

Video Image Detection and Optical Flame Detection for Industrial Applications

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Abstract

In order to provide a technical basis for the selection and use of flame detectors in challenging industrial applications, an experimental study was conducted. Multiple flame detectors were tested in numerous scenarios representative of those expected in industrial applications. The study systematically evaluated the fire detection performance of flame detectors at different distances from fires and with different detector viewing angles relative to fuel type, a range of obstructions and exposure to nuisance/interference sources. Flame detection technologies included multi-spectrum IR, UV, and video imaged detection. The paper details the tests conducted and presents comparative results for the different technologies while pointing out potential application issues.

1.0 Introduction

Industrial applications pose challenging environments for fire protection systems. In many of these occupancies, flame detection is used to provide fast response to growing fires [1] and activation of suppression and safety shut-down systems. Video image flame detectors represent a relatively new technology that has been gaining popularity and use in industrial applications [2–5]. However to date, there have not been any systematic studies evaluating the performance capabilities of traditional optical flame detectors and video image detection (VID) systems. In order to provide a technical basis for the selection and use of flame detectors in challenging industrial applications, an experimental study was conducted. Multiple flame detectors were tested in numerous scenarios representative of those expected in industrial applications. The study systematically evaluated the fire detection performance of devices at different distances from fires and with different detector viewing angles relative to fuel type, a range of obstructions and exposure to nuisance/interference sources.

2.0 Approach

The general approach for this study was to conduct real-scale tests that exposed a set of detectors to a range of fire and nuisance source scenarios. In order to best tailor the test series to an industrial application, the test conditions were designed to encompass specific attributes commonly found in these occupancies. This included use of representative fuels from facilities, various fire scenarios, potential viewing distances, obstructions, and backgrounds. The fire sources were designed to be representative of realistic hazards and included both small fires and immediate exposure of larger fire events to test the limits of detection.

The viewing distance and fire size are the key factors in determining detector sensitivity. This series of tests consisted of detection system evaluations at distances of 7.6 m (25 ft) and 15.2 m (50 ft) between the fire and detectors. Besides distance and fire size, detection performance is also dependent on the presence of obstructions. There can be a significant number of optical obstructions in an industrial application. Large mechanical equipment, piping, or catwalk grating can block considerable portions a fire within the field of view (FOV) of a flame detector. This test series aimed to replicate a number of obstruction scenarios. For an OFD detecting the radiative flux from a fire, obstructions act to reduce the view factor between the detector and the flame and will result in a reduction in the perceived flame intensity. For VID systems, the detection of flames is often based upon the geometry of a typical pattern or

structure in the FOV. Obstructions may significantly alter the apparent shape and size of fires and may reduce the ability of the algorithm to identify flames. In addition to obstructions, flame impingement can also alter the appearance of the flame. This is not an area that had been researched, and thus, various impingement scenarios were considered in this analysis. Since some VID algorithms incorporate routines to deal with ambient lighting conditions, testing was performed in a uniform indoor environment with primarily artificial lighting as is typical to many industrial applications (i.e., limited or no outside light).

The viewing angle of a fire with respect to the detector can significantly affect detection sensitivity, particularly for OFDs. Off-axis viewing of a fire can result in a reduction in the ability to alarm for these systems. OFDs use interference filters to isolate the spectral bands of interest for flame detection. When radiation enters from an angle off from the normal axis, it increases the path length through the filters and can result in a filtered wavelength “blue” shift of up to 6% for 45° angles. For narrow band width detectors, such as those specifically centered at the CO₂ band at 4.4 μm, this can result in a complete failure to detect a flame. The shift from off-axis viewing should not be as significant for wide band or VID systems. The FOV of a detector is important for installation, and thus the ability of all detectors to detect off-axis flames was tested.

In addition to the sensitivity of flame detection, performance testing determined the capacity of the detectors to ignore false alarm and nuisance sources. This included both the avoidance of alarms in the presence of potential sources and the continued ability of the detectors to identify fires while such sources were present.

3.0 Detection Technologies

The primary focus of this study was to evaluate the performance capabilities of triple wave band infrared and video image detection (VID) technologies for flame detection. In addition, a UV flame detector was also included to compare an alternative older technology that is still in use today at some facilities.

3.1 Multi-spectral Infrared

Multi-spectrum technology measures radiant energy in multiple unique IR wave bands simultaneously. The ratios of the energy in the three measurement bands are used to make determinations about flaming fire events. This technology takes advantage of the fact that fires emit spectral radiation in an identifiable profile. For example, burning of hydrocarbon fuel produces CO₂ which has a strong emission of radiation at 4.4 μm. Extremely strong radiation detected at this wavelength compared to other reference wavelengths may indicate the presence of a fire. An additional criterion for fire events is measured in the transient flicker of the incoming radiation. It is known that flames flicker at a frequency of 1–10 Hz. Detection of this type of oscillation may indicate the presence of a fire. The multi-spectrum IR detection algorithms uniquely combine the spectral and temporal profiles of incoming radiation and make a determination about the presence of a fire.

3.2 Video Image Detection

VID fire technologies perform data analysis on real time video images to resolve the presence of a fire [3]. This image is usually recorded in the visible or near IR region of the spectrum and is processed by proprietary software to determine if smoke or flame from a fire is identified in the video. Some systems detect both smoke and flame and some detect just one or the other. The detection algorithms use different techniques to identify the flame and smoke characteristics and can be based on spectral, spatial or temporal properties; these include assessing changes in brightness, contrast, edge content, motion, dynamic frequencies, and pattern and color matching.

3.3 Detection Systems

In addition to comparing the detection performance of several “state of the art” devices, this test series also included several other devices currently employed in protection of industrial facilities. This test series included three triple IR flame detectors, an older UV detection device, and both an older and newly released VID detection system. This allowed for the direct comparison of newer product alternatives to the devices currently installed in existing facilities. Table 1 displays the detectors used in this test series. The devices have reported specifications of being able to alarm to a 0.3 x 0.3 m (1 x 1 ft) n-heptane pan fire within 5 seconds at distances ranging from 15 m (50 ft) to 61 m (200 ft).

Table 1. Detectors Tested.

ID	Type
OFD-A	Multi-spectrum IR
OFD-B	Multi-spectrum IR
OFD-C	Multi-spectrum IR
OFD-UV	UV
VID-A	VID (older model)
VID-B	VID (new model)

4.0 Test Setup and Procedures

4.1 Test Facility

This test series was conducted in the Baltimore laboratory of Hughes Associates, Inc. (HAI). The tests were conducted for detector-to-fire distances of 7.6 m (25 ft) and 15.2 m (50 ft) within a semi-conditioned warehouse space. The facility was configured with artificial light, and although natural light could be introduced via skylights, the majority of fire tests were conducted at night. The backdrop of the fires consisted of two 1.2 x 2.4 m (4 x 8 ft) drywall panels mounted vertically and painted with a gray semi-gloss paint (Behr Premium Plus Interior 70F-4 Pastel Base). The background was placed 2.1 m (7 ft) behind the standard fire source location under the exhaust hood. Tests were conducted both with and without this background in place in order to determine its effect upon detection performance. This painted background was used for

the majority of tests so that the detectors had a uniform backdrop regardless of position relative to the fire. The selection of the color was to be representative of backgrounds found in many facilities with metal structures and was purposely not to be a highly contrasting background to the obstructions used. The results without the uniform background showed no significant effect of the background on the performance of any of the spectral-based flame detectors. However, the results were mixed for the VID devices. The largest effect of the background on the VID devices was with the lube oil spray fires (described below) for which no VID device produced alarms.

4.2 Detector Mounting Scenarios

In order to complete the full range of test scenarios simultaneously, the detectors were mounted in several different configurations. The configurations included various viewing distances, angles, and orientations with respect to the fires. Flame detectors were mounted to two test rigs. The detectors were centrally located about the center point of the test rig, placed at a height of 3 m (10 ft) above the floor. Each test rig had two of each detector model mounted to the front surface, one directed at the flame and one directed for off-axis viewing. An overhead view of these two viewing angles is shown in Figure 1. The detectors were mounted in three rows of four detectors, with 0.3 m (1 ft) between detectors in each direction.

The detectors were vertically aligned to provide line of sight viewing to a point 0.9 m (3 ft) above the floor at the flame source location, shown in Figure 2 for a generic distance and angle. All detectors were aligned according to manufacturers' specifications. The optical flame detectors were aligned using laser alignment tools and the VID detectors were aligned using a video screen monitor of the video signal. The off-axis detectors were aligned at the same height, but were angled at 45° to the left of the horizontal line of sight so that the fire source was just within the detector FOV. Upon inspection of the video screen monitors of the VID devices, it was determined that 45° was too great an angle and the fire source was not in the FOV. Thus, the angle of these detectors was adjusted slightly such that the fire source was just on the edge of the FOV.

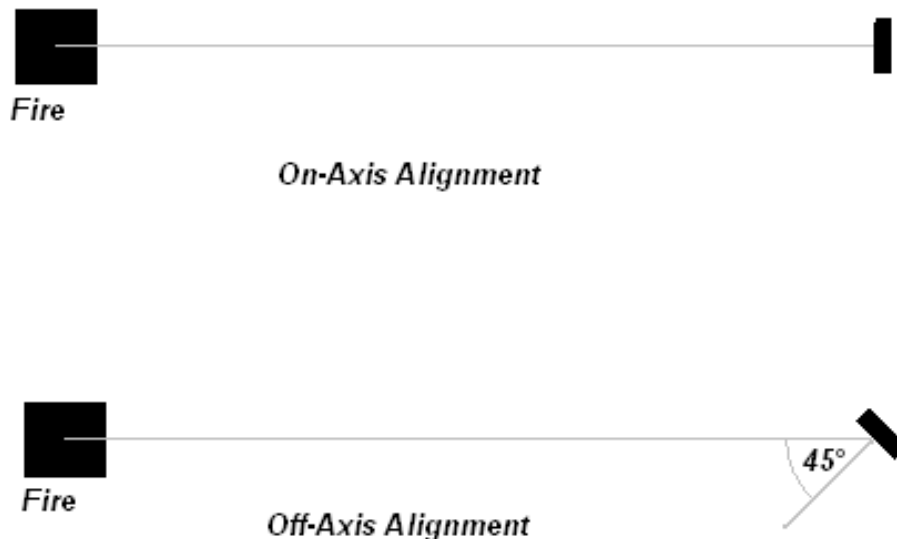


Figure 1. Overhead view of on-axis and off-axis viewing alignment.

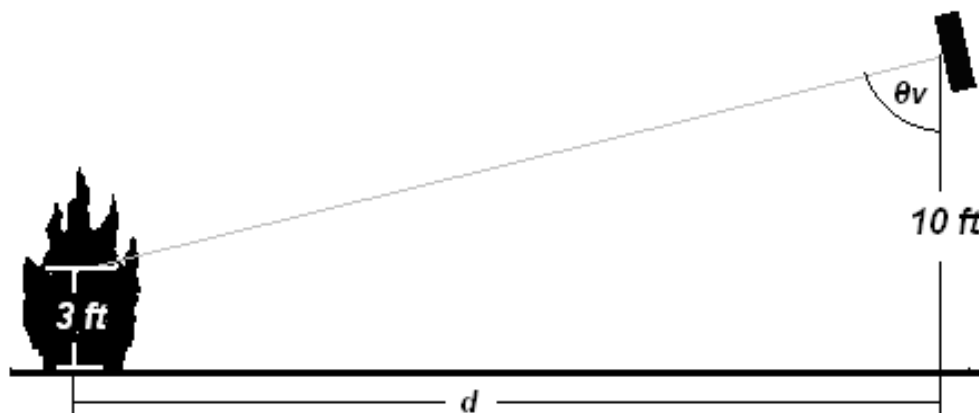


Figure 2. Vertical alignment of flame detectors.

The heat release rates of the fires were measured by conducting the fires under a hood calorimeter. The hood was calibrated and had a general uncertainty in heat release rate of less than 5%. Heat flux transducers were placed at 1 m (3.3 ft) and 2 m (6.6 ft) from the center of the flame source, at the mid-height of the flame. These measurements were used to characterize the test fires and to relate their potential to damage adjacent equipment or materials. The total heat flux transducers were Schmidt-Boelter type (Medtherm, 64 series) with a detection range of 10 kW/m^2 . The OFD and VID device status (alarm, trouble, etc.) were monitored using 4–20 mA outputs. All instruments were connected to a general data acquisition system (National Instruments hardware interfaced with Labview 8.5 data acquisition software).

4.3 Fire Test Scenarios

Although there are an infinite number of possible fire scenarios that can occur in industrial applications, for the purpose of measuring relative detector sensitivity testing, it is suitable to test both a minimum event of concern that could result in damage and a rapid, large event that may saturate the detectors. A detector capable of producing an acceptable alarm for the smallest identified threat scenario and for a large, instantaneous fire is expected to satisfy the range of anticipated fire scenarios.

The sensitivity of a flame detector is measured by determining the time to alarm for a specific fire size at a given distance. For detection, the size of the fire and the distance are related by an inverse square law. FM 3260 recommends several types of fires for the testing of flame detectors [6]. These include*:

- 0.3 x 0.3 m (12 x 12 in.) n-heptane pan fire ~ 126 kW
- 0.3 x 0.3 m (12 x 12 in.) alcohol pan fire ~ 27 kW
- 127 mm (5 in.) propane flame from a 0.53 mm (0.021 in.) orifice ~ 0.32 kW

*HRR values calculated from empirical data presented by Babrauskas [7]

Consistent with the FM standard, a 0.3 x 0.3 m (12 x 12 in.) fire was deemed as representing the smallest fire size needed for detection performance. Particularly since this test program was a relative comparison of detector performance, the 0.3 x 0.3 m (12 x 12 in.) fire was appropriate. The inclusion of heat flux measurements during testing allowed for the assessment of the potential thermal threat from the test fires.

The spectral flame characteristics are a function of the fuel type and the efficiency of combustion. For this test series, only gaseous and liquid fuels were selected. However, multiple fire types were conducted. In addition to the spectral characteristics of these fires, the form of the fire may potentially impact the performance of VID systems. Many VID systems recognize flames via the temporal changes in flame geometry or the general shape. It was particularly necessary for VID systems to observe free and impinging jets and sprays, as well as pool fires to determine detection limitations for various fire scenarios resulting in different flame shapes. An impinging jet or spray is one where the typical plume flame shape is distorted by contact with a solid surface.

The list of tested scenarios is shown in Table 2. Most fire scenarios were tested in triplicate to demonstrate repeatability. Each pool, spray and jet fire type was tested in an unobstructed and open burning test scenario. The relative performance of each detector was determined for each fire type. Fire types used for further testing (e.g., lube oil spray and natural gas) with nuisances and obstructions were selected because these fires presented the greatest challenge for detection among the open burning scenarios.

4.3.1 Pool Fires

Liquid pool fires consisted of n-heptane, diesel fuel, and lubricant oil burned in a 0.3 x 0.3 x 0.05 m (1 x 1 x 0.167 ft) steel pan to conform to the FM standard pan size. This pan was placed on two 0.057 m (2.25 in.) bricks inside a 0.559 x 0.559 x 0.1 m (1.83 x 1.83 x 0.33 ft) larger metal pan. Both metal pans were constructed from 0.6 cm (1/4 in.) thick steel. For heptane and diesel pool fires, the large pan was filled with tap water to a depth of 8.9 cm (3.5 in.). This water provided a temperature sink to maintain a steady burn rate for the fuel. For lube oil pool fires, no water was used as cooling was not needed since it was a high flashpoint fuel (216°C). For these fires, the pan and fuel were preheated to a temperature of 180°C (347°F) on a 3100 W ceramic heater to facilitate ignition.

The base of the pool fires was located 0.62 m (24.5 in.) above the ground. Pool fires were ignited using a propane torch with an attached shield to prevent the detectors from alarming to the torch flame. The fires were ignited at one corner of the fuel pan and allowed to spread naturally across the fuel surface. Each pool fire was intended to burn for approximately five minutes. The tests consumed 0.95 L (0.25 gal), 0.5 L (0.13 gal), and 0.2 L (0.05 gal) and achieved average heat release rates of 72, 48, and 37 kW for n-heptane, diesel, and lubricant oil, respectively.

Table 2. Matrix of Tested Fire Scenarios and Viewing Conditions.

Viewing Conditions	Fire Scenario												
	No Fire	n-heptane pool	Diesel pool	Lube oil pool	Lube oil spray-vertical	Lube oil spray-perpendicular horizontal	Lube oil spray-parallel horizontal	Natural gas jet-vertical	Natural gas jet-perpendicular horizontal	Natural gas jet-parallel horizontal	Propane gas jet-vertical	Propane-Line Burner	n-heptane-Large Spray
Open burn		x	x	x	x	x	x	x	x	x	x	x	x
Impinged flame		x			x	x		x	x				
Horizontal pipe grid		x		x	x			x			x		
Vertical pipe grid		x			x			x					
50% solid horizontal wall		x			x			x					
50% solid vertical wall		x			x			x					
Oil mist	x							x					
Condensed water	x							x					
Blackbody	x	x			x								
Arc welding	x							x					
Metal grinding	x							x					
Torch cutting	x							x					
Halogen lights	x	x			x			x					
Painted wall background removed		x			x			x					

4.3.2 Gas Fires

Propane (99% pure) was supplied via an evaporator supply system controlled by a Dwyer 95 LPM (200 SCFH) air rotameter (RMC-103-SSV-PSI, S34L). The vertical jet was burned from a 1.2 cm (0.5 in.) SCH40 steel vertical pipe with an opening at a height of 61 cm (24 in.). For these tests, gas flow rate was set to 44 LPM (92.5 SCFHair) through the rotameter. The fires were ignited by a Franceformer Interchangeable Ignition Transformer producing a small 10,000V, 23 mA electric arc placed directly above the open fuel pipe and removed immediately upon ignition.

The second propane test was a much larger flame to test the response of detectors when exposed to larger fires. This test utilized a single line of 1.0 cm (3/8 in.) steel tube supplied from both ends with 0.5 cm (3/16 in.) holes drilled at 1.2 cm (1/2 in.) increments along the 2.3 m (7.5 ft) length of the tube. This design was intended to create a wall of fire intended to represent a large, instantaneous fire that would significantly fill the FOV. The propane flow rate was approximately 260 LPM (550 SCFHair). The fire was ignited by pre-positioning two small cups (~ 2 cm diameter) of n-heptane adjacent to the burner holes drilled in the tube. The fire was measured to be 250 kW and was approximately 1.0–1.5 m (3.3–4.9 ft) high. The burner and supply system were not able to provide as large of a fire as desired. However, as will be discussed in the results, this larger fire still provided a challenge for some detectors. To achieve a fire that more substantially filled the detector FOV, a spray n-heptane fire was used.

Natural gas was via the municipal supply and was controlled using a Dwyer rotameter flowing 75 LPM (158 SCFHair). The gas jet was delivered from a 1.2 cm (0.5 in.) SCH40 steel pipe and measured approximately 40 kW. Natural gas jet fires were burned with the outlet of the pipe at 0.61 m (2 ft) high, oriented in the vertical direction, horizontally perpendicular to the detector line of sight, and horizontally parallel to the detector line of sight. These orientations are shown below in Figure 3.



Figure 3. Vertical, perpendicular horizontal, and parallel horizontal natural gas jet fires.

4.3.3 Spray Fires

The spray fires included a small spray of lubricant oil, designed to roughly match the general average heat release rate (HRR) of other test fires included in this series. Maintaining the same HRR allowed for more direct comparison of the effect of fire form on detector performance, while maintaining the same thermal threat. A large n-heptane spray was also included to provide a large, instantaneous fire that would fill a large fraction of the detector FOV.

The lubricant oil spray was produced with a Bete PJ15 misting nozzle with a k-factor of $0.0843 \text{ lpm}/\text{bar}^{1/2}$ ($0.00585 \text{ GPM}/\text{psi}^{1/2}$) operating at a pressure of 689 kPa (100 psi) to yield a 0.22 lpm (0.059 GPM) flow. Tests were conducted with the nozzle pointing in several directions. This included vertically upwards, horizontally perpendicular to the detector line of sight, and horizontally parallel to the detector line of sight. These orientations are shown in the fire photos in Figure 4.



Figure 4. Photos of pilot light and lubricant oil spray fires (vertical spray, perpendicular horizontal, and parallel horizontal spray from left to right).

The basic test setup for the n-heptane spray fire was the same as for the lubricant oil except the nozzle used was a Bete NF03 80° cone standard fan nozzle. This nozzle had a k-factor of $0.683 \text{ lpm}/\text{bar}^{1/2}$ ($0.0474 \text{ gpm}/\text{psi}^{1/2}$) and produced a flow of 1.85 lpm (0.47 GPM) at 689 kPa (100 psi). This setup produced a much larger flame than the lubricant oil fire. These fires were only ignited in the vertical flame orientation and burned for a duration of one minute. The n-heptane spray fire can be seen below in Figure 5. As can be seen, the flame was approximately the size of one of the 1.2 x 2.4 m (4 x 8 ft) sheets used as a backdrop and reached a peak HRR of approximately 600 kW.



Figure 5. N-heptane spray fire.

Both sprays were ignited using a small propane pilot light (see Fig. 4) placed adjacent to the nozzle with the flame extending into the spray. The 1 cm (3/8 in.) pilot was supplied from the propane system described above. The pilot flame was kept small enough such that no detectors produced an alarm condition during the collection of background data before the spray fire was ignited.

4.4 Obstructions

Various obstructions were placed in the line of sight of the detectors during certain fire tests (see Table 2). Such obstructions included large opaque walls placed in various orientations and a network of piping.

4.4.1 Solid Wall Obstructions

Large portions of the test flames were blocked from the FOV in order to reduce the apparent size and shape of the flames to the detectors. The solid wall was constructed from a piece of 1.2 x 2.4 m (4 x 8 ft) gypsum board painted with flat white paint (Behr Premium Plus Interior Flat Ultra White No. 2-1050). The board was oriented in two arrangements 0.9 m (3 ft) in front of the fire. First, the wall was placed vertically so that it blocked one half of the fire down the vertical center. This obstruction could not be placed such that it blocked one half of the fire simultaneously for the 7.6 m (25 ft) and 15.2 m (50 ft) test rigs. Testing with this obstruction for these two scenarios was conducted as separate tests. The 7.6 m (25 ft) detectors have a completely shielded view of the flames when the 15.2 m (50 ft) detector view was 50% obstructed. The wall was placed at a distance of 2.4 m (8 ft) from the fire source along the line of sight of the detectors. The view of the solid vertical wall obstruction from the 7.6 m (25 ft) detectors is shown during a lubricant oil test fire below in Figure 6.

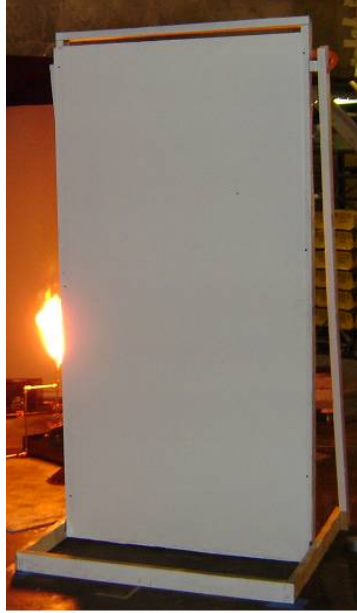


Figure 6. 50% solid vertical wall obstruction with vertical lubricant oil spray fire.

Second, the wall was placed horizontally so that it blocked the entire top half of the fire, leaving only the base of the fire exposed to the detectors. This scenario was designed to remove the characteristic shape and flicker of the flame from the detectors to determine the effect on detection performance. For tall flames, such as natural gas jets and n-heptane pools, the wall was placed with its lower edge at a height of 1.2 m (4 ft) and for smaller flames, such as lubricant oil sprays, the height was lowered to 0.9 m (3 ft). The view of the solid horizontal wall obstruction during a vertical natural gas jet fire is shown below in Figure 7.

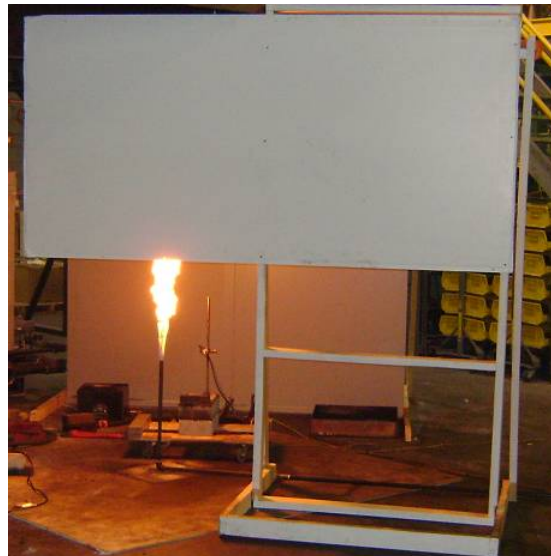


Figure 7. 50% solid horizontal wall obstruction with vertical natural gas jet flame.

4.4.2 Pipe Array Obstructions

Networks of piping, railings, ladders, and various equipment can provide repetitive obstructions in the field of view of a detector. In order to address such potential obstructions, this test series examined the performance of the flame detectors when viewing flames through an array of parallel pipes. An array of sixteen 5 cm (2 in.) diameter, gray SCH40 rigid PVC conduit pipes 2.8 m (9.3 ft) in length were used to construct this obstruction. The pieces of conduit had outer diameters of 6.35 cm (2.5 in.) and were arranged such that each pipe was separated by a gap equal to the outer diameter. Fires were tested with the array of pipes placed in both horizontal and vertical directions at a distance of 2.4 m (8 ft) from the fire source in the detector line of sight. In the horizontal orientation, the first pipe was mounted at a height of 0.66 m (26 in.) and alternated gaps and pipes up to a height of 2.4 m (8 ft). The horizontal pipe array obstruction is shown below with an n-heptane pool fire in Figure 8.

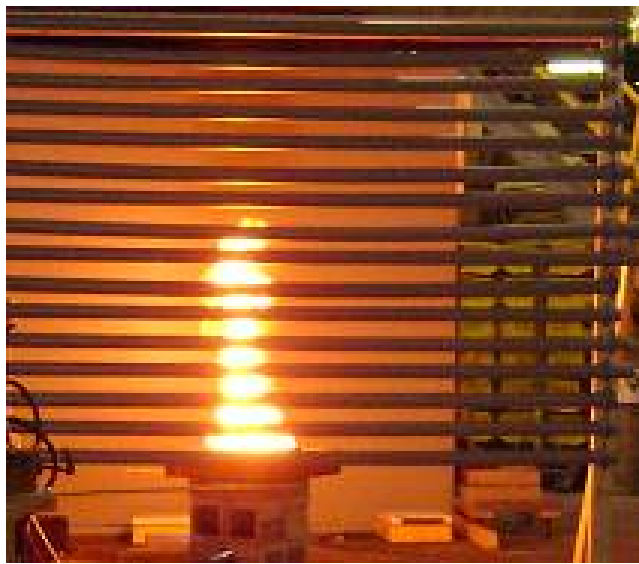


Figure 8. Horizontal pipe array obstruction with an n-heptane pool fire.

4.4.3 Impingement

It is possible that flames may impinge upon adjacent surfaces of equipment or building structures. In addition to greatly increasing the potential for destruction and flame spreading to the impinged surface, this fire scenario may greatly alter the apparent shape and size of a flame. This could result in reduced detection capabilities for flame detectors. Flame impingement was conducted in this test series with the flame surface projected against a 90° bend of sheet steel, 0.4 m (16 in.) on the bottom and side. This duct surface was placed 0.31 m (1 ft) from the base of the test flames. Impingement was conducted for both vertical flames and perpendicular horizontal flame orientations. The various impingement tests conducted are shown below in Figure 9.



Figure 9. Impinged fires, from top left n-heptane pool, vertical lubricant oil spray, vertical natural gas jet; bottom row, horizontal lubricant oil spray, horizontal natural gas jet.

4.5 Nuisances

Nuisance source testing was used to ascertain two main objectives. First, the ability of the detector to avoid false alarms when exposed to the source was evaluated. Second, the tests were conducted to determine the ability of the detector to distinguish a real fire event when a select nuisance source was simultaneously in the FOV. The following sources were selected for this test series: arc welding, torch cutting, sparks from grinding metal, bright work lights, and a hot surface. The sources were located 4.5 m (15 ft) from the fire source location in line with and toward the detectors. The exception to this location was the hot surface source, which due to its construction had to be located at the standard fire location. When a nuisance source operator was involved, he was positioned to the side of the source such that he did not obstruct the detectors view of the operation or the fire.

4.5.1 Arc Welding

The arc welding event consisted of a person using an arc welder set to 100A and a 6013, 3.18 mm (1/8 in.) organic binder rod along a piece of steel set on a 0.9 m (3 ft) steel welding table. During the test, two welding rods were used in succession with a 15 to 18 second down time between changing the rods. For tests with fire detection, the welding began 30 seconds prior to ignition. The welder was positioned to the side of the steel such that he did not obstruct the detectors view of the welding or the fire. These tests were only performed with vertical natural gas jets and the flame was extinguished immediately upon consumption of the second binder rod. A vertical natural gas jet flame with arc welding in the line of sight is shown in Figure 10.



Figure 10. Arc welding nuisance with a vertical natural gas jet flame.

4.5.2 Metal Torch Cutting

A standard oxyacetylene cutting torch was used to cut a 6.4 mm (0.25 in.) steel sheet. The torch cutting was conducted with the torch pointing downward while removing pieces of metal from the steel sheet. The torch was lit and adjusted to a cutting flame in the FOV of the detectors. For tests with fire detection, the torch cutting began 30 seconds prior to ignition of the flame. The operator was positioned to the side of the torch such that he did not obstruct the detectors view of the operation or the fire. These tests were only performed with vertical natural gas jets and the flame was extinguished after 90 seconds of cutting. A vertical natural gas jet flame with torch cutting in the line of sight is shown in Figure 11.



Figure 11. Metal torch cutting nuisance with vertical natural gas jet flame.

4.5.3 Metal Grinding

Metal grinding was used to eject a long train of sparks into the air as a potential nuisance source. Several long welds from a 6013, 3.18 mm (1/8 in.) organic binder rod were placed on a flat steel sheet. A 10,000 rpm, 115 mm (4.5 in.) metal angle grinder with a Norton 4.5 in. metal standard grinding pad was used to remove the beads from the sheet, ejecting the hot metal particles into the air. For tests with fire detection, the grinding began 30 seconds prior to ignition. These tests were only performed with vertical natural gas jets and the flame was extinguished after 120 seconds of grinding.

4.5.4 Bright Lights

A 1500 W halogen commercial electric work lamp consisting of two 500 W and two 250 W bulbs were directed at the detectors. The lights were positioned 3 m (10 ft) in front of the 7.6 m (25 ft) detector test rig in line with the standard fire source location. The bright lights were tested as a nuisance source in several ways. First, the lights were turned on and directed at the detectors providing one minute of steady light. Next, a person walked in front of the lights periodically back and forth for one minute. This provided a steady, alternating on/off scenario. Next, the person left the FOV and the lights were allowed to stay steady for another minute. The person then again stepped in front of the lights and performed random motions for one minute. This included sweeping arm motions, jumping into and out of the FOV, or quickly swaying from side to side. The person then left the FOV and finally the lights were again allowed to shine steadily for one minute. These scenarios provided a number of different possible flicker and motion scenarios.

When conducted as a blinding source during flame detection testing, the lights were turned on and the fire ignited after 30 seconds of steady light. These blinding tests were conducted for n-heptane pools, vertical natural gas jets, and vertical lubricant oil sprays.

4.5.5 300 °C Hot Surface

A stationary blackbody-type source was created using a laboratory furnace with a 5 mm (3/16 in.) thick steel side that was heated by the internal natural gas burners. The steel sheet was 1 x 1 m (3.3 x 3.3 ft). The temperature of the front face of the steel sheet was monitored with a type-K thermocouple welded to the surface. The furnace temperature was adjusted until the front surface reached a steady state temperature of 300°C (572°F). The hot surface was tested as a nuisance source in several ways consistent with the variations performed with the halogen lamps. The approach taken in these tests was to provide a range of motions and activities that could be representative of people and equipment working or being moved around hot objects.

When conducted as a blinding source during flame detection testing, the hot surface was allowed to reach steady state and the fire was ignited after 150 seconds of exposure. These blinding tests were conducted with n-heptane pools and vertical lubricant oil sprays. In this scenario, the fire was moved 1.5 m (5 ft) in front of the hot surface. This placed the fires at distances of 6.1 m (20 ft) and 13.7 m (45 ft) from the detectors. Detectors were not realigned during this test phase for the slight shift in the location of the fire. Consequently, the fires may have been just outside the 45 degree field of view for the off-axis detectors. The shift may have

resulted in detectors with a sharp cut-off in performance at off-axis viewing (i.e., VID devices) to exhibit poor detection results for off-axis viewing conditions.

5.0 Results and Discussion

5.1 Flame Characterization

The average heat release rate (HRR) over the time interval from 100 seconds to 200 seconds after ignition and the peak HRR for each fire type are listed in Table 3. In addition, where heat flux measurements were available, the average radiative fraction for each fire is provided along with the average intermittent flame height. For general flame testing, the average HRR best describes the flame size during the early part of the tests when most detection results occurred. It should be noted, however, for any devices that did not alarm the peak HRR is the most meaningful value because the detectors monitor the fires in real time, and thus were unable to alarm even at these peak values. The larger (pseudo-saturation) fire events, i.e., the propane line burner and n-heptane spray fires, are represented only with peak HRR values due to the short duration of the tests, during which a steady-state period was not fully established. Except for the n-heptane spray fire, all of the fires were generally about 1 m high.

Table 3. General Fire Test Characterization.

Fire	Avg. HRR [kW] (Std. Dev.)	Peak HRR [kW] (Std. Dev.)	Avg. Radiative Fraction	Avg. Flame Height (m)
Natural Gas Jet*	40 (15)	52 (7)	0.2	1.2
Propane Gas Jet	40 (1)	47 (3)	NM	1.2
n-heptane Pool	72 (10)	82(10)	0.4	1.2
Lube Oil Pool	37 (2)	41 (1)	0.34	0.9
Diesel Pool	48 (2)	51 (1)	NM	0.9
Lube Oil Spray*	48 (14)	58 (17)	0.29	0.7
Propane Line Burner	N/A, no SS period	248 (34)	NM	1.2
n-heptane Large Spray	N/A, no SS period	612 (24)	NM	1.8

NM = not measured

* includes fires of both vertical and horizontal orientations

5.2 Unobstructed Fire Testing

All fire scenarios were tested with no obstructions or nuisance sources and with the uniform gray background in place. These tests were used to provide a basic understanding of the ability of the detectors to alarm to each fire type with fires in plain view. The average time to alarm and the percentage of tests achieving an alarm are shown below in Table 4. The average time only includes tests where an alarm was achieved, failures to alarm are included in the percentage of alarms, but do not adversely affect the average alarm time.

The results in Table 4 provide a general assessment of detector performance across a range of fire conditions. Most of the OFD devices alarmed to all scenarios. The OFD-B and OFD-UV performed the most consistently and quickest. The OFD-UV had difficulty detecting some pool

fires at the 15.2 m (50 ft) off-axis view, while the OFD-B had occasional difficulty detecting spray fires from the same off-axis view.

The OFD-A detectors at 7.6 m (25 ft) performed about the same as the OFD-B detectors, providing average alarm times from 7 to 30 seconds and detecting all fires. However, the OFD-A performance drops off measurably at 15.2 m (50 ft) in both detection time and percentage of alarms. This is true for all fire types with the exception of the 15.2 m (50 ft) gas jet fires in direct line of sight, in which detection occurred in 100% of tests. The performance of the off-axis OFD-A detector at 15.2 m (50 ft) is significantly worse than under the other viewing conditions. The performance drops from 100% at the close viewing distance to 77% for the on-axis detector at 15.2 m (50 ft) and down to only 26% for the off-axis detector.

The OFD-C devices had average alarm times ranging from 16 to 126 seconds and generally good consistency of detection at all viewing angles except for a few failures of the 15.2 m (50 ft) off-axis detector, alarming to 84% of all test fires. These failures occurred to both gas jets and liquid spray fires.

Table 4. Average Detection Response to General Fire Types in Plain View of Detectors.

Devices	Viewing Condition	All small open fires (31 tests)	Liquid Pools (10 tests)	Gas Jets (12 tests)	Lubricant Oil Sprays (9 tests)
		Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)
OFD-A	50 ft on-axis	40 (77%)	62 (70%)	41 (100%)	6 (56%)
	50 ft off-axis	46 (26%)	29 (40%)	19 (25%)	189 (11%)
	25 ft on-axis	12 (100%)	24 (100%)	7 (100%)	7 (100%)
	25 ft off-axis	21 (100%)	26 (100%)	10 (100%)	30 (100%)
OFD-B	50 ft on-axis	18 (100%)	35 (100%)	10 (100%)	9 (100%)
	50 ft off-axis	26 (90%)	42 (100%)	14 (100%)	24 (67%)
	25 ft on-axis	12 (100%)	18 (100%)	10 (100%)	7 (100%)
	25 ft off-axis	12 (100%)	20 (100%)	10 (100%)	6 (100%)
OFD-UV	50 ft on-axis	16 (100%)	35 (100%)	5 (100%)	5 (100%)
	50 ft off-axis	21 (89%)	62 (70%)	6 (100%)	5 (100%)
	25 ft on-axis	7 (100%)	11 (100%)	5 (100%)	5 (100%)
	25 ft off-axis	8 (100%)	12 (100%)	5 (100%)	5 (100%)
OFD-C	50 ft on-axis	31 (100%)	26 (100%)	24 (100%)	46 (100%)
	50 ft off-axis	82 (84%)	38 (100%)	126 (75%)	89 (78%)
	25 ft on-axis	22 (97%)	17 (90%)	23 (100%)	25 (100%)
	25 ft off-axis	20 (100%)	29 (100%)	16 (100%)	16 (100%)
VID-A	50 ft on-axis	27 (48%)	27 (40%)	27 (92%)	Never Alarmed
	50 ft off-axis	62 (42%)	27 (40%)	78 (75%)	Never Alarmed
	25 ft on-axis	26 (81%)	33 (90%)	19 (100%)	31 (44%)
	25 ft off-axis	42 (77%)	48 (90%)	40 (100%)	36 (33%)
VID-B	50 ft on-axis	30 (71%)	33 (80%)	25 (92%)	43 (33%)
	50 ft off-axis	37 (58%)	39 (80%)	27 (67%)	67 (22%)
	25 ft on-axis	26 (87%)	35 (100%)	19 (100%)	26 (56%)
	25 ft off-axis	28 (55%)	33 (70%)	19 (50%)	34 (44%)

The VID detectors had significant problems with consistency of alarming to all fire types. Of the eight total VID detectors tested, only the 7.6 m (25 ft) on-axis VID-B detector viewing pool fires and gas jets had 100% detection. The detection performance of all the VID devices for the liquid spray fires ranged from 0 to 56% detection; the on- and off-axis VID-A units at 15.2 m (50 ft) did not detect any lubricant oil spray fires.

5.3 Pool Fires

Liquid pools fires consisted of n-heptane, diesel fuel, and lubricant oil fires; each with a different HRR. When arranged by decreasing magnitude of HRR from n-heptane to lube oil (average 72, 48, 37 kW, respectively), it is clear that the detection performance deteriorates for these different fuels as the size of the fire decreased. This was apparent by the general increase in average alarm times and slight decrease in the percent of fires detected (i.e., alarm %) for some detectors. A number of detectors never detected some of the smaller diesel and lubricant oil fires, most notable were the OFD-A at 50 ft and the VID-A at 50 ft.

5.4 Gas Jets

In addition to comparing the results of burning gas jets of both propane and natural gas, the natural gas jets were burned in multiple flame orientations. This included a vertical jet, a horizontal jet perpendicular to the detector line of sight, and a horizontal jet parallel to the detector line of sight (and toward the detector). Every OFD and VID detector alarmed to 100% of the propane fires except the OFD-A at 15.2 m (50 ft) off-axis (0%) and the OFD-C 15.2 m (50 ft) off-axis (67%, i.e., 2 of 3 fires detected).

The natural gas jet fires yielded essentially the same results for the OFDs as the propane jets, even at the different flame orientations. However, the natural gas fires were harder for the VID devices to detect. The VID-A at 15.2 m (50 ft) detected none of the vertical natural gas flames off-axis and 67% of the fires on-axis. The VID-B detector at 15.2 m (50 ft) off-axis had decreased performance from the vertical natural gas flame (100%) to 67% for the parallel, horizontal flame to 0% for the perpendicular, horizontal flame. However, the 7.6 m (25 ft) off-axis VID-B detector had 100% detection for the parallel, horizontal flame and 100% for the perpendicular, horizontal flame and the vertical flame.

Overall, the propane gas jet fires were more easily detected than the natural gas fires. And in general, the natural gas jet fires proved to be one of the more challenging fires; therefore the vertical natural gas fires were utilized as one of the primary fire scenarios to evaluate the detectors with obstructions. Changing the orientation of the natural gas jet fire did have an effect on detection performance for several devices. In general, the parallel horizontal jet fires were the easiest of the three to detect. This result is most clearly evidenced by the failure of the 15.2 m (50 ft) off-axis OFD-A to detect any gas jet fires with the exception of the parallel horizontal natural gas jets. Improvements in performance were also seen for the VID-B at 7.6 m (25 ft) off-axis.

5.5 Liquid Sprays

Lube oil liquid spray fires were also burned in various flame orientations, similar to the natural gas jets. In general, the results were similar to the natural gas jet fires. However, burning

the lube oil spray in the horizontal orientations proved to be more challenging for detection for a number of the OFD and VID detectors, except for the UV detector that had 100% detection in 5 seconds for all devices and all lube fire scenarios. The measured HRR of the horizontal fires (29 kW for perpendicular and 31 kW for parallel) was less than in the vertical orientation (48 kW). This was due to less complete combustion as evidenced by more residual fuel spray to the ground for the horizontal fires. Consequently, the horizontal fires were slightly more challenging due to fire size. This was particularly evident with the OFD-A 15.2 m (50 ft) detectors which did not alarm to most of the horizontal oil sprays.

The VID devices all had difficulty detecting the lubricant oil spray fires, even for the vertical spray. No detector alarmed to more than 56% of all of the lube oil spray fires (which was achieved by the VID-B at 7.6 m on-axis). Neither of the VID-A detectors at 15.2 m (50 ft) were able to alarm to any lubricant spray fire. The VID-B detectors at 15.2 m (50 ft) were unable to detect most of the horizontal sprays.

5.6 Effect of Uniform Gray Background

Unobstructed, open fire testing was also conducted for several fire scenarios without the uniform gray background in the FOV of the detectors. With the gray background removed, the background consisted of multiple colored items, including metal structures, carts, and a ladder. The purpose of these tests was to determine if the background was systematically affecting detection results by reflecting radiation back in the direction of the detectors such that certain devices (particularly IR sensing OFDs) may be relatively biased compared to other technologies. This was not the case. The results show no significant effect of the background on the performance of any of the spectral-based flame detectors. This testing was conducted with vertical natural gas jets, vertical lubricant oil sprays, and n-heptane pool fires. These fires were selected to provide the most challenging fires as well as the larger heptane fire to bound the detection performance.

Contrary to the OFDs, the two VID devices were more notably impacted by the change in background. However, the results were not consistent with some VID devices performing better and some worse (including alarming vs. not alarming and vice-versa).

5.7 Fires with Obstructions

After reviewing the unobstructed fire test data, it was determined that continued testing with all fire sources was not necessary to fully describe the general detection performance. It was decided to continue with tests that provided a detection challenge and were representative of the various fire types. It was also determined that continuation with a relatively easy to detect fire type (i.e., the n-heptane pool) would provide additional bounding information about the effect of obstructions and nuisances. The effect of obstructions and nuisances on detection performance was consequently evaluated with n-heptane pools, vertical lube oil sprays, and vertical natural gas jets. The lube oil and natural gas jets were selected because they were the most troublesome fires to detect. The heptane pool was selected because all detectors were capable of detecting it, and thus the effect of various aggravating circumstances could be determined. That is for example, if a detector could not detect the heptane pool fire with an obstruction, then its

performance relative to the obstruction is better bounded than if the detector was only tested with a smaller and harder to detect fire.

The general detection performance results for fires with obstructions are presented in Table 5. The alarm times represent the average time for the detector to alarm to three tests each for vertical natural gas jet fires, vertical lubricant oil spray fires, and three tests for the n-heptane pool fires. For the none obstructed fires (third column), 10 tests represents three of each except four n-heptane.

Table 5. Average Detection Performance to Vertical Natural Gas Jets, Vertical Lubricant Oil Sprays, and n-heptane Pools with Various Obstructions.

Devices	Viewing Condition	Obstructions				
		None (10 tests)	50% Vertical Wall (9 tests)*	50% Horiz. Wall (9 tests)	Vertical Pipes (9 tests)	Horizontal Pipes (9 tests)
		Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)
OFD-A	50 ft On-axis	23 (100%)	27 (44%)	14 (44%)	44 (56%)	39 (33%)
	50 ft Off-axis	61 (50%)	NA (0%)	295 (33%)	NA (0%)	NA(0%)
	25 ft On-axis	7 (100%)	9 (100%)	6 (67%)	9 (100%)	9 (100%)
	25 ft Off-axis	28 (100%)	8 (100%)	6 (89%)	9 (100%)	9 (100%)
OFD-B	50 ft On-axis	13 (100%)	14 (100%)	20 (100%)	13 (100%)	19 (100%)
	50 ft Off-axis	16 (100%)	56 (89%)	14 (67%)	24 (100%)	36 (67%)
	25 ft On-axis	8 (100%)	5 (100%)	11 (100%)	8 (100%)	9 (100%)
	25 ft Off-axis	8 (100%)	6 (100%)	8 (100%)	10 (100%)	10 (100%)
OFD-UV	50 ft On-axis	7 (100%)	12 (100%)	5 (100%)	9 (100%)	9 (100%)
	50 ft Off-axis	8 (100%)	16 (100%)	9 (100%)	12 (100%)	10 (100%)
	25 ft On-axis	5 (100%)	5 (100%)	5 (100%)	6 (100%)	5 (100%)
	25 ft Off-axis	5 (100%)	5 (100%)	5 (100%)	6 (100%)	5 (100%)
OFD-C	50 ft On-axis	20 (100%)	89 (67%)	25 (78%)	46 (89%)	34 (78%)
	50 ft Off-axis	59 (90%)	89 (78%)	54 (100%)	92 (89%)	77 (56%)
	25 ft On-axis	21 (90%)	18 (89%)	18 (100%)	18 (100%)	13 (100%)
	25 ft Off-axis	27 (100%)	17 (100%)	58 (100%)	18 (100%)	29 (100%)
VID-A	50 ft On-axis	30 (60%)	103 (22%)	NA (0%)	36 (33%)	36 (33%)
	50 ft Off-axis	27 (40%)	108 (22%)	NA (0%)	53 (33%)	53 (33%)
	25 ft On-axis	23 (80%)	19 (44%)	NA (0%)	24 (56%)	NA (0%)
	25 ft Off-axis	52 (80%)	19 (44%)	NA (0%)	NA (0%)	NA (0%)
VID-B	50 ft On-axis	29 (90%)	50 (78%)	16 (11%)	32 (56%)	21 (44%)
	50 ft Off-axis	34 (80%)	31 (44%)	16 (22%)	90 (44%)	NA (0%)
	25 ft On-axis	24 (80%)	19 (56%)	46 (11%)	30 (67%)	NA (0%)
	25 ft Off-axis	27 (50%)	18 (56%)	NA (0%)	19 (44%)	NA (0%)

* A total of 18 tests were conducted but each data set is only representative of the 9 tests intended for that test distance.

NA = Never Alarmed

The UV detector was the only device that detected 100% of all fires with all obstructions from all viewing conditions. In general, all of the multi-spectrum IR OFD models showed some decrease in performance for some of the obstructed fires, particularly for devices at the 15.2 m (50 ft) distance. For example, the detection performance of the OFD-C detectors was nearly 100% for all obstructed scenarios from the 7.6 m (25 ft) detector location, with the exception of one test with the vertical wall blocking 50% of one side of a natural gas jet flame. The performance of OFD-C detectors at the 15.2 m (50 ft) view was relatively degraded in both time and alarm percentage for all obstructions compared to the closer devices.

The VID detectors had increased trouble detecting the fires when obstructions were in the FOV. This is most apparent for the horizontal wall and horizontal pipe obstructions, under which five of eight devices were completely unable to alarm to any fire with these obstructions. The best performance of any VID device to the horizontal wall or pipe obstructions was 44% detection for the 15.2 m (50 ft) on-axis new model VID-B. These results show that the horizontal pipes and wall were able to prevent the VID devices from even detecting all of the large n-heptane pool fires.

5.8 Nuisance Sources

5.8.1 False Alarms

The response of the detectors to various nuisance sources is shown below in Table 6. In general, most detectors were immune to most of the nuisance sources. Metal grinding and bright lights are not listed in the table since no detector ever false alarmed to these sources. However, the OFD-C on-axis detector at 7.6 m (25 ft) did alarm during the setup of the lights; but this alarm was not able to be replicated during a recorded test.

The UV model was susceptible to false alarms to most sources with a spark. This included the arc welding and torch cutting sources. These devices even alarmed to the electronic spark used to ignite the natural gas and propane jet fires if persisting for more than one to two seconds.

The arc welding also caused occasional alarms in the OFD-B and the VID-B devices, alarming to 33% of arc welding events for both detectors at select 7.6 m (25 ft) locations. The torch cutting used an oxyacetylene torch flame and also resulted in a number of alarms. The OFD-A and OFD-C detectors occasionally resulted in alarms. The OFD-B always alarmed for both the on- and off-axis 7.6 m (25 ft) location. While this was considered a nuisance source, the torch cutting did involve the use of an actual flame.

The OFD-C detectors were susceptible to the hot surface radiation source. They did not alarm when exposed to the hot source directly, or to periodic motion chopping the source (repetitive walking in front). They did, however, alarm to random swinging arm motions in front of the furnace. This happened most consistently when the person stood sideways and alternately waved their arms up and down. It also occurred occasionally to large circular arm motions. These scenarios were repeatable and consistently resulted in false alarms. As with all nuisance

sources, whether these scenarios are of concern are dependent on the application specific scenarios that may occur.

Table 6. Average False Alarm Detector Response to Various Nuisance Sources

Devices	Viewing Condition	Nuisances		
		Arc Welding (3 tests)	Torch Cutting (3 tests)	300°C Hot Surface (3 tests)
		Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)
OFD-A	50 ft On-axis	Never Alarmed (0%)	Never Alarmed (0%)	Never Alarmed (0%)
	50 ft Off-axis		Never Alarmed (0%)	
	25 ft On-axis		6 (33%)	
	25 ft Off-axis		6 (33%)	
OFD-B	50 ft On-axis	Never Alarmed (0%)	Never Alarmed (0%)	Never Alarmed (0%)
	50 ft Off-axis	Never Alarmed (0%)	Never Alarmed (0%)	
	25 ft On-axis	Never Alarmed (0%)	5 (100%)	
	25 ft Off-axis	56 (33%)	5 (100%)	
OFD-UV	50 ft On-axis	5 (100%)	5 (100%)	Never Alarmed (0%)
	50 ft Off-axis	5 (100%)	5 (100%)	
	25 ft On-axis	5 (100%)	5 (100%)	
	25 ft Off-axis	5 (100%)	5 (100%)	
OFD-C	50 ft On-axis	Never Alarmed (0%)	Never Alarmed (0%)	226 (100%)
	50 ft Off-axis		Never Alarmed (0%)	230 (33%)
	25 ft On-axis		46 (33%)	213 (100%)
	25 ft Off-axis		Never Alarmed (0%)	213 (100%)
VID-A	50 ft On-axis	Never Alarmed (0%)	Never Alarmed (0%)	Never Alarmed (0%)
	50 ft Off-axis			
	25 ft On-axis			
	25 ft Off-axis			
VID-B	50 ft On-axis	Never Alarmed (0%)	Never Alarmed (0%)	Never Alarmed (0%)
	50 ft Off-axis	Never Alarmed (0%)		
	25 ft On-axis	17 (33%)		
	25 ft Off-axis	17 (33%)		

5.8.2 Fire Detection Blinding

The second phase of nuisance source testing was intended to assess whether nuisance sources within the detector FOV would reduce the overall flame detection sensitivity of the detectors. The average time to alarm and detection percentages for vertical natural gas jet flames with various nuisance sources are displayed in Table 7. In these scenarios, the nuisance source was initiated 30 seconds before the ignition of the fires. In some cases the detector alarmed to the nuisance source and therefore, detection of the fire was not discernable.

Overall, there was little effect on detection performance due to the presence of potential nuisance sources. In fact, the presence of metal grinding in the FOV of detectors actually improved detection for several devices, such as the OFD-A and OFD-C (50 ft) off-axis detectors and the VID-A. The only detectors where a detrimental effect on detection was apparent were the 7.6 m (25 ft) OFD-C devices exposed to the bright light nuisance sources. It was noted that one of these devices alarmed during the setup of the lights, and thus the detector was clearly affected by this source. The lights completely eliminated the ability of the device to alarm when both the lights and fire were close to the OFD-C detectors, as denoted with the 0% detection. The VID-A off-axis detector at 7.6 m (25 ft) also had reduced alarm rates for the natural gas fires in the presence of a number of the nuisance sources; this was particularly true for the arc welding.

The detectors were also evaluated with the hot surface and bright lights nuisance source in the FOV of both n-heptane pool fires and vertical lubricant oil spray fires. The detection performance of all devices for n-heptane pool fires was unaffected by the bright lights being in the FOV. The hot steel surface in the FOV had an effect only on a selected number of detectors. The average alarm time increased substantially for the OFD-A 15.2 m (50 ft) off-axis and the OFD-C 7.6 m (25 ft) on- and off-axis detectors. In general for these noted detectors, the average alarm times changed from approximately 0.5 minutes to 2.5–5 minutes.

With the lubricant oil fires, the effect of the light and hot surface nuisance sources was minimal on the performance of the OFDs. In a few cases, alarm times were longer, but in some cases the times were shorter with the lights and hot surface present. The VID devices showed some degradation in general performance with the lights and hot surface (a few less alarms for some), but the detection performance for the unobstructed lubricant spray fire was marginal to begin with.

5.9 Flame Impingement

Flame impingement can greatly change the shape and size of flames. Liquid pool fires consisting of n-heptane were burned in a vertically impinged scenario. Detection of n-heptane pool fires was relatively unaffected by flame impingement despite a reduction in the overall visible size and total HRR of the flame (~10 kW smaller). Only one VID-A detector at 15.2 m (50 ft) off-axis was unable to detect this fire with 100% consistency (it missed one of three fires). For the more challenging natural gas jet and lube oil spray fires, some of the multi-spectrum IR and VID detectors had more difficulty detecting the impinged fires. The UV detectors were unaffected and detected all impinged fires within 15 seconds.

Table 7. Average Detection Response for Vertical Natural Gas Jets with Various Nuisance Sources Present.

Devices	Viewing Condition	Nuisances				
		No Nuisance Source (3 tests)	Arc Welding (3 tests)	Torch Cutting (3 tests)	Metal Grinding (3 tests)	Bright Lights (3 tests)
		Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)
OFD-A	50 ft On-axis	50 (100%)	6 (33%)	17 (67%)	6 (100%)	15 (100%)
	50 ft Off-axis	Never Alarmed (0%)	Never Alarmed (0%)	Never Alarmed (0%)	6 (67%)	Never Alarmed (0%)
	25 ft On-axis	6 (100%)	9 (100%)	6 (100%)	6 (100%)	13 (100%)
	25 ft Off-axis	6 (100%)	9 (100%)	6 (100%)	6 (100%)	13 (100%)
OFD-B	50 ft On-axis	10 (100%)	13 (100%)	16 (100%)	9 (100%)	20 (100%)
	50 ft Off-axis	15 (100%)	16 (100%)	16 (100%)	13 (100%)	16 (100%)
	25 ft On-axis	5 (100%)	13 (100%)	False Alarm (100%)	6 (100%)	16 (100%)
	25 ft Off-axis	5 (100%)	13 (100%)	16 (100%)	6 (100%)	16 (100%)
OFD-UV	50 ft On-axis	5 (100%)	False Alarm (100%)	False Alarm (100%)	6 (100%)	13 (100%)
	50 ft Off-axis	5 (100%)	False Alarm (100%)	False Alarm (100%)	6 (100%)	13 (100%)
	25 ft On-axis	5 (100%)	False Alarm (100%)	False Alarm (100%)	6 (100%)	13 (100%)
	25 ft Off-axis	5 (100%)	False Alarm (100%)	False Alarm (100%)	6 (100%)	13 (100%)
OFD-C	50 ft On-axis	22 (100%)	22 (100%)	16 (100%)	19 (100%)	20 (100%)
	50 ft Off-axis	36 (67%)	26 (100%)	62 (67%)	47 (100%)	98 (67%)
	25 ft On-axis	16 (100%)	26 (100%)	13 (100%)	16 (100%)	Never Alarmed (0%)
	25 ft Off-axis	19 (100%)	26 (100%)	19 (100%)	16 (100%)	Never Alarmed (0%)
VID-A	50 ft On-axis	36 (67%)	44 (100%)	40 (100%)	30 (100%)	40 (100%)
	50 ft Off-axis	Never Alarmed (0%)	37 (33%)	47 (33%)	37 (33%)	67 (33%)
	25 ft On-axis	19 (100%)	37 (100%)	23 (100%)	30 (100%)	33 (100%)
	25 ft Off-axis	87 (100%)	Never Alarmed (0%)	29 (67%)	22 (67%)	41 (67%)
VID-B	50 ft On-axis	36 (67%)	33 (100%)	33 (100%)	33 (100%)	37 (100%)
	50 ft Off-axis	46 (100%)	16 (33%)	32 (67%)	33 (100%)	44 (100%)
	25 ft On-axis	26 (100%)	20 (100%)	20 (100%)	23 (100%)	26 (100%)
	25 ft Off-axis	Never Alarmed (0%)	False Alarm (33%) Did Not Alarm (67%)*	Never Alarmed (0%)	Never Alarmed (0%)	27 (33%)

* VID-B 25 ft off-axis detector never alarmed to a fire test during arc welding, but did achieve an alarm during the welding phase of one test.

The detection performance of all of the detectors to natural gas jet fires and lube oil spray fires, both in vertical and horizontal orientations, as well as both free and impinged is shown in Table 8 and Table 9, respectively. Included in these tables are the average HRR for each fire scenario. This is included because the impingement of flames affected the burning rate of the fires. In general, the fire size was diminished. For example, the vertical impinged natural gas flame was 27 kW compared to 46 kW in the open. Flame impingement had a similar effect on the HRR of the lubricant oil spray fires. In the vertical orientation, the HRR was decreased from 48 to 34 kW. However, the HRR of the horizontal impinged spray fire increased from 29 to 53 kW compared to the open perpendicular horizontal spray fire. This increase with the horizontal impingement is due to oil that collected on the surface of the metal duct and burned as a secondary attached flame on the duct setup. The increase in HRR for the horizontally impinged lubricant oil spray fires did not result in an increase in detection performance. All VID devices were unable to detect these flames, as well as the OFD-A and OFD-B off-axis devices at 15.2 m (50 ft).

Table 8. Average Detection Response to Free and Impinged Natural Gas Jets in Both Horizontal and Vertical Orientations.

Devices	Viewing Condition	Natural Gas Jet			
		Vertical (3 tests) Alarm Time (sec) (Alarm %)	Vertical Impinged (3 tests) Alarm Time (sec) (Alarm %)	Perpendicular Horizontal (3 tests) Alarm Time (sec) (Alarm %)	Impinged Horizontal (3 tests) Alarm Time (sec) (Alarm %)
OFD-A	50 ft On-axis	50 (100%)	7 (67%)	19 (100%)	16 (100%)
	50 ft Off-axis	NA (0%)	6 (33%)	NA (0%)	6 (33%)
	25 ft On-axis	6 (100%)	20 (100%)	11 (100%)	16 (100%)
	25 ft Off-axis	6 (100%)	20 (100%)	13 (100%)	16 (100%)
OFD-B	50 ft On-axis	10 (100%)	NA (0%)	12 (100%)	18 (100%)
	50 ft Off-axis	15 (100%)	NA (0%)	16 (100%)	23 (100%)
	25 ft On-axis	5 (100%)	5 (100%)	16 (100%)	15 (100%)
	25 ft Off-axis	5 (100%)	5 (100%)	16 (100%)	15 (100%)
OFD-UV	50 ft On-axis	5 (100%)	5 (100%)	5 (100%)	15 (100%)
	50 ft Off-axis	5 (100%)	9 (100%)	5 (100%)	15 (100%)
	25 ft On-axis	5 (100%)	5 (100%)	5 (100%)	15 (100%)
	25 ft Off-axis	5 (100%)	5 (100%)	5 (100%)	15 (100%)
OFD-C	50 ft On-axis	22 (100%)	22 (67%)	16 (100%)	16 (67%)
	50 ft Off-axis	36 (67%)	NA (0%)	138 (67%)	16 (67%)
	25 ft On-axis	16 (100%)	33 (100%)	26 (100%)	26 (100%)
	25 ft Off-axis	19 (100%)	36 (100%)	16 (100%)	26 (100%)
VID-A	50 ft On-axis	36 (67%)	NA (0%)	26 (100%)	NA (0%)
	50 ft Off-axis	NA (0%)	NA (0%)	121 (100%)	NA (0%)
	25 ft On-axis	19 (100%)	NA (0%)	23 (100%)	NA (0%)
	25 ft Off-axis	87 (100%)	NA (0%)	29 (100%)	NA (0%)
VID-B	50 ft On-axis	36 (67%)	NA (0%)	33 (100%)	NA (0%)
	50 ft Off-axis	46 (100%)	NA (0%)	NA (0%)	NA (0%)
	25 ft On-axis	26 (100%)	NA(0%)	19 (100%)	36 (33%)
	25 ft Off-axis	NA (0%)	NA (0%)	NA (0%)	16 (33%)
Average HRR (kW)					
Standard Deviation (kW)		46 (0.8)	27 (0.3)	43 (0.2)	50 (0.4)

NA = Never Alarmed

Table 9. Average Detection Results For Free and Impinged Lubricant Oil Spray Fires in Vertical and Horizontal Orientations.

		Lubricant Oil Spray			
		Vertical (3 tests)	Vertical Impinged (3 tests)	Perpendicular Horizontal (3 tests)	Impinged Horizontal (3 tests)
Devices	Viewing Condition	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)
OFD-A	50 ft On-axis	6 (100%)	36 (100%)	Never Alarmed (0%)	6 (67%)
	50 ft Off-axis	189 (33%)	Never Alarmed (0%)	Never Alarmed (0%)	Never Alarmed (0%)
	25 ft On-axis	9 (100%)	6 (100%)	6 (100%)	6 (100%)
	25 ft Off-axis	77 (100%)	6 (100%)	6 (100%)	6 (100%)
OFD-B	50 ft On-axis	12 (100%)	9 (100%)	5 (100%)	12 (100%)
	50 ft Off-axis	19 (100%)	19 (100%)	16 (33%)	Never Alarmed (0%)
	25 ft On-axis	5 (100%)	5 (100%)	5 (100%)	9 (100%)
	25 ft Off-axis	8 (100%)	5 (100%)	5 (100%)	5 (100%)
OFD-UV	50 ft On-axis	5 (100%)	5 (100%)	5 (100%)	5 (100%)
	50 ft Off-axis	5 (100%)	5 (100%)	5 (100%)	5 (100%)
	25 ft On-axis	5 (100%)	5 (100%)	5 (100%)	5 (100%)
	25 ft Off-axis	5 (100%)	5 (100%)	5 (100%)	5 (100%)
OFD-C	50 ft On-axis	19 (100%)	19 (100%)	60 (100%)	26 (100%)
	50 ft Off-axis	114 (100%)	49 (100%)	87 (67%)	94 (100%)
	25 ft On-axis	31 (100%)	33 (100%)	23 (100%)	23 (100%)
	25 ft Off-axis	16 (100%)	16 (100%)	16 (100%)	16 (100%)
VID-A	50 ft On-axis	Never Alarmed (0%)	Never Alarmed (0%)	Never Alarmed (0%)	Never Alarmed (0%)
	50 ft Off-axis	Never Alarmed (0%)	Never Alarmed (0%)	Never Alarmed (0%)	Never Alarmed (0%)
	25 ft On-axis	46 (33%)	Never Alarmed (0%)	26 (67%)	Never Alarmed (0%)
	25 ft Off-axis	56 (33%)	26 (33%)	26 (67%)	Never Alarmed (0%)
VID-B	50 ft On-axis	43 (100%)	42 (67%)	Never Alarmed (0%)	Never Alarmed (0%)
	50 ft Off-axis	56 (33%)	53 (100%)	Never Alarmed (0%)	Never Alarmed (0%)
	25 ft On-axis	46 (33%)	Never Alarmed (0%)	19 (100%)	Never Alarmed (0%)
	25 ft Off-axis	56 (33%)	46 (33%)	31 (67%)	Never Alarmed (0%)
Average HRR (kW) Standard Deviation (kW)		48 (3)	34 (4)	29 (4)	53 (7)

The majority of the multi-spectrum IR detectors were little affected by the impingement of the natural gas and lube oil spray flames. There were specific devices, typically the 15.2 m (50 ft) off-axis units that did not respond to selected impinged fires. The largest impact was to the OFD-C model. The apparent smaller size of the vertical impinged fires generally correlates to the reduced alarm percentages.

For the VID detectors, the impinged fires were more difficult to detect. This was true even for fires with the same or higher HRRs (e.g., no VID detector alarmed to an impinged horizontal lube oil fire). Therefore, it is reasonable to assume the flame shape had a significant affect for the VID flame detectors.

5.10 Saturation Fires

Two larger, immediate (instantaneous growth) fire events were tested. This included a propane line burner fire and an n-heptane spray fire. Both fires were intended to ignite instantaneously and provide larger flames, filling a significant part of the FOV of the detectors. There have been claims that specific flame detector algorithms may not alarm to a saturation-type flame exposure; this is a result of algorithms being designed to avoid nuisance events, such as the sudden exposure to bright lights, sun or a brief large flash. The results of these sets of tests are shown in Table 10 compared to the detection performance for the corresponding smaller, unobstructed fire tests.

Table 10. Average Detection Performance to Instantaneous, Larger Fire Events Including Propane Line Burner Fires and n-heptane Spray Fires Compared to Smaller Fires of the Same Fuel.

Devices	Viewing Condition	Vertical Propane Jets (3 tests)	Propane Line Burner (3 tests)	n-Heptane Pool Fires (4 tests)	n-Heptane Spray Fires (3 tests)
		Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)
OFD-A	50 ft On-axis	86 (100%)	9 (100%)	17 (100%)	7 (100%)
	50 ft Off-axis	NA (0%)	9 (100%)	29 (100%)	NA (0%)
	25 ft On-axis	6 (100%)	9 (100%)	7 (100%)	12 (67%)
	25 ft Off-axis	16 (100%)	9 (100%)	7 (100%)	NA (0%)
OFD-B	50 ft On-axis	5 (100%)	12 (100%)	14 (100%)	6 (100%)
	50 ft Off-axis	10 (100%)	12 (100%)	14 (100%)	NA (0%)
	25 ft On-axis	5 (100%)	9 (100%)	12 (100%)	6 (100%)
	25 ft Off-axis	5 (100%)	12 (100%)	9 (100%)	28 (33%)
OFD-UV	50 ft On-axis	<5 (100%)	9 (100%)	10 (100%)	6 (100%)
	50 ft Off-axis	<5 (100%)	9 (100%)	12 (100%)	6 (100%)
	25 ft On-axis	<5 (100%)	11 (100%)	6 (100%)	6 (100%)
	25 ft Off-axis	<5 (100%)	9 (100%)	6 (100%)	6 (100%)
OFD-C	50 ft On-axis	43 (100%)	33 (100%)	19 (100%)	NA (0%)
	50 ft Off-axis	148 (67%)	19 (100%)	29 (100%)	Never Alarmed (0%)
	25 ft On-axis	26 (100%)	209 (50%)	15 (75%)	9 (100%)

Devices	Viewing Condition	Vertical Propane Jets (3 tests)	Propane Line Burner (3 tests)	n-Heptane Pool Fires (4 tests)	n-Heptane Spray Fires (3 tests)
		Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)	Alarm Time (sec) (Alarm %)
	25 ft Off-axis	14 (100%)	NA (0%)	42 (100%)	20 (100%)
VID-A	50 ft On-axis	24 (100%)	NA (0%)	27 (100%)	NA (0%)
	50 ft Off-axis	19 (100%)	16 (33%)	27 (100%)	NA (0%)
	25 ft On-axis	16 (100%)	16 (67%)	19 (100%)	Never Alarmed (0%)
	25 ft Off-axis	19 (100%)	26 (67%)	24 (100%)	Never Alarmed (0%)
VID-B	50 ft On-axis	16 (100%)	16 (33%)	14 (100%)	Never Alarmed (0%)
	50 ft Off-axis	16 (100%)	16 (67%)	19 (100%)	Never Alarmed (0%)
	25 ft On-axis	16 (100%)	16 (50%)	17 (100%)	Never Alarmed (0%)
	25 ft Off-axis	22 (100%)	63 (100%)	19 (100%)	Never Alarmed (0%)

VID-B and OFD-C at 7.6 m (25 ft) on-axis experienced alarms to the ignition source, each for one test (negative alarm times) and this data has been disregarded. Thus only two of three tests are included in this data set, with each experiencing one alarm and one failure to alarm, hence a 50% detection percentage.

The n-heptane spray fire was roughly twice the size, in HRR, than the propane line burner (612 kW v 249 kW) and was almost 10 times larger than the n-heptane pool fires (72 kW). The propane line burner was roughly five times the size of the smaller propane jet fires (40 kW). In general, the sudden exposure to the larger fires was a problem for several detectors. Except for the UV OFD, no other detector model was able to alarm to all the larger fire scenarios.

For the propane line burner fire, all devices, except the 7.6 m (25 ft) OFD-C and most of the VID detectors, were able to detect 100% of the fires. The 7.6 m (25 ft) off-axis OFD-C detector was unable to detect any of the larger propane fires. The on-axis detector detected 50% of the fires and took a substantially longer time to alarm (over 3 minutes compared to 0.5 minutes to the smaller propane jet). Both 7.6 m (25 ft) OFD-C devices were able to detect the smaller propane jet flame with 100% consistency with relatively fast response.

As the fire size was further increased with the n-heptane spray fire, the performance of many devices degraded. Contrarily, the OFD-C devices at 7.6 m (25 ft) actually reversed their performance from the propane line burner and detected this fire with 100% accuracy, but the OFD-C detectors at 15.2 m (50 ft) were unable to detect the large n-heptane flame. The OFD-B detectors showed significant reduction for both off-axis detectors, decreasing 100% to 0% and 33% alarm detection. Similar to the OFD-B, the off-axis OFD-A detectors did not alarm to larger n-heptane fires, although they had 100% detection for the smaller n-heptane pool fires. Both VID devices were entirely unable to detect the large n-heptane spray fires for any detector location or FOV.

These results indicate that there may be significant limitations to multi-spectrum IR and VID flame detectors when exposed to large fire events. Such events are certainly possible in many industrial applications. Considering that the larger fires tested (max 612 kW) are relatively small compared to potential industrial fire incidents, the performance of these detectors should be evaluated further to a larger scope of potentially saturating fire scenarios.

6.0 Summary and Conclusions

Multiple flame detectors were tested in numerous scenarios representative of industrial applications. While each fuel, fire type, obstruction, viewing angle, and nuisance scenario produced an array of different results for the different flame detectors, several underlying themes were evident.

The fires conducted in this test series ranged in size from about 40 to 600 kW. They consisted of pool fires (diesel fuel, lubricant oil, n-heptane), gas jets (propane and natural gas), and spray fires (n-heptane and lubricant oil). The natural gas jets (~40 kW) and the lubricant oil spray fires (~48 kW) were generally the most difficult fires for the flame detectors to detect. The easiest fire to detect was the open n-heptane pool fire (~72 kW). Obstructions consisted of arrays of pipes and solid objects shielding half the fire, and metal surfaces to deflect impinging flames.

Detectors were mounted at about 3 m (10 ft) above the ground at 15.2 m (50 ft) and 7.6 m (25 ft) from the fires. Detectors were also aligned for direct line of sight (on-axis) with the fire and at the outer edge of the field of view (45 degrees off-axis in the horizontal direction). For the majority of the tests, the fires were in front of a solid gray background so that all detector views of the fire would be equivalent. Several tests with the gray background removed demonstrated there was no significant effect of the background on detector performance.

The results of this study have demonstrated that the inclusion of realistic obstructions into fire tests as well as the use of fire scenarios where flames impinge on objects can yield different flame detection performance than obtained for standard fires in the open. In general, these fire scenarios will result in equivalent or poorer detection performance than for the open fires. It is recommended that any further testing of flame detectors take into account realistic fire conditions that produce deflected flames or obstructed fields of view. It is important to base a detection system design on non-ideal, but realistic fire scenarios that take into account the detector sensitivity across the entire field of view. The effect of the detectors observing the growth of the fire relative to sudden exposure to a shielded FM 3260 test fire was not evaluated in this study, but may impact how some of the detector algorithms assess the fire, and thus, the response.

The exposure of flame detectors to larger (612 kW) n-heptane spray fires proved to be a challenge for several detector configurations for most detector models, except the UV optical flame detector. In particular, both VID devices were entirely unable to detect the large n-heptane spray fires for any detector location or FOV. It is quite possible to have initial fire events, particularly those related to gas leaks and fuel sprays, be larger than the 612 kW n-heptane spray fires. Therefore, it is recommended that the response of detectors to even larger fires be evaluated.

The results of these tests show that all multi-spectrum IR OFDs do not provide equivalent performance. Therefore, if the application requires sensitivity to small or obstructed fires, then close attention should be given to the performance of individual models relative to the fuel type and fire scenarios of concern. This may require testing to demonstrate performance for the anticipated fire scenarios as opposed to standardized results for simple flames in the open.

For example, the OFD-C multi-spectrum IR detectors generally performed well, achieving high detection percentages. However, these devices experienced several failures to detect some of the larger fire scenarios, such as the n-heptane spray fires (~612 kW). The OFD-C detectors also produced some of the longest delays in alarm times, often taking more than 30 seconds to alarm and occasionally taking longer than 200 seconds. This device was also the most susceptible to the hot surface nuisance source.

The UV detector and the OFD-B multi-spectrum IR detector showed the most consistent and fastest alarms for most fire scenarios. The UV OFD experienced almost 100% detection for all scenarios and performed the fastest for nearly every test. The OFD-B showed similar results, but was occasionally slower and failed to detect some flames, especially when viewed from the off-axis position (i.e., 45° horizontally). The primary difference between the performances of these devices was the sensitivity to nuisance sources. While both devices experienced some nuisance alarms, the UV detector produced consistent alarms to all arc welding and torch cutting events, while the multi-spectrum IR OFDs showed less frequent alarms to these sources. In addition, the UV detectors produced false alarms to prolonged ignition sparks used for gas jet fires, and the unshielded propane torch flame used to ignite liquid pool fires.

The VID devices did not alarm in many fire scenarios. Although able to detect the larger n-heptane pool fires in most scenarios, these VID detectors had low alarm rates to the smaller, unobstructed fire sources (e.g., lubricant oil sprays, lubricant oil pools, and diesel pools). The devices were particularly susceptible to obstructions in the FOV, showing significant degradation in performance; sometimes not detecting the n-heptane pool fires. In general, the newer model units (VID-B) were able to detect more fire scenarios than the older model units. This result is reflective of the continuing advances being made in VID technologies. Concurrent with the writing of this paper, additional testing of revised versions of VID devices has shown substantial improvements compared to the results in this report.

7.0 REFERENCES

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