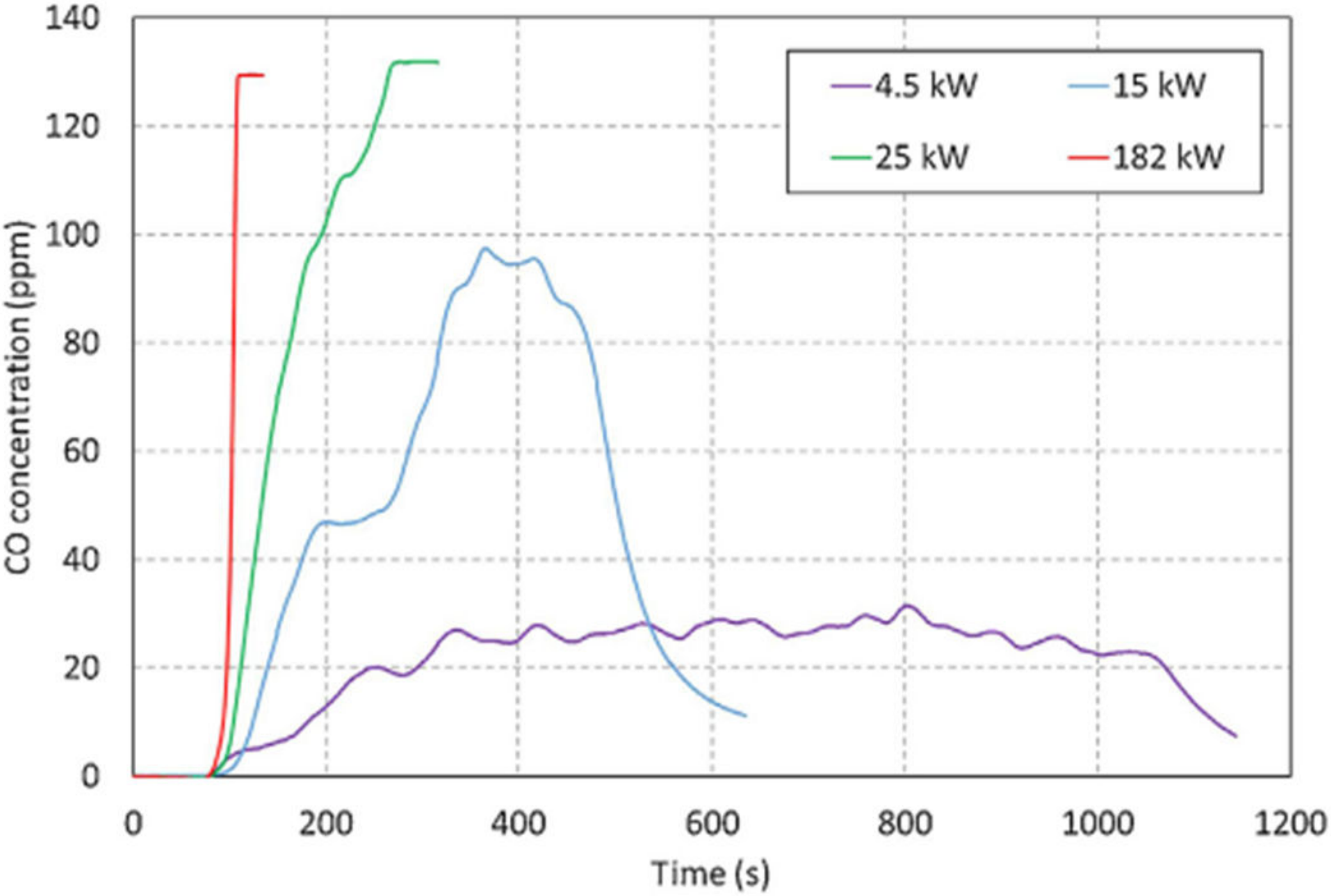


Fig. 6.
CO concentrations with different heat release rates.

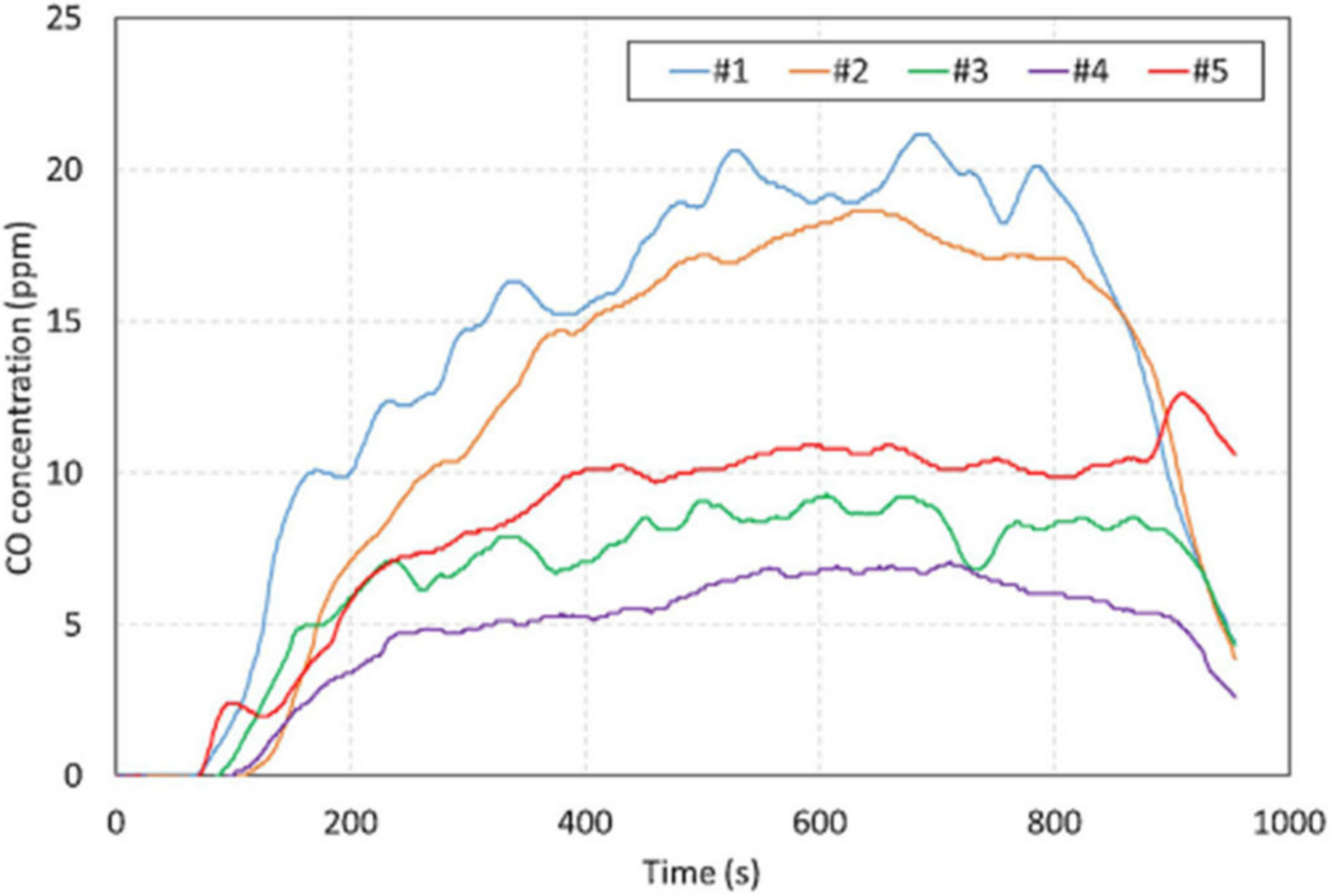


Fig. 7.

CO concentrations at different sensor locations: small diesel fire.

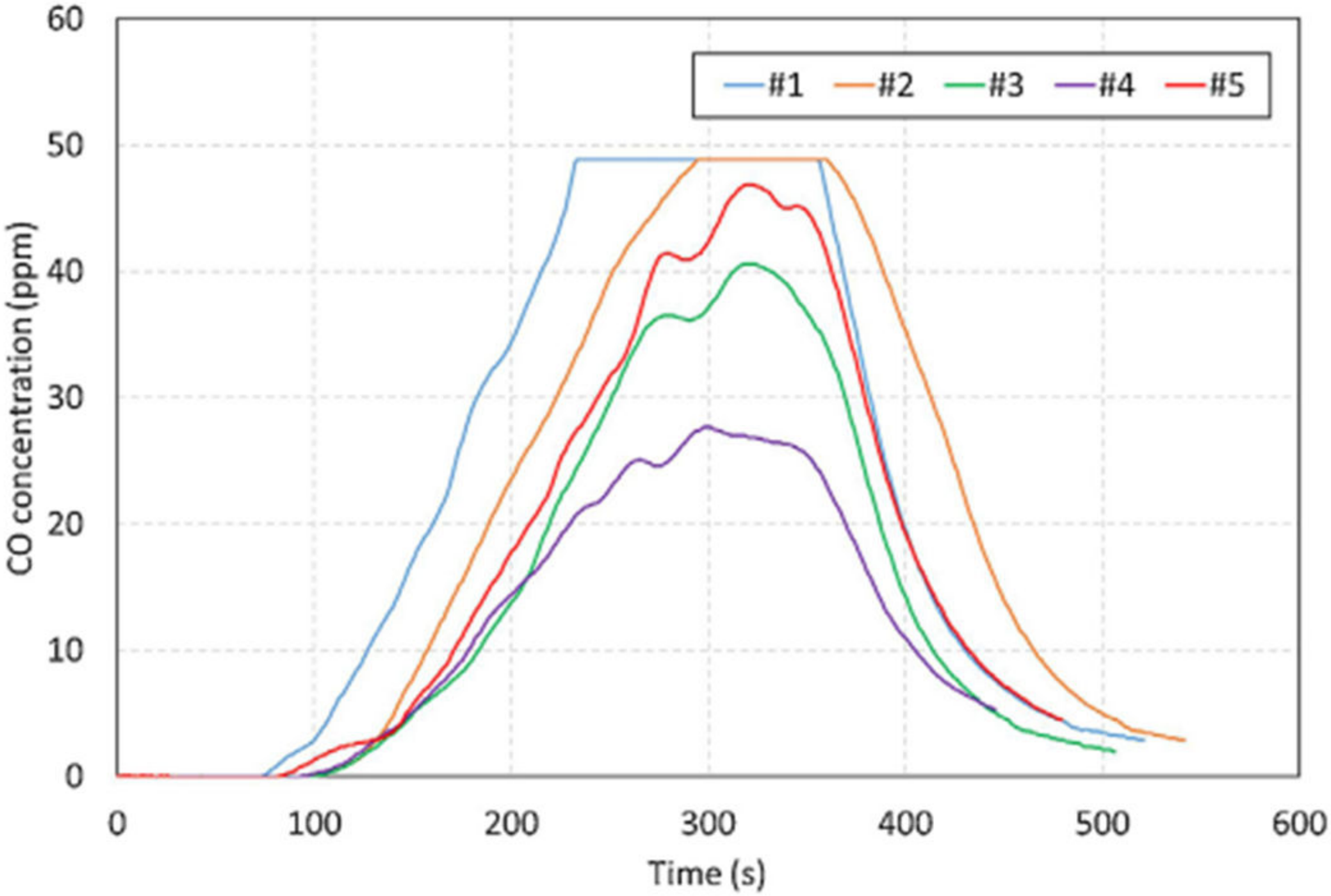


Fig. 8.

CO concentrations at different sensor locations: large diesel fire.

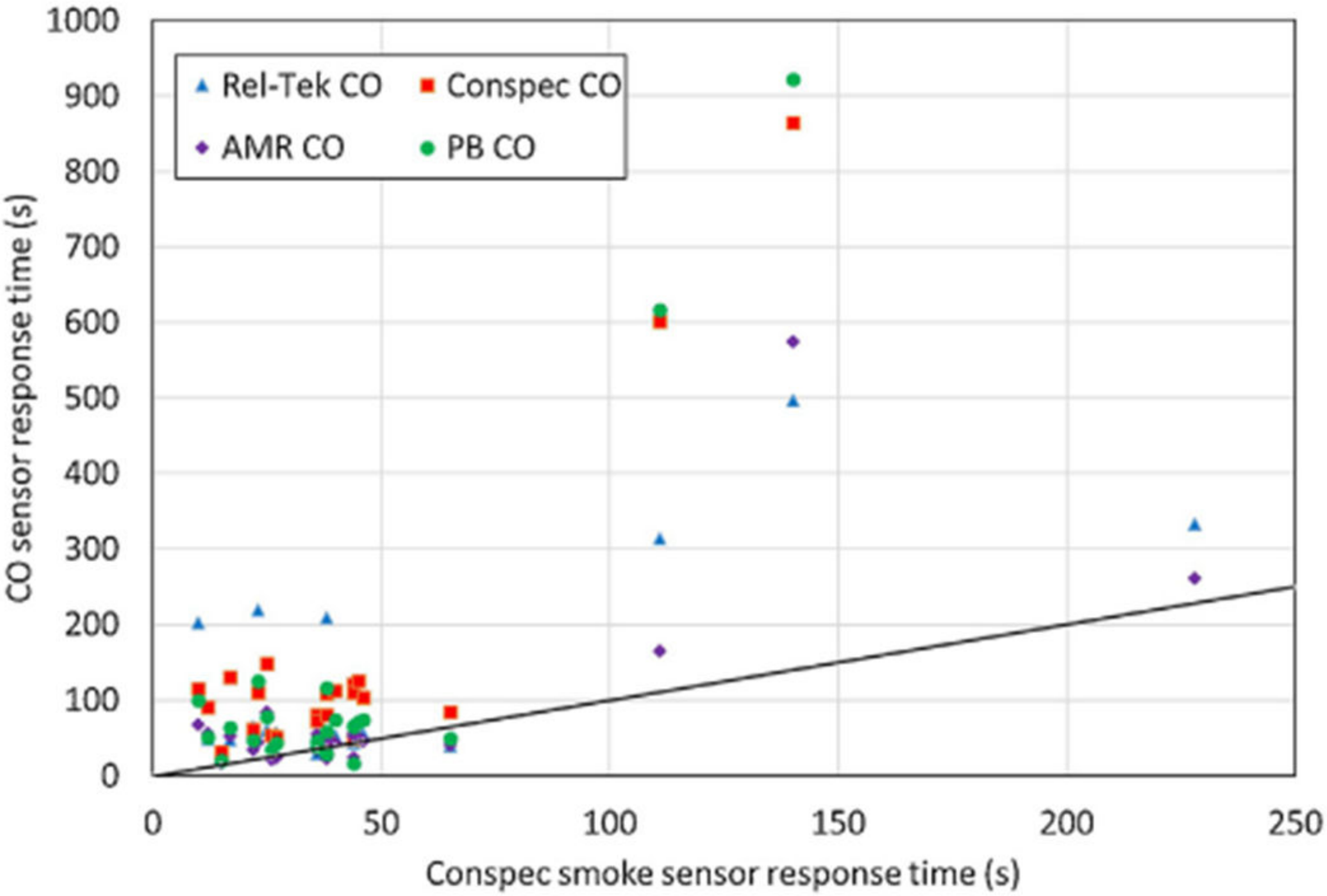


Fig. 9.

Sensor response time comparison between CO sensors and smoke sensor.

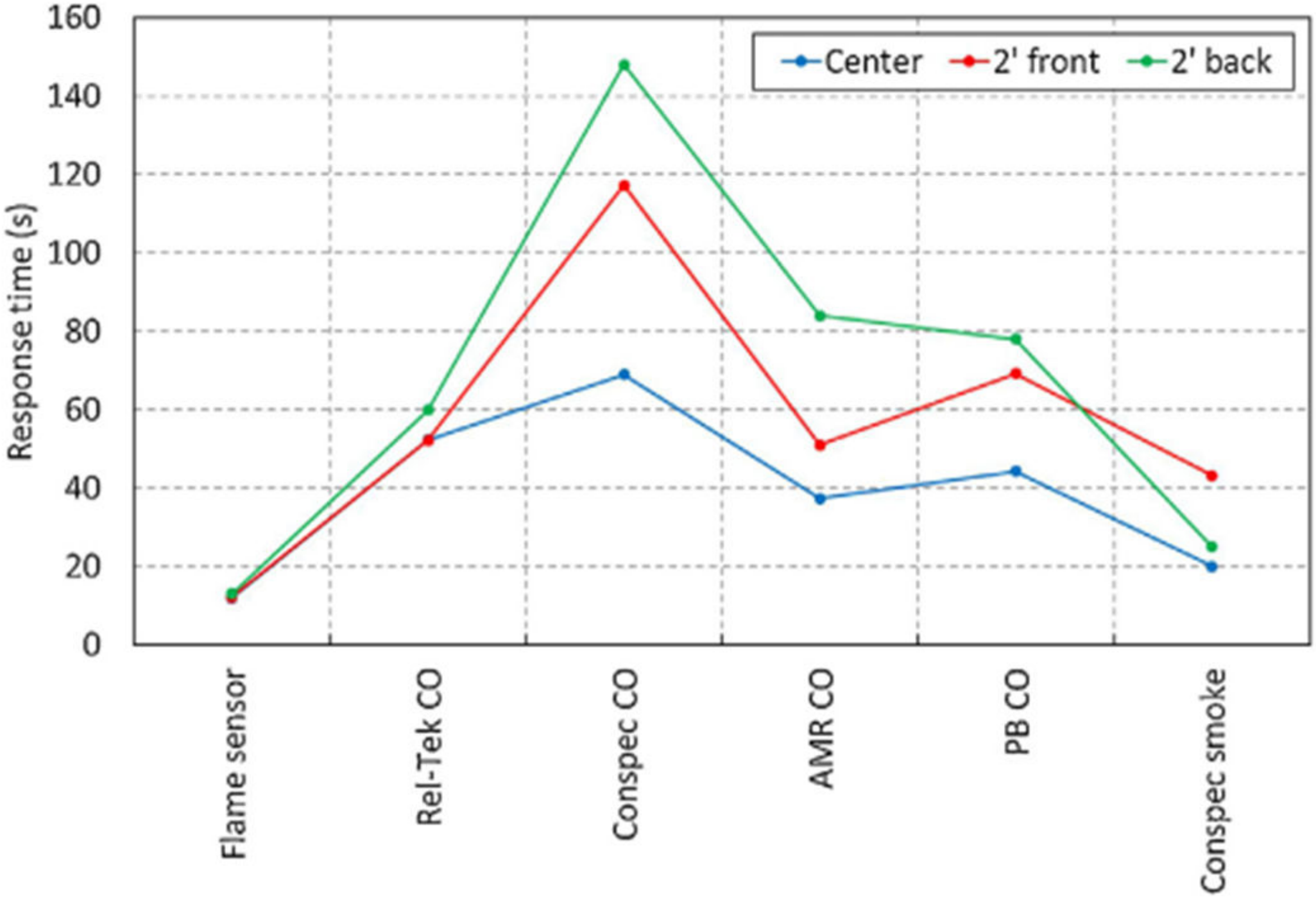


Fig. 10.

Sensor response time comparison between CO, smoke, and flame sensors: small diesel fire.

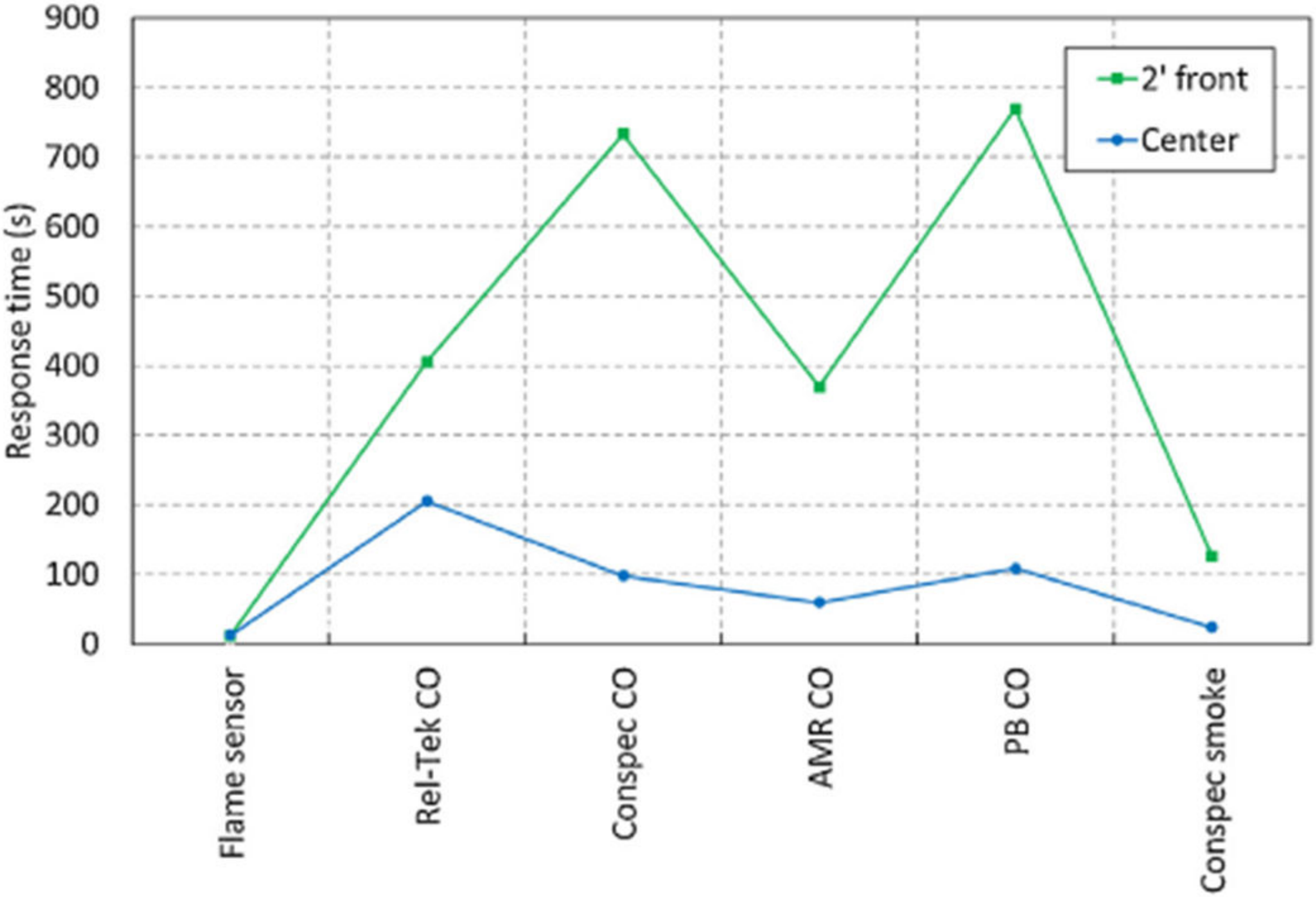


Fig. 11.

Sensor response time comparison between CO, smoke, and flame sensors: large diesel fire.

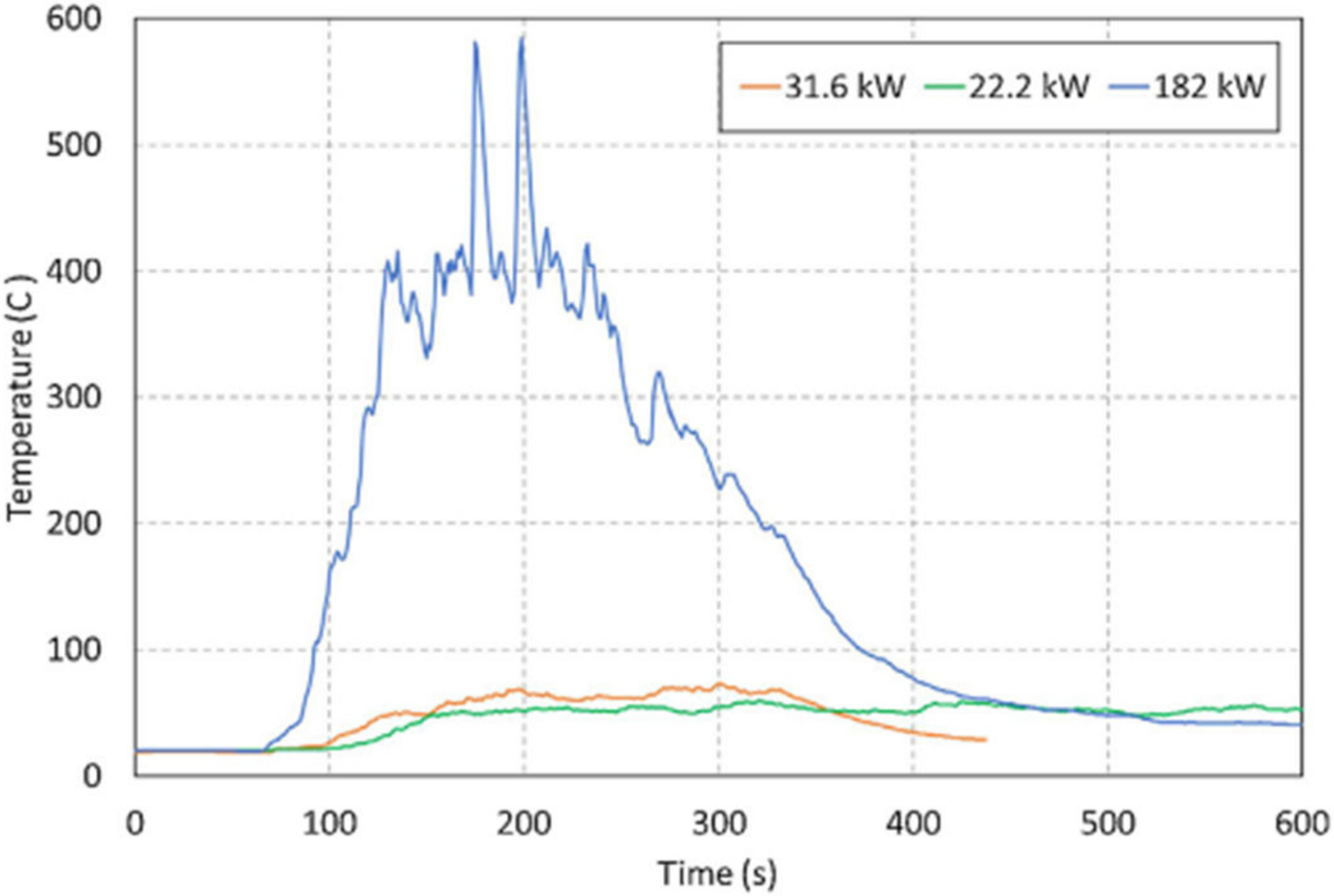


Fig. 12.

Gas temperatures with different heat release rates.