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The Scalability of Smoke Detectors and the Viability of New Detection Methods in Aircraft

August 2019

Technical Thesis

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16. Abstract

Fire detection is a topic of interest in aircraft applications, specifically cargo compartments, given the unique operating environment and accessibility challenges in the event of a fire. The use of unit loading devices inside cargo compartments have also presented a delay in alarm challenge due to their enclosed nature. However, despite the importance of detection, there is yet to exist a standard testing and certification method for fire detection in cargo compartments. The current requirement for a cargo compartment detection system is that a fire has to be detected in 1 minute, and in that time be so small that the fire is not a significant hazard to the airplane. Nuisance alarms also plague the industry, with upwards of 90% of fire alarms being false warnings. These problems have been partially addressed through the analysis of smoke density and state of the art detection technology. Both flaming and smoldering fires were conducted using an array of materials such as heptane, polyurethane foam, shredded paper, wood chips, suitcase, baled cotton, and boiling water. The response of aspirating smoke detectors, dual wavelength technology, and gas detectors were analyzed. It was found that smoke density scales with volume, leading to the suggestion that detection testing could happen outside of cargo compartments and results be appropriately scaled. The response of aspirating smoke detectors, dual wavelength technology, and gas detectors were all found to follow patterns similar to that of light obscuration measurements and were thus deemed viable options for use in cargo compartments. Carbon dioxide and the loss of oxygen were detected 100-600 seconds faster than visible smoke for smoldering polyurethane and smoldering cotton tests, suggesting an increase in gas concentration could be a precursor to visible smoke in certain situations. All new detection technologies were identified for their theoretical improvement in nuisance immunity.

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ABSTRACT

Title of Thesis: THE SCALABILITY OF SMOKE DENSITY AND THE VIABILITY OF NEW DETECTION METHODS IN AIRCRAFTS

Selena K. Chin, Master of Science, 2018

Thesis Directed By: Professor James A. Milke, Department of Fire Protection Engineering

Fire detection is a topic of interest in aircraft applications, specifically cargo compartments, given the unique operating environment and accessibility challenges in the event of a fire. The use of unit loading devices inside cargo compartments have also presented a delay in alarm challenge due to their enclosed nature. However, despite the importance of detection, there is yet to exist a standard testing and certification method for fire detection in cargo compartments. The current requirement for a cargo compartment detection system is that a fire has to be detected in 1 minute, and in that time be so small that the fire is not a significant hazard to the airplane. Nuisance alarms also plague the industry, with upwards of 90% of fire alarms being false warnings. These problems have been partially addressed through the analysis of smoke density and state of the art detection technology. Both flaming and smoldering fires were conducted using an array of materials such as heptane, polyurethane foam, shredded paper, wood chips, suitcase, baled cotton, and boiling

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THE SCALABILITY OF SMOKE DENSITY AND THE VIABILITY OF NEW DETECTION METHODS IN AIRCRAFTS

by

Selena K. Chin

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
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Advisory Committee:
Professor James A. Milke, Ph.D., Committee Chair
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List of Abbreviations

AC: Advisory Circular

AS: Aerospace Standard

ASD: Aspirating smoke detection

CFD: Computational fluid dynamics

CO: Carbon monoxide

CO_2: Carbon dioxide

FAA: Federal Aviation Administration

FAATC: Federal Aviation Administration Technical Center

H_2: Hydrogen

HRR: Heat release rate

IATA: International Air Transport Association

IR: Infrared

LED: Light emitting diode

LHD: Linear heat detector

MLR: Mass loss rate

NTSB: National Transportation Safety Board

O_2: Oxygen

OD: Optical density

PU: Polyurethane foam

RH: Relative humidity

SAE: Space Age Electronics

S-O-A: State of the art

SGSA: Smoke generator standardization apparatus

ULD: Unit load device

UMD: University of Maryland

UPS: United Parcel Service

VESDA: Very early smoke detection apparatus

VLC: laserCompact

VLF: laserFOCUS

Chapter 1: Introduction

The intent for fire detection in any application is to provide early notification of a fire, by sensing one or more aspects of a fire signature, such as smoke, heat, gas, or infrared/ultraviolet light radiation. The desirable features for a detector include quick detection time, immunity to nuisance sources, and reliability. That is, the detector can accurately respond early enough to threatening conditions in order to allow sufficient response time to mitigate or extinguish the fire. The fire detector should also be able to reliably operate within the environmental conditions to avoid false positives.

1.1 Motivation

Fires occur on commercial aircrafts in a variety of spaces, including the passenger cabin, cargo compartments and hidden spaces. Because of this, fire detection serves a useful purpose on commercial aircrafts. Requirements for these spaces, however, are either vague or nonexistent. For existing detection, nuisance alarms plague the aviation industry, with a reported 100:1 false alarm ratio in aircraft cargo compartments [1]. More recent data suggests slightly lower numbers for nuisance alarms – approximately 91.3 % of reported incidents in all cargo compartments and 93.5 % for inaccessible cargo compartments [2]. However, this is still a high and undesirable percentage. These nuisance alarms have been attributed to sources such as dust, insecticides, and water particles due to humidity. Aside from causing a loss of trust in the validity of the fire detection equipment, nuisance alarms have caused diversions and emergency landings, which are costly and time consuming at the expense of the airline. Significant events refer to any occurrence resulting in diversion, return to departure airport, rejected take-off, emergency evacuation, depressurization, fuel dump, inflight thrust engine shutdown, emergency descent, emergency declared, emergency services deployed, ground damage, airplane damage, and overweight landing. In 2011, about 400 significant events occurred in passenger airplanes while about 60 events occurred in freighter airplanes [3]. Thus, a means for full and accurate fire detection in aircrafts is sought.

The purpose of this project is to address the ability of state-of-the-art (S-O-A) detectors and detection systems to substantially address the current aircraft fire detection deficiencies, as outlined above. Emphasis is placed on smoke density in relation to detection of fires in cargo compartments and unit loading devices (ULDs), as well as the reduction of false positives. The review of S-O-A detectors is not limited to only those technologies that are certified for use on aircraft. This review also does not take into account market considerations to exclude detectors using a particular technology by manufacturers who have not historically been involved with the aviation industry.

1.1.1 Cost Analysis

Both fires and false alarms on aircrafts have been the cause for diversions, unscheduled landings, injuries to personnel, fuel jettisoning, airplane damage, and delays and cancellations. All of these have associated costs, which can be quite expensive. A study done by RGW Cherry & Associates Ltd compiled data from multiple sources to summarize some of these numbers [3]. Tables 1.1-1.3 are reproduced from Cherry. These costs are presented at 2016 levels and reflect conservative estimates. It should be noted that airplane out of service time is not presented in these numbers due to insufficient data. However, such is likely to be a significant cost factor.

Flight Diversions

From a ten year period between 2002 to 2011, the cost of flight diversions for passenger airplanes averaged $11,000,000 per year, which was more than 50% of all costs accrued in that time span. Table 1.1 summarizes the minimum, maximum, and mean flight diversion costs for regional, narrow, and wide body airplanes. Logically, the larger the airplane, the higher the costs associated with a flight diversion. On top of fuel costs, maintenance, and ground/flight crew expenses, there are also passengers to compensate, which could include re-accommodating them on other flights, meal vouchers, etc.

Table 1.1: Flight diversion costs at 2016 USD levels.

	Min	Mean	Max
Regional	958	25,762	50,565
Narrow	1,379	26,159	75,804
Wide	6,859	62,469	105,063

Flight Delays

Inflated 2016 numbers for flight delays suggest the average cost of a delay for a passenger airplane is about $7,000. It is assessed that the costs incurred from events leading to flight delays comprise of between 5% and 6%, or $1,100,000 per year for passenger airplanes. It is emphasized that these figures are conservative, as the cost analysis was only done on events that occurred prior to the flight. Table 1.2

summarizes the minimum, maximum, and mean flight delay costs for regional, narrow, and wide body airplanes. As seen with diversions, the larger planes cost the airlines more for delays, for the same reasons.

Table 1.2: Flight delay costs at 2016 USD levels.

	Min	Mean	Max
Regional	264	3,834	12,837
Narrow	542	10,648	40,917
Wide	1,269	24,967	87,401

Flight Cancellations

Inflated 2016 numbers for flight cancellation costs suggest the average cost of a cancellation for a passenger airplane is approximated between \$14,000 and \$16,000. It is assessed that the costs incurred from events attributing to flight cancellations comprise of between 3.5% and 4%, or \$800,000 per year for passenger airplanes. Table 1.3 summarizes the minimum, maximum, and mean flight cancellation costs for regional, narrow, and wide body airplanes. As seen with diversions and delays, the larger planes cost the airlines more, for the same reasons.

Table 1.3: Flight cancellation costs at 2016 USD levels.

	Min	Mean	Max
Regional	3,029	7,426	11,530
Narrow	7,426	18,205	28,266
Wide	38,302	93,901	137,138

Emergency Evacuations

Emergency evacuations where escape slides are deployed are also costly and can lead to injury. In the ten year time span, there were about 130 emergency evacuations due to fire, smoke, or fume events. For passenger airplanes, removal and replacement of escape slides accounted for 3% of the total costs, or $600,000 per year.

Personnel Injury

Payouts resulting from injury to personnel were assessed to be about $4,000,000 per year, or 7% of all costs over the ten year period for both passenger and freighter airplanes. Based on wage forecasts from 2016, there is an expected 1.07 percent annual growth rate in median wages spanning 2013-2043. Thus, this would likewise increase payouts in the subsequent years.

Fuel Jettisoning

Fuel jettisoning is the act of dumping fuel to reduce the aircraft's weight. It is typically done in emergency situations where the plane is heavier than the maximum structural landing weight due to the excess fuel that hadn't been burned off yet. This is a trivial cost compared to the other categories, only accounting for 0.1% to 0.2% of the costs, or $120,000 per year.

Airplane Damage

There were 33 airplanes damaged over 2002-2011. The majority of the damaged was classified as minor, but there were more serious incidents such as the United Parcel Service (UPS) DC-8 fire in 2006 [4] and UPS freighter accident in 2010 [5]. Airplane damage was assessed to account for between 20% and 30% for passenger airplanes, which averaged $5,500,000 per year.

1.2 Fire Detection Technologies

This section provides a broad overview of commercially available fire detection technologies, including a brief description of the mechanisms utilized and performance characteristics of each technology.

1.2.1 Ionization Smoke Detector

An ionization type smoke detector uses a small amount of radioactive material in the sensing chamber to ionize the air, making the air conductive thereby providing a current flow between two charged electrodes. When the smoke particles enter the sensing area, they attach themselves onto the ions causing a reduction in ion mobility and the conductance of the air is decreased. The detector responds when the conductance, i.e. current flow between electrodes falls below a threshold level. This is shown in Figure 1.1.

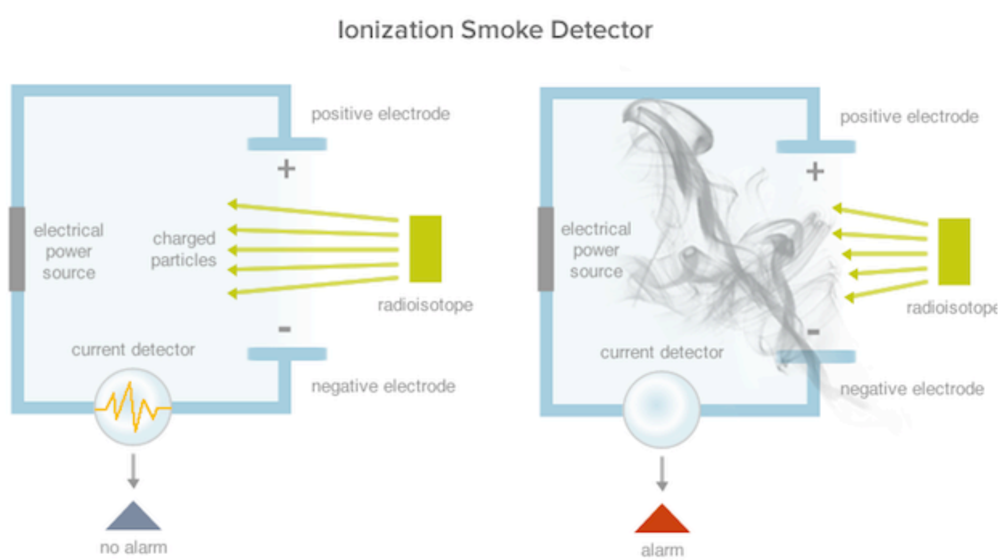


Figure 1.1: How an ionization detector works. Source: https://simplisafe.com/blog/smoke-detector-alarms-guide

Ionization smoke detectors are most sensitive to small particles [6,7]. Small particles are predominantly produced by flaming fires (as compared to smoldering fires that produce larger particles). As such, ionization smoke detectors have been demonstrated to be more sensitive to flaming fires than smoldering fires. A disadvantage of ionization smoke detection is their increased sensitivity to small particles from nuisance sources.

1.2.2 Photoelectric Smoke Detector

The presence of smoke particles affects the propagation of a light beam passing though air. Traditional photoelectric smoke detectors detect fire through forward scattering, though back scattering has been incorporated into more contemporary developments. Early photoelectric smoke detectors also utilized light obscuration, though such a mechanism is now only used with projected beam detectors (described in the next subsection). Figure 1.2 shows how a photoelectric detector works.

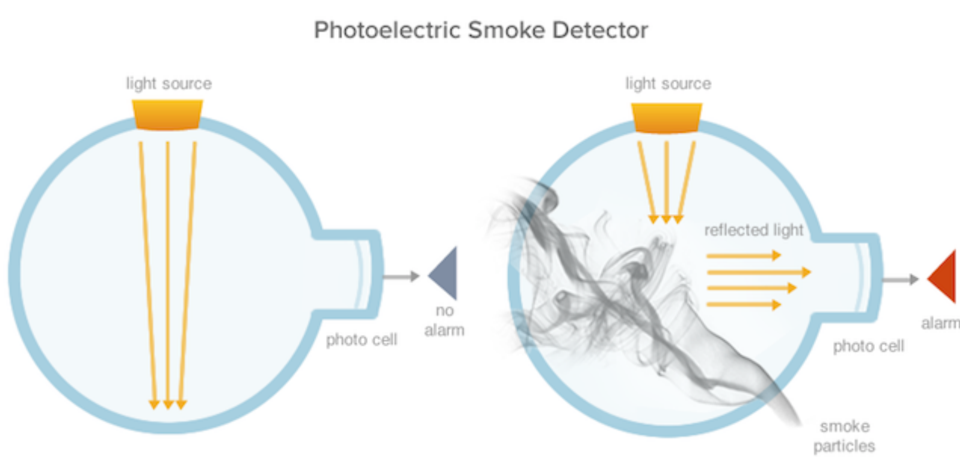


Figure 1.2: How a photoelectric detector works. Source: https://simplisafe.com/blog/smoke-detector-alarms-guide

The light source in photoelectric smoke detectors is typically an infrared light emitting diode (LED). Lasers have been incorporated into recently developed photoelectric smoke detectors. Wavelengths other than those in the infrared range have been incorporated into some contemporary photoelectric smoke detectors and some detectors include dual bands to assist with discrimination between particles produced by fires versus nuisance sources. A disadvantage of photoelectric smoke detection is their reduced sensitivity to small particles.

1.2.3 Projected Beam Detectors

Generally, projected beam detectors are used in large open spaces such as atriums, arenas, and warehouses. Projected beam detectors operate based on the principle of light obscuration by smoke particles. Projected beam detectors typically include one light source (typically an infrared LED) and a photocell [8]. More recently developed projected beam detectors utilized two beams with two wavelengths, e.g. infrared and ultraviolet, to assist with discrimination between fire and nuisance sources [9]. With two beams, the attenuation of light due to smoke, solid objects, dust, and other nuisance sources varies with the wavelengths of light emitted by the two beams. When smoke particles from a fire are present in the space between the emitter and receiver, they reduce the ultraviolet beam more than the infrared. When other particles reach the ultraviolet and infrared beams both beams will be blocked at roughly the same amount. The premise of a projected beam detector is shown in Figure 1.3.

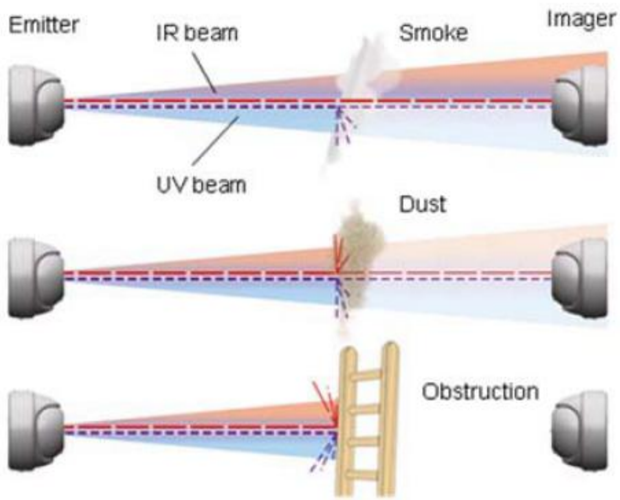


Figure 1.3: How a projected beam detector works.
Source: https://www.umbra-fsp.de/en/portal-en/trade/distribution-en/xtralis.html

Projected beam detectors require a direct line of sight between the LED and receiver with no obstructions. Also, projected beam detectors require that the alignment of the emitter and receiver is maintained, with any movement in the alignment being cause for a nuisance alarm (in early models), or a trouble alarm with more recently developed versions.

1.2.4 Aspirating Smoke Detector

An aspirating smoke detector (ASD) draws smoke from an area and transports it via tubing to optical monitoring equipment, as shown in Figure 1.4. The optical monitoring equipment operates similar to other technologies with light beams. Use of a laser does increase the sensitivity of the unit appreciably.

ASDs were initially developed for rooms containing electronic data processing or telecommunication equipment. However, in recent years, ASDs have been utilized in a wide variety of applications, including areas with high ceilings like warehouses, atriums, and large manufacturing spaces.

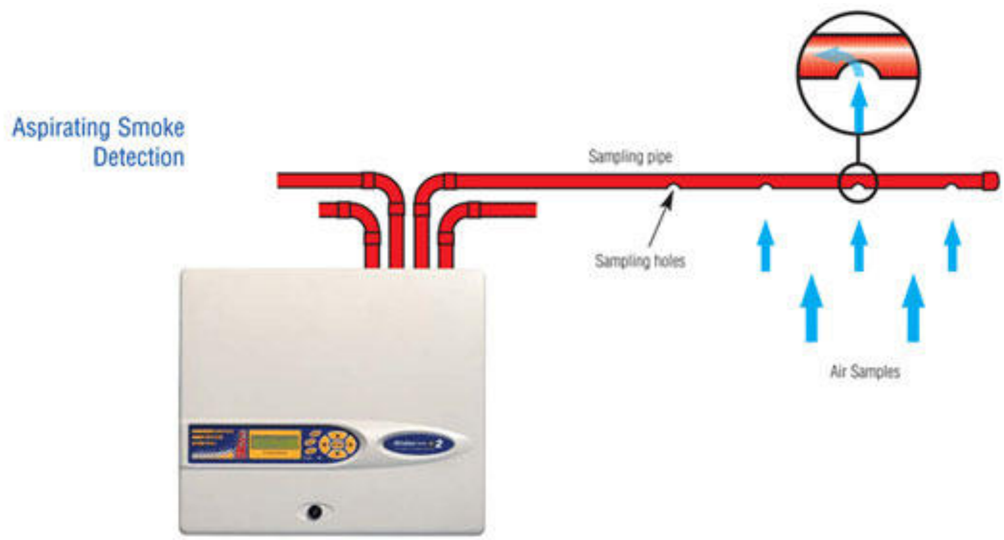


Figure 1.4: How an ASD works. Source: https://electroviees.wordpress.com/2013/11/25/smoke-detectors/

A principal advantage of an ASD is that it is capable of protecting large areas at a high sensitivity level. ASD units are not as sensitive to air velocities, temperature, or humidity conditions as compared to other smoke detector technologies [10].

A disadvantage of ASDs have been that it is unable to identify the specific sampling point that smoke entered the chamber, making it more difficult to locate the fire as compared to an addressable detector. However, with recent developments, an addressable ASD unit is now available from one manufacturer such that the location of the sampling source drawing in smoke can now be identified [11].

1.2.5 Dual Wavelength Detection

Smoke detection that is able to reject nuisance sources is valuable in the aviation industry due to the high percentage of false alarms. One type of technology uses size discrimination, utilizing both blue and infrared (IR) light scattering. Typically, smoke particles are less than 1 μm in diameter, while nuisance sources are larger than 1 μm [12]. For a range of fires of different materials, setups, researchers, and instrumentation, smoke particles were found to range between 46 nm to 1100 nm, averaging a size of 263 nm [12]. Furthermore, smoldering fires typically have larger particles than flaming fires.

Being at a shorter wavelength and higher frequency, blue light scatters smaller particles more efficiently than IR light. Thus, the blue light should theoretically interact strongly with both small and large particles, while the longer IR wavelength should predominantly be affected by larger particles [9]. This means blue and IR wavelengths should measure about the same changes for smoldering fires and blue should increase more for flaming fires. Thus, this technology would be useful both in detecting smoke particles and distinguishing nuisance sources by using the difference in the blue and IR signals to provide some idea of particle size.

1.2.6 Gas-Sensing Fire Detectors

An assortment of gas species is generated as combustion products from a fire. Fires involving all organic fuels will produce carbon monoxide, carbon dioxide and water vapor. A drop in oxygen typically accompanies fires due to oxidation [13]. In recent years, carbon monoxide and carbon dioxide sensors have become popular for monitoring the atmosphere in building applications for general health or environmental control purposes. Some recently developed multi-sensor fire detectors have included carbon monoxide or carbon dioxide sensors.

Previous work by Milke [14] and Hagen and Milke [15] indicated the advantages of using carbon monoxide and carbon dioxide sensors in multi-sensor fire detectors as a means of providing prompt fire detection as well as significantly reducing nuisance alarms. Basing detection off of gas assures nuisance sources such as dust or skin particles cannot trigger an alarm since fires release gases that are largely absent among nuisance sources. Water vapor due to humidity should also not set off a gas alarm for any of the aforementioned gases.

Aside from the benefit of nuisance immunity, gas detection also has the potential to respond quicker than detection that relies on sensing smoke particles. Smoke particles are transported predominantly by convection (due to heat), while gas is transported by both convection and diffusion [16]. There has also been an observed "heat layer" that appears in some smoldering fires, where temperature differences between near ceiling positions and the room create a layer that delayed smoke particles from passing through [16]. Thus, gas detectors should theoretically be able to efficiently and reliably detect fires while lowering rates of false alarms.

Disadvantages of gas sensing detection are that current sensors do not have a long life span and sensors have the potential to drift (i.e. go out of calibration) over time or as a result of being in a harsh environment [17].

1.2.7 Video Detection

Video fire detection systems monitor the magnitude or changes in brightness displayed in some pixels to identify the presence of a flame or smoke. Video detection is used principally in large open spaces such as atria and warehouses.

Advantages of using video smoke detection include the large coverage area and fast response time. Video detection also can display a visual image that the camera sees to permit confirmation of events by remote observers. Additionally, continuous recording of the images allows for post-event analyses.

The disadvantage of video smoke detection is it is hard to detect smoke in areas with low light levels. Video detection also requires maintenance to keep the camera lens clean, which can be particularly challenging in harsh environments.

1.2.8 Spot Heat Detector

Spot heat detectors respond to the thermal energy released by the fire. Typically, the response of spot heat detectors is governed by convective heating rather than radiative heating. Depending on the particular model of a spot heat detector, they respond to a fixed temperature level, rate of temperature rise or both. Given that smoldering fires usually have very low energy output, a heat detector is unlikely to be responsive to a smoldering fire.

1.2.9 Line-Type Heat Detector

A typical line-type heat detector is a cable that contains a pair of wires in a normally open circuit. The wires are separated by heat sensitive insulation. When the temperature limit is reached, the insulation melts and the two wires come in contact signaling the alarm. Linear heat detection is used most often in spaces where traditional detection technologies are not viable, such as conveyor belts, mines or tunnels.

The advantage of linear heat detection is it requires minimal maintenance. Linear heat detection can be used in environments with harsh conditions and minimal clearance (hence the application in conveyor belts). A disadvantage of linear heat detection, as with any thermally activated detector, is the inability to respond to smoldering fires which generate minimal thermal energy.

1.2.10 Radiant Energy Detector

Radiant energy detectors respond to radiant emissions from a fire. Commercially available radiant energy detectors (also referred to as 'flame detectors') monitor radiant emissions in the infrared, ultraviolet or visible wavelengths. Radiant energy detectors may be capable of monitoring a single wavelength, or multiple wavelengths, where those being able to monitor a combination of wavelengths have improved fire versus nuisance source discrimination abilities.

Radiant energy detectors are line-of-sight detectors, similar to projected beam detectors. Hence, an unobstructed line of vision is needed. These detectors require any fire source to be emitting some radiant energy (threshold levels vary), such that these detectors are unlikely to be effective in detecting smoldering fires or fires behind obstructions.

1.2.11 Discussion

With the exception of video and duel wavelength detection, all of these technologies have been adopted for commercial use since the 1970's with little change. Since then, the principal advances in fire detection have been associated with improved identification of the location of the actuated detector (or location along a linear heat detector) or with the capability to discriminate between fires and changes in the environment due to non-fire sources.

The discrimination capabilities have been incorporated through the use of multiple sensors or algorithms. Multi-sensor detectors may include two (or more) technologies of the types described previously in this section, or may include the same sensor, such as one using two beams with different wavelengths. Appreciable research effort has been expended over about the last 25 years to develop algorithms where multiple sensors are involved [18-20].

The applicability of the different detector technologies in aircrafts and the principal challenges associated with each type of detector are included in Tables 1.4 and 1.5 respectively.

Table 1.4: Applicability of fire detection technologies for commercial aircrafts [21]

Technology	Sensitivity – flaming fires	Sensitivity – smoldering fires	Nuisance alarm susceptibility	Maintenance
Ionization	H	M	H	H
Photoelectric	M	H	M	M
ASD	H	M-H	M	H
Projected beam	M	H	M	H
Video	H	H	M	H
Spot heat	H	L	L	L
Linear heat	H	L	L	L
Radiation	H	L	L	H
Gas	M-H	M-H	H	H

H = High, M = Moderate, L = Low

Table 1.5: Challenges in applying detection technologies in commercial aircrafts [21]

Technology	Principal Challenge
Ionization	Nuisance alarm susceptibility, modest response to smoldering fires
Photoelectric	Modest response to flaming fires with limited visible smoke
ASD	Maintenance of filters
Projected beam	Maintenance of photo-receiver, provision of clear pathway for light beam
Video	Provision of clearance space for viewing, lighting
Spot heat	Slow response to smoldering fires
Linear heat	Slow response to smoldering fires
Radiation	Maintenance of optics
Gas	Stability of sensors

1.3 Overview of Aircraft Spaces

This section defines the relevant aircraft spaces for this study and provides a summary of the current fire detection protocols followed in these areas.

1.3.1 Passenger Cabin

Definition

The passenger cabin is the upper area of the aircraft where passengers travel.

Current Fire Detection Protocol

The only requirement for detection in the passenger cabin is in the lavatory, as it is a non-continuously occupied area. Lavatories on planes with a passenger capacity of 20 or more are equipped with a smoke detector in accordance with the Federal Aviation Regulation 25.854 [22].

1.3.2 Cargo Compartment

Definition

A cargo compartment is an internal space designed to carry baggage or other cargo. For passenger aircrafts, these spaces are found in the lower half of the plane. An example of a cargo compartment is shown in Figure 1.5. There are several classifications of cargo compartments, and in order for a compartment to be classified, it must pass necessary tests including smoke detection, if applicable. Cargo compartments are classified A through F and are defined in Title 14 Code of Federal Regulations 25.857 [22]. Class D is no longer recognized as a class. These classification and detection requirements are included in the remainder of this section.

Figure 1.5: Example of a cargo compartment space (Class E).

Current Fire Detection Protocol

A Class A cargo or baggage compartment is one in which the presence of a fire would be easily discovered by a crewmember while at his station and each part of the compartment is easily accessible in flight. They are not required to install smoke detection systems and must only pass smoke detection tests if a system is installed.

Due to the fire's close proximity to a crewmember, the fire can easily be spotted and promptly extinguished. Among all classes of the cargo compartments, Class A is the only compartment not requiring smoke detection.

A Class B cargo or baggage compartment is one in which there is sufficient access in flight to enable a crewmember, standing at any one access point and without stepping into the compartment, to extinguish a fire occurring in any part of the compartment using a handheld fire extinguisher. This means that the cargo compartment area is limited to the main deck and it has been recommended that a fire could be successfully fought if the compartment does not exceed a 52-inch radius [23]. It also requires that no hazardous quantity of smoke, flames, or extinguishing agent, will enter any compartment occupied by the crew or passengers when the access provisions are being used. A separate approved smoke detector or fire detector system is required in the compartment, providing warning at the pilot or flight engineer station.

A Class C cargo or baggage compartment is one not meeting the requirements for either a Class A or B compartment but in which there is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station; there is an approved built-in fire extinguishing or suppression system controllable from the cockpit; there are means to exclude hazardous quantities of smoke, flames, or extinguishing agent from any compartment occupied by the crew or passengers; and there are means to control ventilation and drafts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment.

A Class E cargo compartment is found only on all-cargo planes. There is a separate approved smoke or fire detector system to give warning at the pilot or flight engineer station; there are means to shut off the ventilating airflow to, or within, the compartment, and the controls for these means are accessible to the flight crew in the crew compartment; there are means to exclude hazardous quantities of smoke, flames, or noxious gases, from the flight crew compartment; and the required crew emergency exits are accessible under any cargo loading condition.

A Class F cargo or baggage compartment must be located on the main deck and is one in which there is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station; there are means to extinguish or control a fire without requiring a crewmember to enter the compartment; and there are means to exclude hazardous quantities of smoke, flames, or extinguishing agent from any compartment occupied by the crew or passengers.

Per Title 14 Code of Federal Regulations 25.858, the cargo compartments that require detection must meet the following:

(a) The detection system must provide a visual indication to the flight crew within one minute after the start of a fire.

(b) The system must be capable of detecting a fire at a temperature significantly below that at which the structural integrity of the airplane is substantially decreased.

(c) There must be means to allow the crew to check in flight, the functioning of each fire detector circuit.

(d) The effectiveness of the detection system must be shown for all approved operating configurations and conditions.

Furthermore, Advisory Circular (AC) 25-9A specifies that the smoke or fire detection systems should provide warning before the fire and the smoke detection test is designed to demonstration that the smoke detection system installation will detect a smoldering fire producing a small amount of smoke. From the literature, these requirements are vague, and the only quantitative provision is the 1 minute detection time. Details are not provided on aspects such as size of the fire or how much smoke is a “small amount.” Additionally, the requirements neglect testing with the flaming mode of combustion even though a detector would need to be able to respond to a flaming fire. Both flaming and smoldering tests are required in UL268 for detectors in building applications, and they should logically apply to aircraft testing as well.

1.3.3 Unit Load Device (ULD)

Definition

A ULD is a container or pallet used to neatly store cargo in the cargo compartment. The advantage of using ULDs is that it saves the ground crew time in having fewer units to load into and from the aircraft, thus leading to fewer delays. The International Air Transport Association (IATA) reports there are over 900,000 ULDs in service valued at over one billion USD [24]. The ULDs are typically made of aluminum or a combination of aluminum and polycarbonate and can accommodate a variety of volumes depending on the type of ULD. These volumes range from 3.5-15.9 m^3 for containers and 39.6 m^3 for pallets [25]. An example of a ULD is shown in Figure 1.6.

Figure 1.6: Example of a ULD.

Current Fire Detection Protocol

There are no requirements for fire detection in ULDs. This is a concern especially for the containers because the enclosed environment prevents detectors located near the ceiling of the cargo compartment from sensing the early stages of a fire. Only once the fire has grown enough to breach the container would the detectors alarm, but by then there is likely not enough time for a sufficient response to the fire. This problem has been somewhat exacerbated in recent years, as fire resistant containers are being introduced [26]. This would further increase the time for a fire to breach the ULD, allowing even less time for a response from the crew before threatening conditions are generated.

1.4 Detection Certification

Smoke detector certification tests are conducted at both ground and inflight conditions due to differences in environmental and atmospheric conditions. Variables such as pressure, airflow, and temperature all fluctuate between ground and flight conditions. According to AC 25-9A, the smoke detection testing should be "conducted during cruise at normal cabin-to-ambient pressure differential with maximum normal ventilation flow rate. The airplane should be operated in the various dispatchable ventilation and pressurization configurations (one air conditioning pack, two air conditioning packs, unpressurized, etc.) for the cruise condition. The combustible material used for testing should be representative of what would be expected to burn in the area under consideration" [23]

Ventilation flow rates can vary depending on the plane, but a source suggests newer airplanes can have air ventilation rates of 10-11 cubic ft/min, while others such as a DC10 can be as high as 50 cubic ft/min [27]. Temperature within the cargo compartments track ambient temperature, though airlines usually seek to maintain temperatures above freezing through the installation of small heaters [17]. Relative humidity within the compartment is generally uncontrolled and hence follows ambient levels. Relative humidity will typically range from 10-20%, but in extreme conditions could be as low as 1% [27].

Aerospace Standard (AS) 8036A details the extreme conditions in which detectors should accurately perform. This includes ramping to 95% relative humidity

(RH) at an average rate of 6%/minute and to a temperature to 50 °C at a rate of 5 °C per minute, maintaining these conditions for 30 minutes. The temperature should then be ramped down to 0 °C at a rate of 5 °C per minute and the humidity to ambient conditions at an average ramp rate of 6% RH/minute. The chamber is ramped from the test site pressure to 15,000 feet pressure altitude and these conditions are maintained for 1 hour [28].

DO-160G categorizes most of the different environments present in aircrafts and details the range of operating conditions in which detectors in those environments should meet. This includes a low operating temperature ranging from -15 to -55 C depending on the environment and a high operating temperature ranging from 55 to 70 C depending on the environment. In some environments, it is noted that the detector low and/or high operating temperature is declared by the detector manufacturer. With cargo compartments typically being somewhat temperature and pressure controlled, the environments would likely be classified as type A, meaning the low and high operating temperatures should be -15 and 70 C, respectively. They should also not be adversely affected by exposures to temperatures between -55 and 85 C or pressures between 23 to 170 kPa.

1.5 Modes of Combustion

There are two principal ways that fires can burn, and fire detectors must be able to accurately detect both types consisting of smoldering and flaming combustion. Characteristics of smoldering combustion include slow burning, low temperature, and lack of flame. While there is enough heat and oxygen to sustain the reaction, there is limited oxygen and/or limited heat that keep the fire from growing or transitioning to a flaming fire. The reaction is sustained by the heat evolved when oxygen directly attacks the surface of a condensed phase fuel [29], and it is capable of producing hazardous amounts of toxic gases [13]. Flaming combustion is characterized by rapid growth, higher temperatures, and flame, as the name suggests. It involves gaseous fuel mixing with oxygen and releasing heat, and the process can also produce different gases depending on the fuel [30].

Chapter 2: Literature review

2.1 Performance of Fire Detectors

Smoke detector response time was brought to the attention of the Federal Aviation Administration (FAA) via the National Transportation Safety Board (NTSB). They expressed a concern in response to an in-flight cargo fire in a United Parcel Service DC-8 aircraft in 2006 [31]. Although the flight crew discussed smelling burning wood, the smoke detection system did not alarm until 20 minutes later. The fire initiated from an unknown source in a cargo container. Coupled with the lack of an on-board fire suppression system, the slow detector response time led to the growth of the fire and subsequent loss of the plane [32]. With the integration of fire resistant barriers on cargo containers, the concern for prolonged detection times is exacerbated. Having fire resistant barriers would contain the fire further, allowing it to grow and possibly be uncontrollable by the time it is detected. This would reduce the time for the crew to respond in order to execute a safe, emergency landing.

The FAA conducted a series of tests to evaluate how smoke detection times were affected by both the loading of the cargo compartment and active containers, which introduced additional airflow patterns through climate control systems. Smoke was introduced at different locations in multiple tests for empty and fully loaded cargo compartments, using aspirated photoelectric smoke detection with ten sampling points. Smoke detection times were consistently faster in the fully loaded compartments than the empty ones. For active containers, tests were conducted in fully loaded cargo compartments with smoke generated at different positions and either two, four, or six fans in the active cargo containers turned on. The results were highly variable between tests, leading the FAA to conclude that active containers did not influence smoke detection [31].

Another concern with the current state of fire detection in aircraft is the high proportion of false alarms [3]. Over a ten year period of 2002-2011, virtually all of the alarms smoke detection systems on board aircraft were false warnings. False warnings may be caused by a proper response of a sensor to presence of particulate matter provided by a non-fire (i.e. “nuisance”) source or may be due to a problem within the sensor or communication network itself. This same issue is at the forefront of the detection industry for building applications as well, with new tests adopted in UL 268 [33] to assess the ability of smoke detectors to ignore “smoke” from prevalent nuisance sources.

From the study by RGW Cherry & Associates Ltd, false warnings accounted for 90% of detector events in inaccessible cargo bays, while only 1% of the warnings were actual fires. These false warnings caused 59% of passenger planes and 57% of freighter planes to engage in unscheduled landings. Rejected take-offs occurred for 1% of passenger planes and 2% of freighter planes. In accessible cargo bays, false warnings accounted for 94% of detector events, while 0% of the warnings were actual fires. These false warnings caused 26% of regional airplanes to engage in unscheduled landings, and 3% were rejected take-off. In main deck cargo bays, false warnings accounted for 73% of detector events, while 1.4% of the warnings were actual fires. These false warnings caused 40% of freighter airplanes to engage in unscheduled landings, and 7% were rejected take-off.

In some cases, false warnings may be initiated by passengers or crew. These are often the result of condensation or hydraulic fluid or engine oil leaks into the Environmental Control System.

False warnings have resulted in unscheduled landings and rejected takeoffs in almost half of the incidents on board all aircraft (passenger or freighter). Nuisance alarms in aircraft cargo compartments present an especially difficult challenge due to the inaccessibility of cargo compartments on most passenger aircraft and the potential for significant fire development leading to the loss of flightworthiness of the aircraft. The false warnings result in interruptions in service and delays which then result in appreciable costs being sustained by the airlines [34]. If an emergency evacuation is initiated, passengers are put at risk of injury. The alternative of ignoring the signals from smoke detectors by crews is also not acceptable. Hence, the cause of the false warnings, and identification of solutions is a high priority.

The NTSB has also recommended that fires in hidden areas and the source of non-fires be studied. Detection is not currently required in these spaces, but those areas have been identified as a potential gap in the fire safety measures provided given that fires can be initiated and grow in these spaces.

Advisory Circular (AC) 25-9A suggests appropriate smoke generators and fuels for smoke detection tests in sections 9a.1 and 9a.2 respectively, along with test guidelines in section 10 that comply with regulations. Flight tests typically utilize simulated smoke (smoke generators) for safety reasons [22]. Examples of acceptable smoke generators include a Rosco theatrical smoke generator or a Woodsman bee smoker [23]. It should be noted that extra measures should be taken when working with theatrical and beekeeper type smoke generators in order to produce the correct amount of smoke. More information can be found in section 10a.3 for theatrical smoke generators. Examples of acceptable fuels include plastic, paper, or burlap; however, resin blocks, suitcases, and Jet A fuel have been widely considered for use in certification tests [35].

Because fire detection systems need to prove their effectiveness for all possible fire scenarios, the most critical scenario is tested. This is a smoldering fire that produces a small amount of smoke; however, "small amount" is subjective to parameters such as compartment size and materials [36]. Most cargo compartment smoke detectors are photoelectric type detectors. Photoelectric detectors alarm based on light scattering from smoke particles. Ionization detectors alarm from smoke particles disrupting ionized air and causing a drop in current. Photoelectric detectors are better suited for detecting smoldering fires with large particles, while ionization detectors are better suited for detecting flaming fires with high concentrations of smoke particles. SAE AS 8036A requires detectors to operate between 0 and 50 °C and up to a relative humidity of 95% [28]. Successful operation would satisfy the requirement of detecting fires well below temperatures that would compromise structural integrity.

It should be noted that the FAA had conducted experiments back in 2008 that targeted nuisance alarms [37]. These tests aimed to develop a multisensor detector that would provide better nuisance alarm rejection while still complying with Title 14 Code of Federal Regulation smoke detection requirements. This included developing algorithms for the detector to distinguish between fire and nuisance sources and comparing its performance to that of conventional aircraft smoke detectors. The multisensor detector comprised of a measuring ionization chamber, smoke meter, gas probe, and thermocouple. The detector was tested with real fire and nuisance sources, and their respective fire signatures were characterized. In order to predict the detector's range, it was then tested with a computational fluid dynamic (CFD) model from Sandia National Laboratories. Using data from the four sensors, five algorithms were developed for the multisensor detector which all included rate of rise parameters. Using rate of rise has also been identified as a good strategy in building applications [18,19].

For the initial tests, the fire sources used were denatured alcohol, polyurethane foam, alcohol-soaked rags, shredded newspaper, and a suitcase. The nuisance sources were a vaporizer, Arizona test dust, a heat gun, human respiration, and exhaust fumes. The detector was placed in the center of a Boeing 707 cargo compartment, with test fires taking place in the center, sidewall, forward starboard (front right), aft port (rear left), and aft starboard (rear right). Only the center of the cargo compartment held tests for all ten fire and nuisance sources; however, perimeter testing was done for the polyurethane foam, alcohol-soaked rags, and shredded newspaper sources in the forward starboard and aft starboard corners, as well as for Arizona test dust two and four feet from the detector. Additionally, a resin block was tested in the center and also used in perimeter tests at the forward starboard and aft starboard corners, and sidewall starboard. Because resin blocks are repeatable fire sources, the main use of the resin block was to determine the accuracy and performance of the sensors.

Perimeter testing aided in selecting algorithm thresholds for cargo fires farther from the detectors.

Standard photoelectric detectors in cargo compartments are designed to alarm at smoke levels between 4-40%/ft, meaning the fastest they could alarm is when 96% light transmission per foot is measured. Ionization detectors have varying alarm thresholds; the voltage threshold for the model used in experiments was found to be 4.1 volts. From the resin block, nuisance, and fire testing, the photoelectric and ionization detectors mostly alarmed under the required 60 seconds and were usually comparable to the multisensor detector with all five algorithms. However, it is important to note that the photoelectric and ionization detectors had 6/8 and 4/8 false alarms respectively, while the multisensor detector had 0 false alarms for all five algorithms. In addition, the photoelectric and ionization detectors either alarmed too late or not at all 22% and 17% of the time, while for the multisensor detector, algorithm 1 was 17%, algorithms 2 & 5 were 0%, and algorithms 3 & 4 were 5.5%.

From this experiment, it was concluded that a multisensor detector would be an exceptional replacement for conventional aircraft smoke detectors. Two algorithms provided 100% nuisance immunity as well as 100% success rate in detecting all fires and alarming within 60 seconds. This was better than the photoelectric (66.67% success rate) and ionization (73.33% success rate) detectors, which failed 4/5 and 2/5 nuisance source tests respectively. Algorithm 5 had the best performance, with 100% success rate, 100% nuisance immunity, and the fastest responses times. Using CFD for the resin block fires found good agreement in predicting alarm times for the detectors. For the best performing algorithms (2 & 5) with the multisensor detector, there was a maximum difference of 4 s, and an overall average of 1.75 s. This suggests that CFD could be utilized in simulating detector times for cargo compartment fires and can also adequately assess the physical range of a detector.

Chapter 3: Experimental Setup

3.1 Fire Tests

Different detection technologies were sought from various manufacturers to test their viability for aircraft applications. The different detectors included linear heat detectors, wireless detectors, spot detectors, and aspirating smoke detectors. Many companies were invited to participate in the study and anyone agreeable was included. Fire tests were conducted in different volumes at UMD and FAATC. The spaces, instrumentation, sources used, and protocol followed are described below.

3.1.1 UMD Box

A 1 m^3 box was constructed using 18-gauge angle irons and 1/2” thick insulation board. A thermocouple tree placed 9 thermocouples every 3.5” from the top, measuring the temperature 15” in from the side of the box. The thermocouple wires were insulated with copper refrigeration tubing so only the beads were exposed to heat. A light obscuration meter was placed 18” from the bottom of the box and 10” from the side. The box sat on 7.5” high bricks and the insulation board on top was attached via a hinge for ease of getting in and out of the box. ASD sampling points were placed at the middle point on the top insulation board. Dimensions are shown in Figures 3.1 and 3.2, and photos from testing are shown in Figures A.1-A.3. In order to test in a volume of 0.7 m^3, insulation board was placed in the box so as to cut off 30% of the volume. This is shown in Figure A.4.

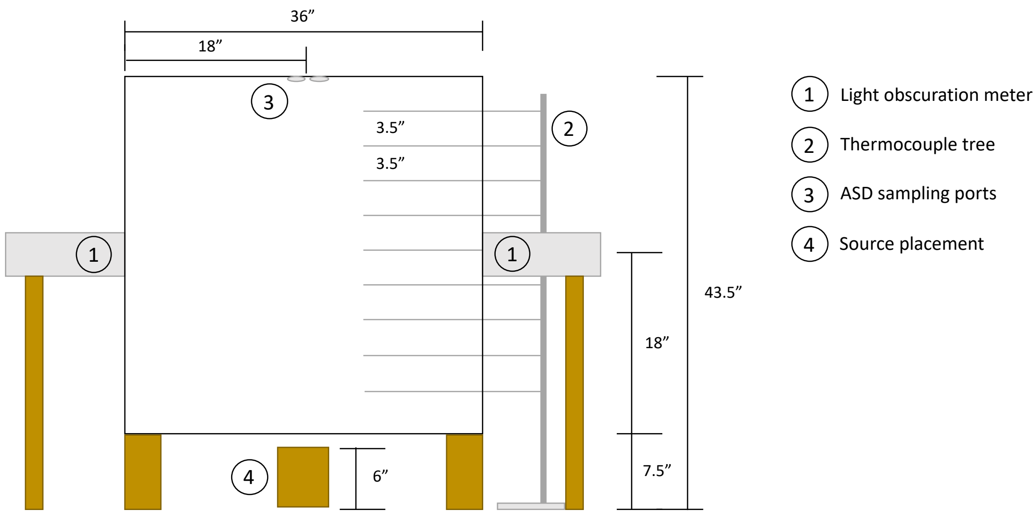


Figure 3.1: UMD box and instrumentation dimensions (front view).

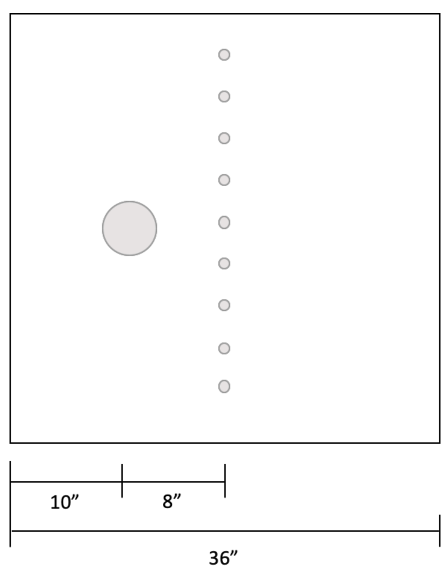


Figure 3.2: UMD box and instrumentation dimensions (right side view).

3.1.2 FAATC ULD

At FAATC, tests were done in an LD3 ULD mockup, which had a volume of 4.5 m3. A thermocouple tree placed 8 thermocouples every 3.5” from the top, measuring the temperature above where the source was placed. Additionally, four ceiling thermocouples were placed in the ULD. Part of one side of the ULD was replaced with a Plexiglas door on a piano hinge for ease of getting in and out of the ULD to start and end tests, as well as for airing out the space after each test. Four obscuration meters were placed about 4 ft apart near ceiling height. A dual wavelength detection setup, also known as Smoke Generation Standardization Apparatus (SGSA), was placed near ceiling height on the right wall. Exact dimensions and locations of instrumentation are shown in Figures 3.3-3.5. It should be noted that in Figure 3.4, a 13" gas burner is shown, but that was only the setup for most of the smoldering tests. The flaming tests were conducted on a plate 4" off the ground and the shredded paper tests were conducted on a 11.75" high ring stand. This is called out in Table A.1. A photo from testing can be seen in Figure A.5.

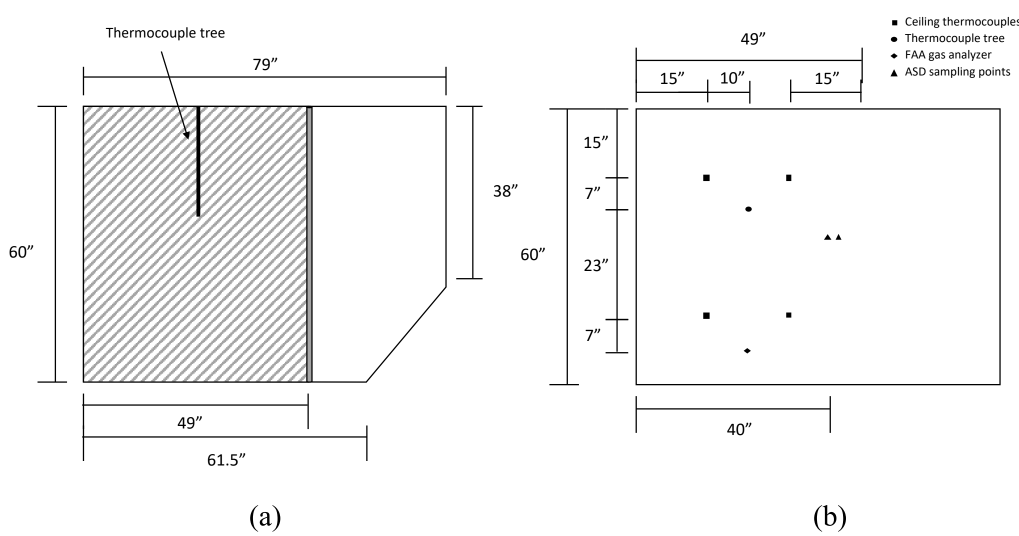


Figure 3.3: (a) Front view of ULD with shaded Plexiglas door. (b) Top view of ULD.

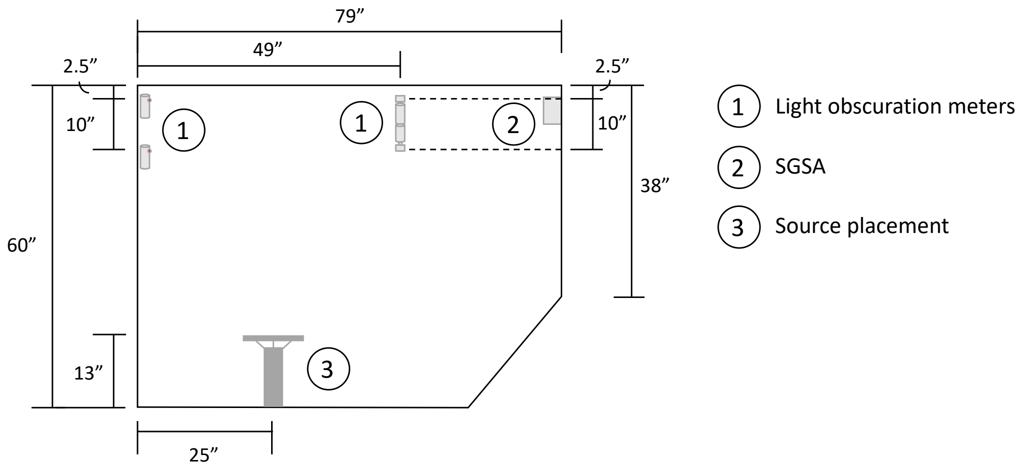


Figure 3.4: Inner front view of ULD with light obscuration meters, SGSA, and source placement.

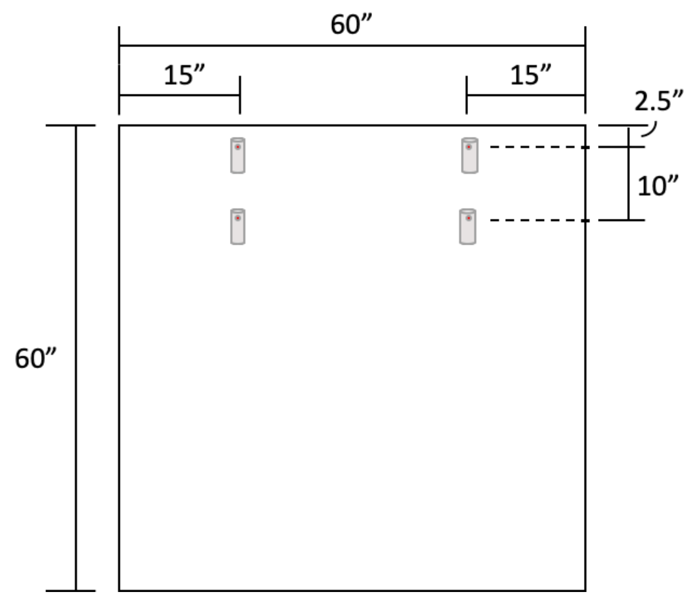


Figure 3.5: Inner left side view of ULD with light obscuration meter placements.

3.1.3 FAATC Cargo Compartment

Testing was also done in a DC-10 cargo compartment. The entire volume was not utilized due to time constraints and the smaller nature of the fire tests. Instead, a little more than half of the 3500 ft3 volume was partitioned off and testing occurred in a volume of 1600 ft3 (45 m3). A thermocouple tree placed 8 thermocouples every 3.5” from the top, measuring the temperature above where the source was placed. Additionally, 25 ceiling thermocouples were used. Four light obscuration meters were used and were placed in the same setup as the ULD. The SGSA was attached to the right most part of the obscuration meter frame. Exact dimensions and locations of instrumentation are shown in Figures 3.6-3.7 and A.6. It should be noted that in Figure 3.7, the source location is representative of the flaming tests regarding height of the sample. The smoldering tests were conducted on a gas burner 13” off the ground and the shredded paper tests were conducted on a 11.75” high ring stand. This is called out in Table A.1. A photo from testing can be seen in Figure A.7.

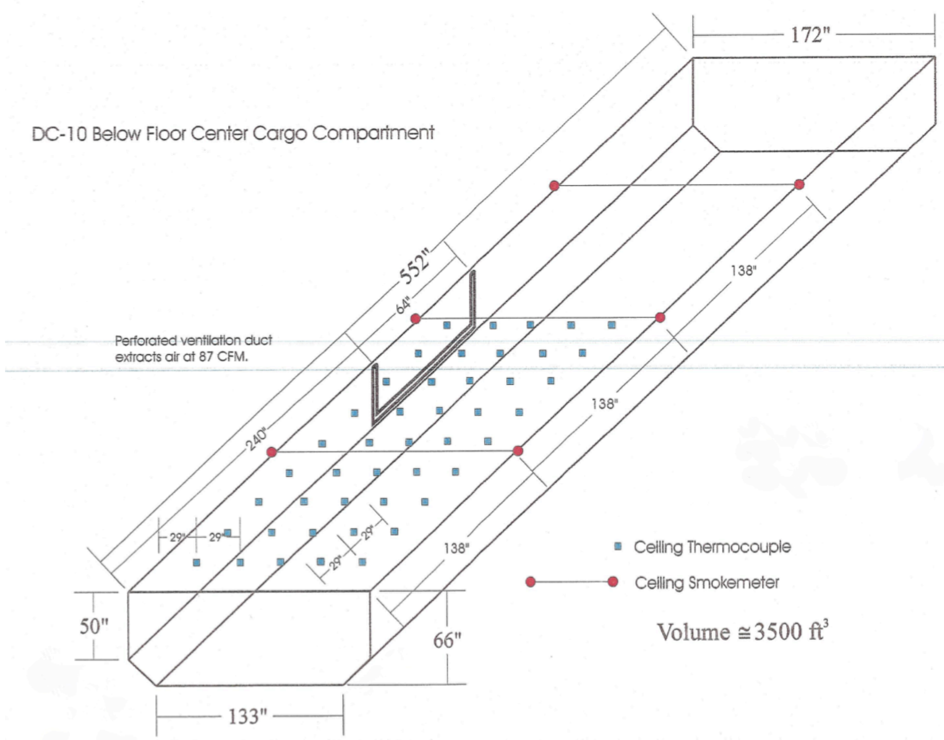


Figure 3.6: Full dimensions of the DC-10 cargo compartment with available instrumentation also denoted.

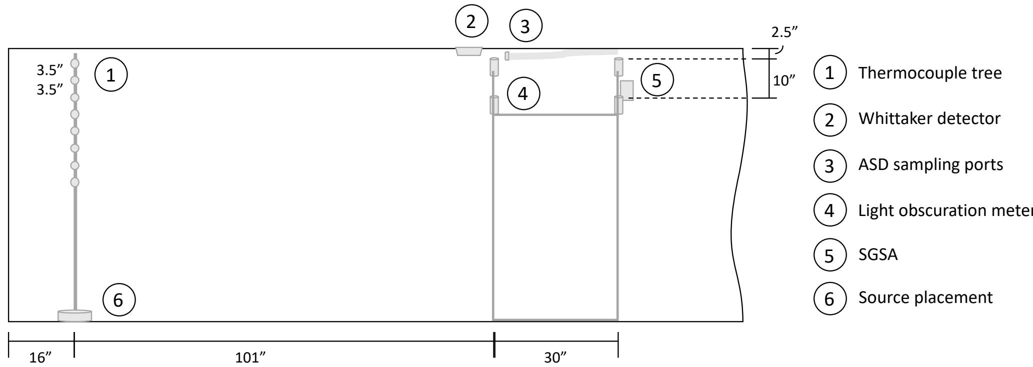


Figure 3.7: Inner front view of ULD with light obscuration meters, blue/IR wavelength detection, and source placement.

3.1.4 FAATC ULD in Cargo Compartment

Limited testing was conducted with the ULD inside the cargo compartment. Temperature measurements were not taken with the thermocouple tree, but all other instrumentation remained in place in the cargo compartment. The ULD was placed flush and center on the front wall of the cargo compartment, with sources placed the same as they were in ULD testing. A photo from testing is shown in Figure A.8.

3.1.5 Photoelectric Spot Detector

A Whittaker Model 601 optical beam smoke detector typically used in cargo compartments was tested alongside the ASD in the cargo compartment in order to compare performance. Being a photoelectric detector, the Whittaker operated on principles of light scattering. The Whittaker and ASDs were placed so that they were measuring smoke signatures at similar areas, but the spot detector was measuring a few inches in front of the ASD, as can be seen in Figure A.8. This detector worked by outputting a voltage when in alarm, which occurred between 95-97%/ft light transmission. For this particular testing, the detector was set to alarm at 96%/ft light transmission. More information on the detector can be found in Figure A.9 in the Appendix.

3.1.6 Aspirating Smoke Detectors

Three versions of the Very Early Smoke Detection Apparatus (VESDA) aspirating smoke detectors were obtained for testing in ULD and cargo compartment. The VESDA VLC (laserCOMPACT) is currently used for hazardous areas with zone 2 classification, the VESDA VLF (laserFOCUS) is currently used for small business type areas, and the VESDA-E VEA is a newer technology with the ability to connect up to 40 air sampling channels with addressable capability.

The VESDA systems are optical smoke detectors, and thus measure light scattering. These detectors all work by continuously drawing air into a distributed pipe network and passing it through filters to remove extraneous particles such as dust and dirt. The air sample is then passed through the detection chamber, where light is scattered in the presence of smoke particles. The systems alarm in 4 stages: alert, action, fire 1, and fire 2. When the obscuration exceeds a set threshold, the obscuration data is recorded. Testing primarily occurred at standard sensitivity. As an example, this meant the VLF needed a minimum change of 0.0062 %/ft to record a change in data. The “alert” alarm happened at 0.025 %/ft obscuration, “action” happened at 0.0438 %/ft, and “fire 1” happened at 0.0625 %/ft.

For testing, the VLC and VLF were additionally fitted with gas detection for carbon monoxide (CO), carbon dioxide (CO_2), and hydrogen (H_2).

3.1.7 Blue/IR Wavelength Detection

The Smoke Generator Standardization Apparatus (SGSA) measures both blue and IR signals using a blue 470 nm LED light and IR 850 nm LED light. It can quantitatively characterize particle diameter and smoke density and has proven its accuracy over multiple tests. At FAATC, the SGSA was connected in conjunction with the smoke meters, gas probes, and thermocouples in order to analyze its prospect of use in future detection.

3.1.8 Thermocouples

Thermocouples were placed in each space in order to monitor temperature and assist in calculating heat release rates of some of the fires. All testing areas (bench scale University of Maryland (UMD) box, FAA ULD, FAA cargo compartment) were fitted with a thermocouple tree which placed thermocouples every 3.5" from the top. The UMD thermocouple tree featured 9 thermocouples while the FAA thermocouple tree featured 8. The large scale testing included extra thermocouples in the ceiling of both the ULD and cargo areas.

3.1.9 Obscuration Meters

Bench scale testing made use of light obscuration using a photocell and white light, where the light obscuration was placed halfway up the box. Full scale testing utilized four lasers and photocells – two 2.5" from the ceiling and two 12.5" from the ceiling. These all operated linearly by reading a voltage which dropped as obscuration increased.

3.1.10 Sources

The materials burned were heptane, polyurethane (PU) foam, suitcase, shredded paper, baled cotton, wood chips, and boiling water. Having a variety of materials ensured a diverse set of fire signatures. For example, flaming fires such as heptane and flaming PU have smaller mean particle sizes, whereas smoldering fires such as smoldering PU and cotton have larger mean particle sizes. However, materials with high surface area to volume ratios such as PU foam generate more particles per consumed mass than most other materials. Other materials such as paper, wood, and cotton fell in different places along the spectrum regarding mean particle diameter, peak heat release rate (HRR), particle count, and CO/CO_2 yields [7]. Some materials were selected based off their presence in related standards. For example, UL268 specifies a paper, fire, wood fire, flaming/smoldering PU, and flammable liquid fire [X]. EN54-7 specifies TF2 (Smouldering Wood Fire) and TF5 (Flaming Liquid) [28]. Similar protocols were followed for those fires but were not intended to exactly replicate the standard. Soft suitcase material was burned as a more realistic aircraft fire scenario. Limited nuisance source testing was conducted during bench scale portion of testing at UMD. This was completed with boiling water tests which were intended to replicate the presence of water particles in an area due to condensation.

3.1.11 Protocol

The VESDA systems were first set up for bench scale testing at UMD alongside a light obscuration meter and thermocouples. Different sources were burned, as discussed in Section 3.2, and response times were measured in order to capture the detector responses to different fire signatures. Transport times were calculated for the gas analyzers and ASD systems by measuring the time taken for the systems to register a surge of smoke. These values were subtracted from the raw response times recorded. Large scale testing at the FAATC followed in a similar fashion with the larger spaces. The tests were scaled up, with the addition of shredded paper and smoldering cotton tests and exclusion of the boiling water tests.

Every test was timed from the moment the source was ignited/placed on the burner until the fire went out/was taken off the burner. The data collection started an arbitrary time before ignition of each test in order to obtain a baseline, and it was stopped after the source was removed. After each test, the space was aired out using fans until the instrument readings were showing baseline levels. Table 3.1 provides detail on what materials were used and where the tests were carried out. A detailed protocol can be found in the Appendix for each test.

Table 3.1: Test matrix.

Source/Location	**UMD**	**FAATC ULD**	**FAATC Cargo Compartment**	**FAATC ULD in Cargo Compartment**
Heptane	X	X	X	X
PU foam (flaming)	X	X	X	
PU foam (smoldering)	X	X	X	
Suitcase (soft)	X	X	X	X
Shredded paper	X	X	X	X
Wood	X	X	X	
Baled Cotton		X		
Boiling Water	X			

3.2 Wireless Detectors

Two different brands of photoelectric wireless detectors were obtained and tested for their viability in ULDs. The advantage to wireless detectors is that they could be placed in each ULD without the worry of wiring when moving ULDs in and out of the aircraft. One brand was the Beacon Wireless Fire Alarm from Space Age Electronics (SAE) and the other brand was an unnamed wireless photoelectric detector, henceforth referred to as System 2.

The SAE units included a base station, two call points, a smoke and heat detector, and a dust resilient smoke and heat detector. The call points comprised of strobes and horns with a manual call point. This alarm system is currently used and marketed for construction type applications. They also allow for unit numbering which offers some addressability. System 2 allows for up to 49 devices per gateway and up to 4 gateways per panel (assuming the panel can accommodate for that many addresses), and it is an addressable system. It is typically used in building type applications and operates as a Class A loop to provide a second path of communication for each device in the event that a device stops operating.

Instead of including these in the fire tests, confirmation was first needed that they would be able to reliably operate in an airplane environment. There were concerns that System 2 would have trouble forming a mesh near metal. Thus, preliminary testing was conducted at UMD using similar metal and gauge type to ULDs. One detector was placed inside a metal receptacle while the other was kept outside to see if the transmission was still adequate. This same process was repeated at the FAA Tech Center (FAATC) in actual ULDs.

Chapter 4: Results

4.1 Smoke Density Scaling

Voltage readings from the obscuration meters were converted into optical density per foot (OD/ft) using Eq. (1) from UL 217. In Eq. (1), V_c is the steady voltage when the space is clear (i.e. near maximum voltage reading), V_s is the voltage reading at steady smoke obscuration (i.e. near minimum voltage reading), and d is the distance between the light and photocell, set at 5 ft for the UMD mockup space as recommended by UL 217 [36]. At FAATC, the ULD space was tested first. Since the width of the container was just 60.4 in, the obscuration meters were fixed to a 4 ft wide frame that was placed inside the LD3. This was done instead of drilling holes into the sides, which would introduce more potential for leakage. This frame was subsequently used in the cargo compartment. The voltages were taken as averages from observed steady state periods. In each test, the data acquisition system was started up to a minute before the test, which recorded a baseline for determining V_c.

$$\frac{OD}{ft} = \frac{\log_{10}\left(V_c/V_s\right)}{d} \tag{1}$$

Because the heptane fires were different pool sizes and thus had differently behaved fires, the OD/ft was scaled by mass entrainment rate, $\dot{m}_a$, calculated for each diameter by Heskestad's correlation, found in Eq. (2). In this equation, Q_c is the convective HRR, assumed to be 70% of the total HRR, and z is the clear height, or the position of smoke layer interface above the top of fuel surface [39]. In this analysis, the clear height is approximated as the total height of the enclosure to calculate the maximum dilution for the area. The entrainment rate affects optical density because it dilutes the smoke layer with the air brought in, and this amount varies for the different diameter fires. This relationship can be seen in Eq. (3), taken from the SFPE Handbook, where OD is calculated as a function of mass loss, M, volume, V_u, and mass optical density, D_m [39]. This suggests the relationship that OD/$\dot{m}_a \propto 1/V$.

$$\dot{m}_a = 0.071 Q_c^{1/3} z^{5/3} + 0.0018 Q_c \tag{2}$$

$$OD(t) = \frac{D_m M}{V_u} = \frac{D_m \int \dot{m}\,dt}{V_u} \tag{3}$$

Eq. (2) calculates $\dot{m}_a$ as a function of convective HRR, Q_c, and height, z, and it was used to adjust the smoke density so that it could be compared between the different diameter fires. In order to find HRR, five tests were conducted at each of the small diameters, as correlations for convective driven pool fires were not easily found in literature. The average steady HRR was found by burning heptane fires at diameters of 51, 90, 97, and 100 mm and recording the mass loss over time steps of 10 s. The mass loss was found at each time step, and the steady mass loss rate (MLR) was then calculated by only averaging the mass loss values up until there was 20% or larger drop in mass loss. This occurred near the end of burning for the pool fires, where the flame was unsteady and residual heptane was burning around the edges of the pan. The average steady HRR was then calculated by Eq. (4), where $\dot{m}$ is the steady MLR, ΔH_c is the heat of combustion, which is 44.6 kJ/g for heptane, and A_f is the area of the pool. It should be noted that the average MLR for the 100 mm diameter is slightly less than what was found from the 97 mm diameter pool fires. This is likely due to the small difference in diameters and errors associated with calculations. By finding errors of two standard deviations from the mean, it can be seen that the average MLRs calculated are within each other's errors.

$$HRR = \Delta H_c \dot{m}'' A_f \tag{4}$$

The larger 203 mm pool diameter mass loss was calculated from Eq. (5), found in the SFPE Handbook [39]. In Eq. (5), $\dot{m}_\infty''$ is the asymptotic diameter mass loss rate, defined as 0.101 kg/m^{2}s, and $k\beta$ is the product of the extinction-absorption coefficient of the flame and the mean beam length corrector, defined as 1.1 m^{-1}. The HRR values can be found in Table 4.1 for the different diameters.

$$\dot{m}'' = \dot{m}_\infty'' \left(1 - e^{-k\beta D}\right) \tag{5}$$

Table 4.1: Heptane HRRs for different diameter pool fires.

Diameter (mm)	HRR (kW)
51	0.69
90	2.31
97	2.55
100	2.57
203	29.18

The OD/(ft*$\dot{m}_a$) values were plotted against the inverse of the room volume in order to obtain a linear graph for heptane. As can be seen in Figure 4.1, OD appears to scale with volume, which agrees with theory from Eq. 3. A least squares regression line was determined, setting the intercept at 0 since the optical density in an infinite volume should theoretically approach 0. The r^2 values range from 0.92-0.96, suggesting a clear relationship between volume and optical density.

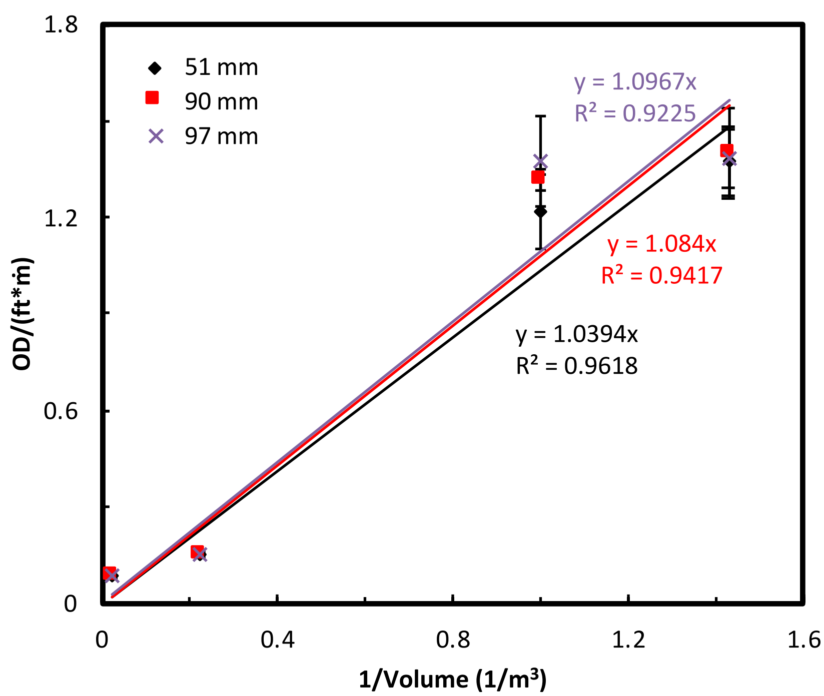


Figure 4.1: Relationship between optical density and inverse volume for heptane fires.

The error bars are calculated from two standard deviations from the mean. An error of up to 30% would not be surprising principally due to the variation in box leakage. During testing, the UMD box was not airtight and leakage was varied somewhat due to inexact lid placement. Attempts were made to mitigate this effect by making sure the lid was covering the openings; however, it was impossible to repeatably close the box the same way. As mentioned earlier, there was leakage in the FAATC ULD through the forklift holes and Plexiglas door. The cargo compartment was closed using a clear, flexible paint curtain, which was also not airtight and leaked depending on how well the curtain was closed after starting each test.

The other materials were not compared the same way as heptane due to unknown HRRs. However, they were used to compare response times from the ASD systems. Comparing its response time in several tests, the VEA results support the theory that smoke density is independent of volume. This is especially evident in the heptane fires. Because the ASDs alarm at a certain obscuration level and thus a certain OD, and OD is influence by MLR, it was assumed that response time would also be influenced by MLR. Thus, the VEA response times were multiplied by the smoke production rates found from Eq. (2) so that they could be compared across the different diameter fires. They were then scaled by volume. The results are presented in Table 4.2 and Figure 4.2a. The same process was done for the other materials of similar setups, except the mass loss rates were assumed steady and used to estimate ratios of smoke production in lieu of smoke production rate, as HRRs weren't known.

Table 4.2: Average VEA response times scaled by MLR and V.

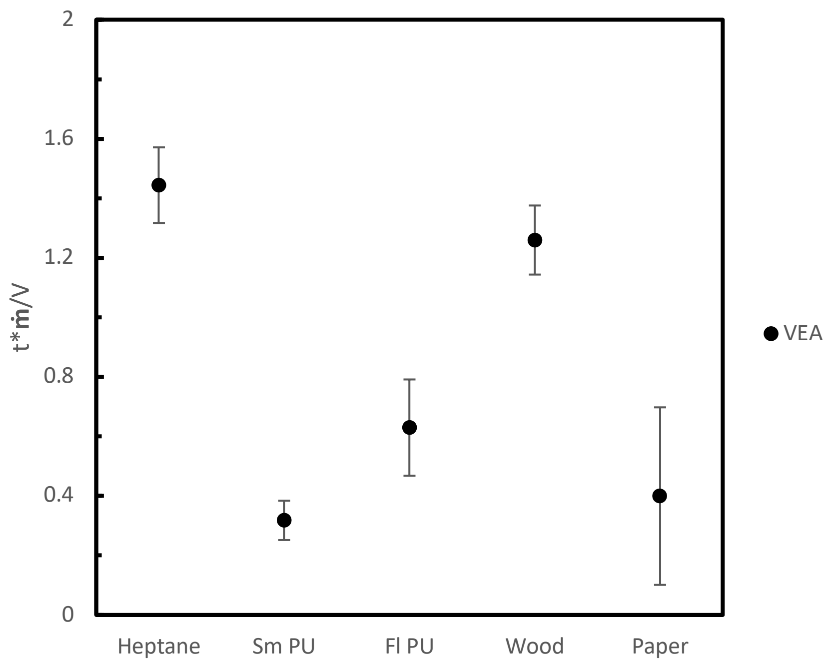
	Average VEA $t \cdot \dot{m}/V$
Heptane	1.44 ± 0.13
Smoldering PU foam	0.32 ± 0.01
Flaming PU foam	0.63 ± 0.16
Wood	1.26 ± 0.12
Paper	0.40 ± 0.30

The VLF and VLC response times are presented in Figure 4.2b, following the same analysis protocol as with the VEA response times. For the most part, the VLF and VLC respond quite similarly to one another in the diverse range of tests. However, they appear to deviate from the VEA, especially in the wood tests, but also somewhat in the flaming PU and paper tests. Generally during testing, the VEA was observed to respond slower than the VLF and VLC even when accounting for the larger lag time associated with the 100 ft tubing. This was largely influenced by the sensitivity setting of the VEA. In a one-off test with the wood in the ULD, changing the VEA sensitivity from 2.5%/ft to 0.5%/ft caused the VEA to alarm nearly 250% faster than the average $t^*\dot{m}$ from the previous wood experiments at standard sensitivity (2.5%/ft).

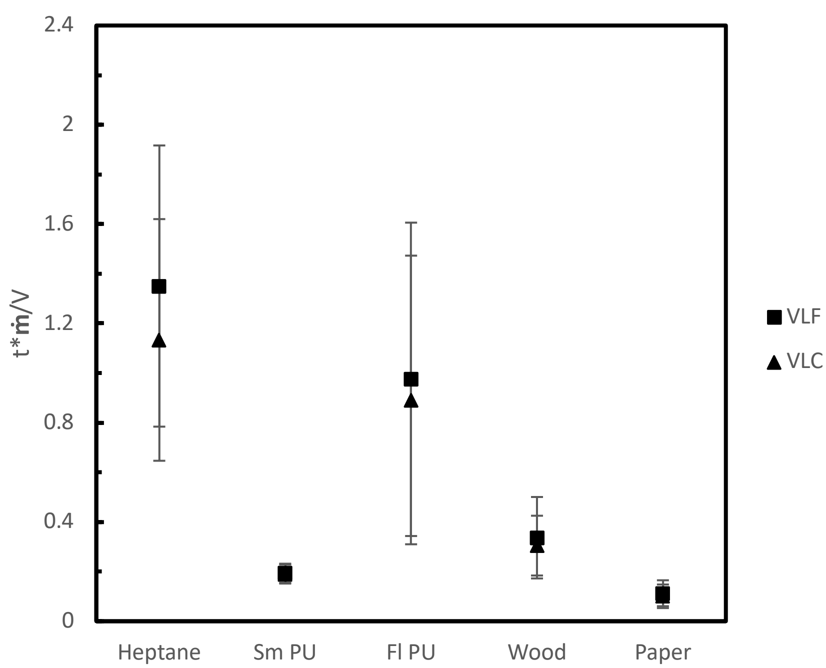
Aside from the heptane tests, it was challenging to replicate each test exactly, but a solid protocol was developed and followed for each material in order to work with time and money constraints. Raw OD data for each material is presented in Appendix B.

4.1.1 Implications

Because of the linear relationship between inverse volume and optical density, optical density is shown to scale with volume. This information can be applied towards aircraft detector testing. Instead of having to test the detectors in entire cargo compartments, they could be tested in a smaller area. Their performance in that smaller area would be equivalent to the same scenario scaled up for a cargo compartment.



(a)



(b)

Figure 4.2 (a) VEA response times scaled by MLR and volume for select tests. (b) VLF and VLC response times scaled by MLR and volume for select tests.

The response time of the VEA helps confirm this, as the product of response time and mass loss rate scales with volume, with little error for the heptane, smoldering PU, flaming PU, and wood tests.

It is also important to note that there does not appear to be a clear trend between flaming and smoldering tests for response times, suggesting detector response is influenced by both smoke density and particle size. This is similar to observations from Karp [40] and furthermore challenge the current 1 minute detection time requirement, which is not based on hazardous conditions.

4.2 ASD Comparison to Photoelectric Detector

The performance of the VESDA systems in the cargo compartment was compared to a Whittaker photoelectric spot detector which is commonly used in aircraft cargo compartments. The spot detector was set to alarm at 96% light transmission and recorded a voltage increase at alarm.

From the total of 20 tests run, the performance of the ASD systems exceeded that of the Whittaker. In fact, the Whittaker did not alarm at all for 11 of the tests. For 19/20 tests, the VLF alarmed faster than the Whittaker, with response times ranging from 17.6% to 177.0% faster. The VLC alarmed faster than the Whittaker for all 20 tests, ranging from 2.0% to 181.5% faster. The VEA response time was more on par with the Whittaker detector, alarming 4.3% to 11.0% slower in 4 tests, the same time for 4 tests, and 69.8% faster in 1 test. However, what still sets the VEA apart are the 5 tests where it alarmed while the Whittaker detector did not. A summary of response times is presented in Figure 4.3 for the tests where both the Whittaker and at least one VESDA system alarmed. The times are presented as percentages of the Whittaker response time. Thus, a positive percentage indicates the VESDA system alarmed before the Whittaker while a negative percentage indicates the VESDA system alarmed after the Whittaker.

Of the 20 tests, 5 were conducted inside a ULD inside the cargo compartment.

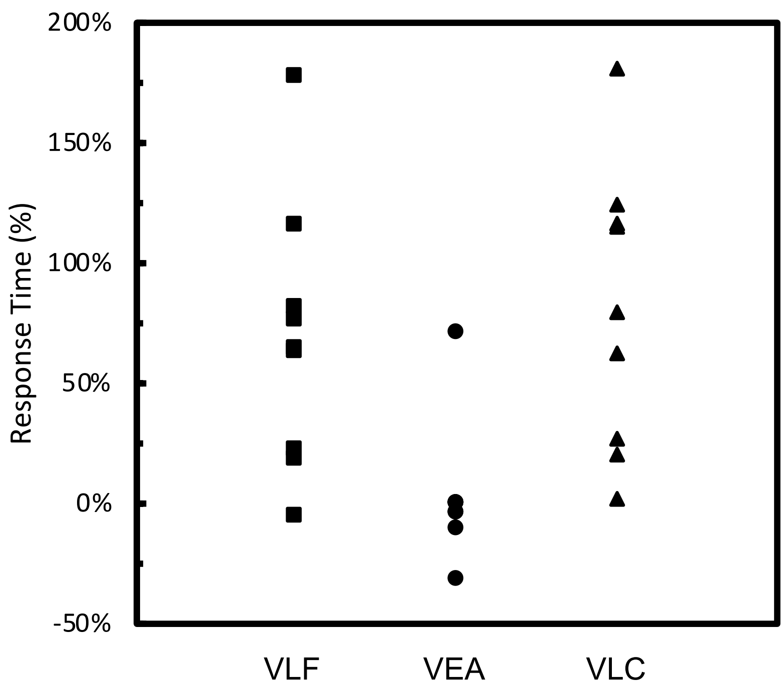


Figure 4.3: Total comparison of response times between ASDs and Whittaker photoelectric detector. Comparison in response time is presented as a percent difference to the Whittaker detector. Positive percentages indicate the VESDA system alarmed before the Whittaker while negative percentages indicate the VESDA system alarmed after the Whittaker.

This simulated current potential scenarios, where a fire inside a ULD would have to breach the ULD before being detected by the cargo compartment detector. It should be noted that the leakage in the ULD used was much larger than an actual ULD and in reality, the fires would have taken much longer to breach the ULD. The 5 tests comprised of two heptane, two shredded paper, and a smoldering suitcase test. Comparing these tests to their counterparts done in an open cargo compartment, performance was about the same regarding response time between the VESDA systems and the spot detector. The Whittaker did not alarm for the heptane tests in either scenario, but data from the shredded paper and suitcase test can be seen in Table 4.3. The response times are vastly improved in the ULD shredded paper tests. In the ULD suitcase test, the VLF and VLC systems have a lower percentage of response time compared to the cargo test; however, the margin is larger and translates to the systems alarming over 7 minutes before the spot detector.

Table 4.3: Comparison of ASDs and Whittaker detector response times.

	VLF % Faster	VEA % Faster	VLC % Faster
Cargo Shredded Paper #1	-5.7%	-4.8%	2.0%
Cargo Shredded Paper #2	64.0%	0.0%	115.8%
Cargo Suitcase	114.9%	0.0%	116.5%
ULD Shredded Paper #1	76.0%	69.8%	79.8%
ULD Shredded Paper #2	177.0%	0.0%	181.5%
ULD Suitcase	62.9%	0.0%	62.9%

Note: Comparison in response time is presented as a percent difference to the Whittaker detector. Positive percentages indicate the VESDA system alarmed before the Whittaker while negative percentages indicate the VESDA system alarmed after the Whittaker.

4.3 Dual Wavelength Smoke Detection

4.3.1 FAATC Testing

Examples of data are shown in Figure 4.4a and 4.4b, with percentage increase in voltages shown both individually and together respectively. For some tests, the individual wavelengths appeared to contradict scattering theory; however, together the signals strongly mimic obscuration. As can be seen in Figure 4.4b, the combined blue and IR signal shows strong correlation to the OD. Comparisons of other materials can be found in Appendix B.

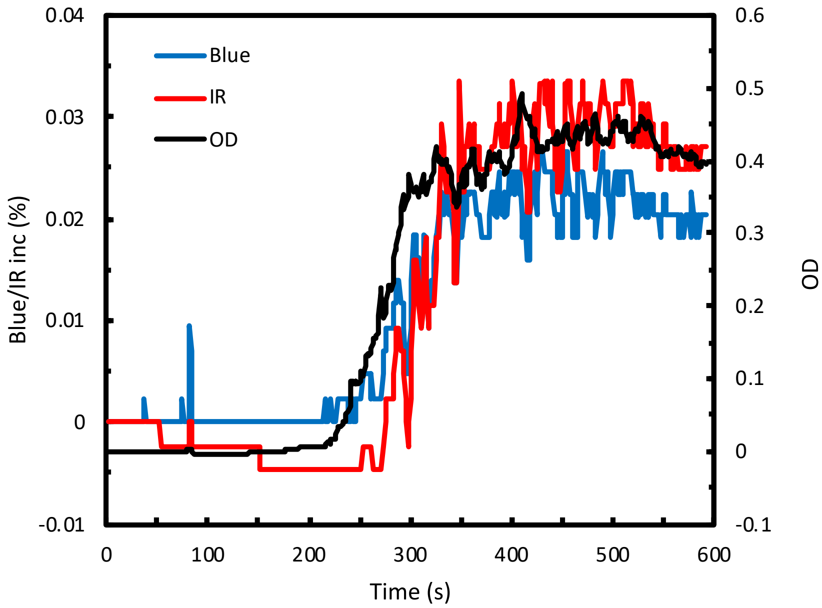
4.3.2 Implications

Because of the correlating relationship between the combined wavelengths and OD in aircraft settings, dual wavelength technology is identified as a prospective detection method for aircrafts. More testing would have to be done with nuisance sources and confirming scattering theory; however, the blue and IR wavelengths could potentially be used to identify smoldering fires, flaming fires, and nuisance sources.

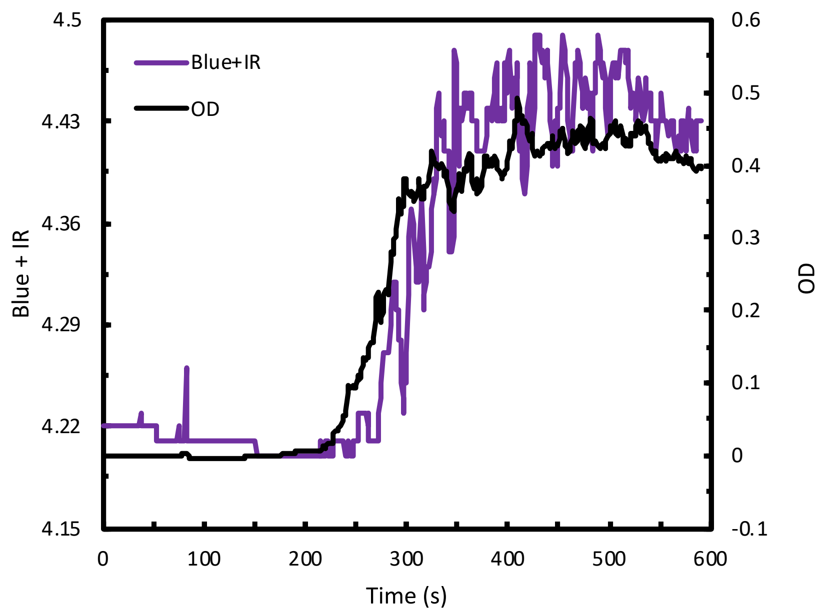
4.4 Gas Detection

4.4.1 FAATC Testing

FAA gas analyzers were set up in the ULD and cargo compartment tests, measuring CO, CO_2, and O_2. These measurements were compared to OD for all tests, finding that they behaved very similarly. This was more evident in CO_2 and O_2 measurements, as seen in Figure 4.5 however, CO did mimic OD for materials such as suitcase (Figure 4.5b) and shredded paper. The other tests produced little CO and no trends were seen over the noise of the measurements. Gas detection comparisons for other materials can be found in Appendix B. In Figure 4.5, the gas curves are presented as a change in gas concentration from a starting baseline which was unique for each test. This was done because the initial gas concentrations could vary slightly based on how well the space was ventilated. The change in concentration for CO and



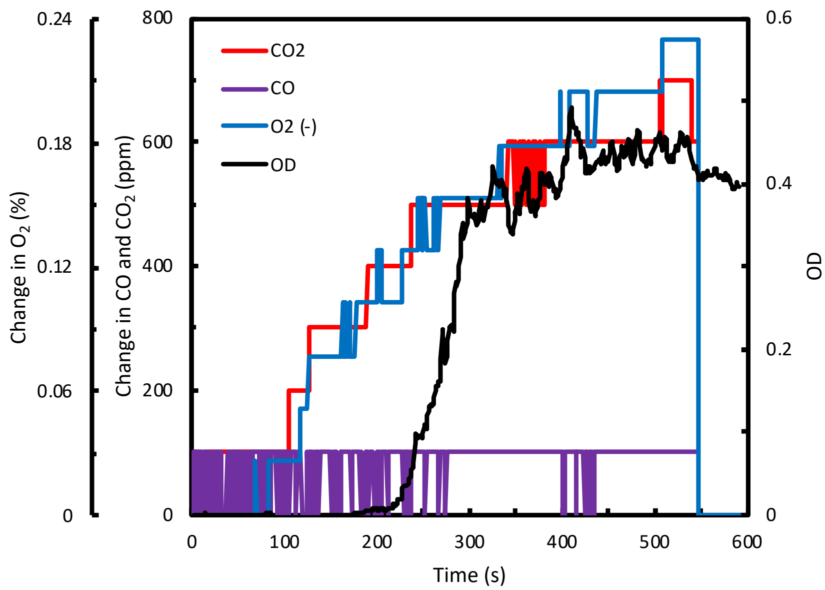
(a)



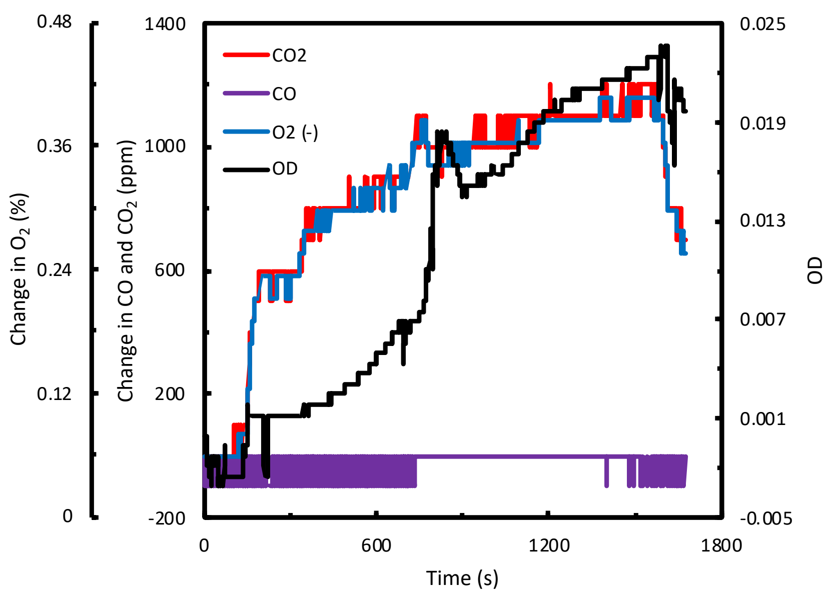
(b)

Figure 4.4: (a) Smoldering PU foam OD and blue/IR measurements. shown individually as percentage increases from a baseline. (b) Smoldering PU foam OD and blue/IR measurements added together as percentage increases from a baseline.

CO_2, is presented in parts per million (ppm) while O_2 is presented as a percentage. In all of these tests, both CO_2 and O_2 measurements either mimicked OD behavior in the transient stage or were recognized beforehand. This was especially evident in the smoldering PU foam, wood (Figure 4.5a), and cotton tests (Figure 4.5b).



(a)



(b)

Figure 4.5: (a) Smoldering PU foam gas measurements compared to OD (b) Smoldering cotton gas measurements compared to OD.

4.4.2 Implications

The strong relationship between OD, CO_2, and O_2 suggests that gas detection could be a good choice for nuisance immunity. Basing detection on gas means detection would not be influenced by variable environmental factors or particles of any kind. Measuring at least two types of gases would help confirm a correct fire alarm, especially since the behavior of the gases in the transient time frame closely resembles that of OD. Thus, a fire can still be reliably detected while mitigating the propensity for false alarms.

4.5 Wireless Detectors

While the SAE detectors were able to successfully transmit with ease through the metal, System 2 had trouble consistently forming a strong connection, and was thus deemed unfit for use in aircraft applications.

4.5.1 Implications

Testing with these detectors was limited to proof of concept type testing, so no fire tests were conducted with these detectors. For the SAE detectors that easily transmitted through metal, more testing could be done to observe their response under fire conditions; however, results of the preliminary testing seem promising for their use in ULDs. Given their UL listing, their response to fires is expected to be reasonable.

4.6 Nuisance Source – Boiling Water

From the boiling water tests, none of the VESDA systems went into alarm. In fact, none of the systems surpassed the threshold to record a change past the baseline measurement. While this helps to confirm the systems' responses to nuisance sources, more nuisance source testing is needed under realistic flight conditions in order to fully test the ability of nuisance immunity. More testing was not completed because of the lack of information able to be attained on in flight conditions.

Chapter 5: Conclusions and Future Work

5.1 Conclusions

Fire detection plays an important role on aircrafts given the nature of the space. However, test requirements for fire detectors for approval of use in aircrafts are vague and are loosely tied to hazard development. The goal of this project was to explore some avenues for standardizing the smoke detection requirements as well as analyze S-O-A detection technology for potential use in aircrafts. Emphasis was placed on smoke density in relation to detection of fires in cargo compartments as well as the reduction of false positives.

Using smoke density measurements from a variety of burning materials and volumes, it was confirmed that smoke density scales with volume. Thus, detector testing can be conducted in small volumes and results can reliably be applied to larger aircraft spaces such as cargo compartments. Compared to testing in a cargo compartment, this would make testing more efficient, as clearing a space of smoke took significantly longer for larger volumes during testing. Additionally, flight environments could be replicated based off of information available in DO-160G, meaning the in-flight portion of detector testing could instead be conducted on the ground.

S-O-A technology tested included ASDs, blue and IR wavelength technology, and gas detection. The ASDs were compared to a standard photoelectric spot detector (Whittaker), finding that they outperformed the Whittaker in both response and response time. The VLF averaged a 77.0% faster response time than the Whittaker, where it responded faster in 19 or the 20 tests. The VLC averaged a 81.3% faster response time than the Whittaker, where it responded faster in all 20 tests. The VEA response times were more on par with the Whittaker but exceled in responding while the Whittaker did not respond at all for 55% of the tests. The VEA is identified as the outstanding choice for ASD in aircrafts due to its addressability.

Blue/IR wavelength and gas detection technology were both compared to OD, finding that they responded in strong similarity to OD. They were both identified as viable options and are furthermore based on principles that suggest they would do well with nuisance immunity. Furthermore, the gas detection technology was able to sense gas signatures 100-600 s before visible smoke was detected in smoldering PU foam and smoldering cotton tests. This confirmed gas signatures are a precursor to visible smoke in certain situations. Thus, gas detection was found to be an improvement over current detection for its ability to provide warning before hazardous conditions develop.

5.2 Future Work

Future work should include conducting tests similar to the ones in this project to confirm the conclusions made. Nuisance sources should be tested to confirm the competency of ASDs, dual wavelength, and gas detection systems. For nuisance source testing, information on conditions in cargo compartments would be needed to replicate realistic scenarios.

Additional areas such as hidden spaces have historically had fires occur in that area and could benefit from fire detection. However, testing would need to occur in order to assess the viability of that notion. Both ASDs and linear heat detectors (LHDs) are identified as possible detection solutions for hidden spaces. For LHDs, there are no concerns over nuisance alarms as this detector responds to an increase in temperature, which is not expected to be replicated by ambient variations. The addressability capability would be helpful given the accessibility limits. However, the disadvantage of this technology is that it may not work as well for smoldering fires.

ULDs were previously identified as areas that impeded detection do to its enclosed nature. Wireless photoelectric detection technology was proposed as a potential solution to this issue, but only proof of concept testing was completed to see if the devices could form a network. The SAE detectors were able to communicate with each other, leading to the prospect of fire testing being done to assess their response.

Overall, a move towards standardizing detection in cargo compartments is necessary for the future of aircraft fire detection. There should be more quantitative requirements that focus on a detector’s ability to respond to hazardous conditions rather than a time constraint.

Appendix A

Table A.1: Detailed protocol for all testing.

Source/Location	UMD	FAATC ULD	FAATC Cargo Compartment	FAATC ULD in Cargo Compartment
Heptane	• 51, 90, 97 mm diameter pool fires burned 6" off the ground • 5 mL of heptane for 51 mm fires, 10 mL for 90, 97 mm fires • Ignited via lighter and test run until flame ceases	• 100 mm diameter pool fires burned 4" off the ground • 15 mL of heptane • Ignited via lighter and test run until flame ceases	• 203 mm diameter pool fires burned on the ground • 125 mL of heptane • Ignited via lighter and test run until flame ceases	• 100 mm diameter pool fires burned 4" off the ground • 15 mL of heptane • Ignited via lighter and test run until flame ceases
PU foam (flaming)	• 3.0 by 3.0 by 2.0 in. (76 by 76 by 51 mm) burned 6" off the ground • Bottom and sides wrapped in aluminum foil • Use of 1 mL of heptane to assist ignition (poured in corner) • Ignite corner • Test run until flame ceases	• 3.0 by 3.0 by 2.0 in. (76 by 76 by 51 mm) burned 4" off the ground • Bottom and sides wrapped in aluminum foil • Use of 1 mL of heptane to assist ignition (poured in corner) • Ignite corner • Test run until flame ceases	• 11.0 by 11.0 by 2.0 in (279 by 279 by 51 mm) burned on the ground • Bottom and sides loosely wrapped in aluminum foil • Use of 5 mL of heptane to assist ignition (poured in corner) • Ignite corner • Test run until flame ceases	

PU foam (smoldering)	• 3.0 by 3.0 by 2.0 in. (76 by 76 by 51 mm) • Bottom and sides wrapped in aluminum foil • Smoldering induced via 13" tall hot plate at a constant temperature ranging between 400-600 F • Test run until the detectors alarm at Fire 1 or it was determined they would not alarm	• 3.0 by 3.0 by 2.0 in. (76 by 76 by 51 mm) • Bottom and sides wrapped in aluminum foil • Smoldering induced via 13" tall hot plate at a constant temperature ranging between 400-600 F • Test run until the detectors alarm at Fire 1	• 11.0 by 11.0 by 2.0 in (279 by 279 by 51 mm) • Bottom and sides loosely wrapped in aluminum foil • Smoldering induced via 13" tall propane burner at a constant temperature ranging between 400-600 F • Test run until the detectors alarm at Fire 1	
Suitcase (soft)	• 3.0 by 3.0 in. sample • Smoldering induced via 13" tall hot plate at a constant temperature ranging between 400-600 F • Test run until the detectors alarm at Fire 1	• 3.0 by 3.0 in. sample • Smoldering induced via 13" tall hot plate at a constant temperature ranging between 400-600 F • Test run until the detectors alarm at Fire 1	• Entire suitcase standing up, filled with rags and cardboard • Smoldering induced via electric charcoal starter at 550 W • Test run until the detectors alarm at Fire 1	• Entire suitcase standing up, filled with rags and cardboard • Smoldering induced via electric charcoal starter at 550 W • Test run until the detectors alarm at Fire 1

Shredded paper	• Paper strips approximately 6 – 10 mm in width by 25.4 – 102 mm in length • Paper was taken from an office shredder, with paper classified as 20 lb (weight of 500 sheets) and 75 g/m^2 • 42.6 g (1.5 oz) tamped down in a 1' tall metal tube with 1"x1" flue space in the center. Tube was enclosed with wire mesh on bottom. • Tube was placed on a 11.75" high ring stand and ignited via an 8" Bunsen burner with an approximate 4" flame. • Test terminated more than 4 minutes after ignition	• Paper strips approximately 6 – 10 mm in width by 25.4 – 102 mm in length • Shredded paper provided by FAA, which consisted of a mix of 20 lb paper and cardstock • 42.6 g (1.5 oz) tamped down in a 1' tall metal tube with 1"x1" flue space in the center. Tube was enclosed with wire mesh on bottom. • Tube was placed on a 11.75" high ring stand and ignited via an 8" Bunsen burner with an approximate 4" flame. • Test terminated more than 4 minutes after ignition	• Paper strips approximately 6 – 10 mm in width by 25.4 – 102 mm in length • Shredded paper provided by FAA, which consisted of a mix of 20 lb paper and cardstock • 42.6 g (1.5 oz) tamped down in a 1' tall metal tube with 1"x1" flue space in the center. Tube was enclosed with wire mesh on bottom. • Tube was placed on a 11.75" high ring stand and ignited via an 8" Bunsen burner with an approximate 4" flame. • Test terminated more than 4 minutes after ignition	• Paper strips approximately 6 – 10 mm in width by 25.4 – 102 mm in length • Shredded paper provided by FAA, which consisted of a mix of 20 lb paper and cardstock • 42.6 g (1.5 oz) tamped down in a 1' tall metal tube with 1"x1" flue space in the center. Tube was enclosed with wire mesh on bottom. • Tube was placed on a 11.75" high ring stand and ignited via an 8" Bunsen burner with an approximate 4" flame. • Test terminated more than 4 minutes after ignition

Wood	• 20 g of hickory wood chips • Smoldering induced via 13" tall hot plate at a constant temperature ranging between 500-700 F • Test run until the detectors alarm at Fire 1	• 50 g of hickory wood chips • Smoldering induced via 13" tall hot plate at a constant temperature ranging between 400-600 F • Test run until the detectors alarm at Fire 1	• 100 g of hickory wood chips • Smoldering induced via 13" tall propane burner at a constant temperature ranging between 400-600 F • Test run until the detectors alarm at Fire 1 or until more than 20 minutes have passed	
Baled Cotton			• 15 g of cotton • Smoldering induced via 13" tall hot plate at a constant temperature ranging between 400-600 F • Test run until the detectors alarm at Fire 1 or until more than 15 minutes have passed	
Boiling Water	• 1 L of boiling water with the lid on, heated via hot plate at a constant temperature ranging between 500-700 F • After first minute, repeat 30 seconds intervals with the lid off the container and lid on (to create surge) • Test run for 5 minutes			

Figure A.1: Back right view of the box setup at UMD.

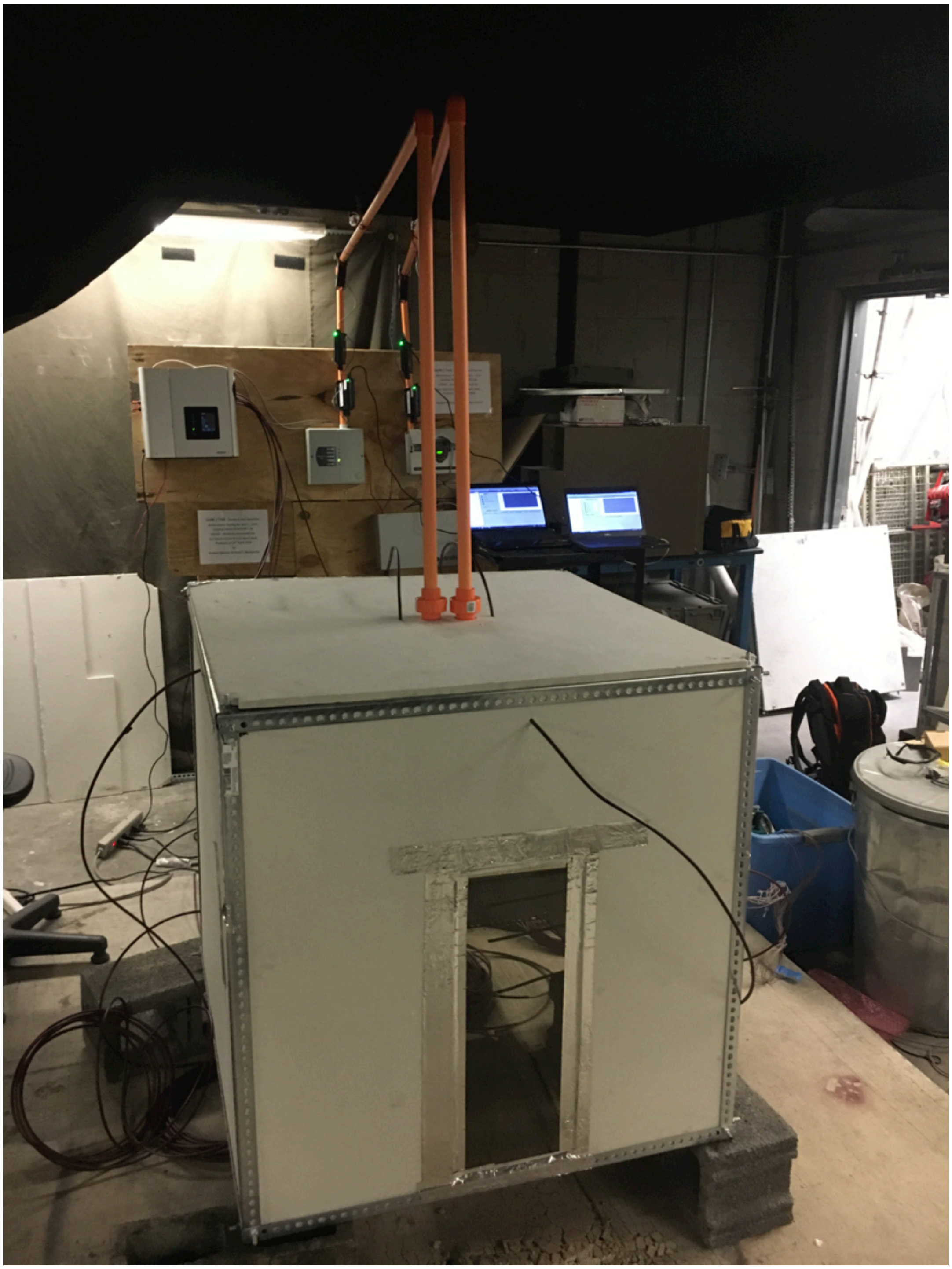


Figure A.2: ASD setup at UMD.

Figure A.3: Close-up of ASD setup at UMD.

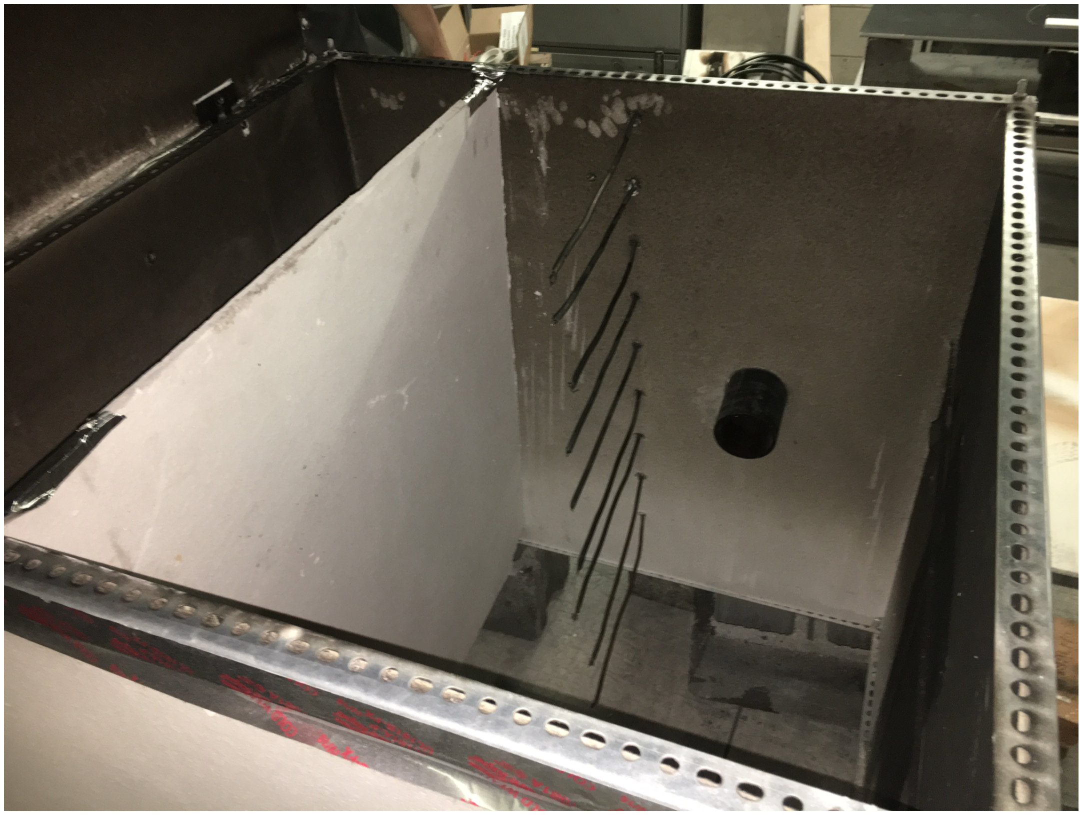


Figure A.4: Inside box view of volume 0.7 m^3 at UMD.

Figure A.5: Photo from FAATC ULD heptane test.

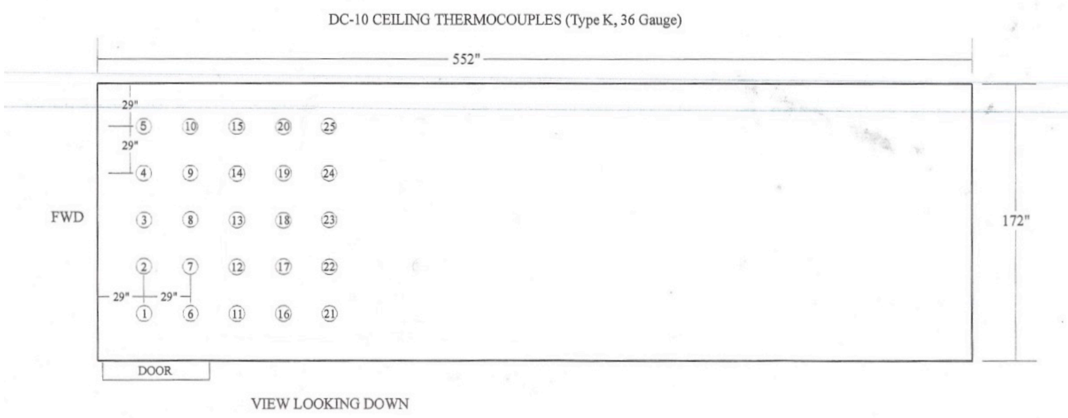


Figure A.6: Ceiling thermocouple placement in DC-10 cargo compartment.

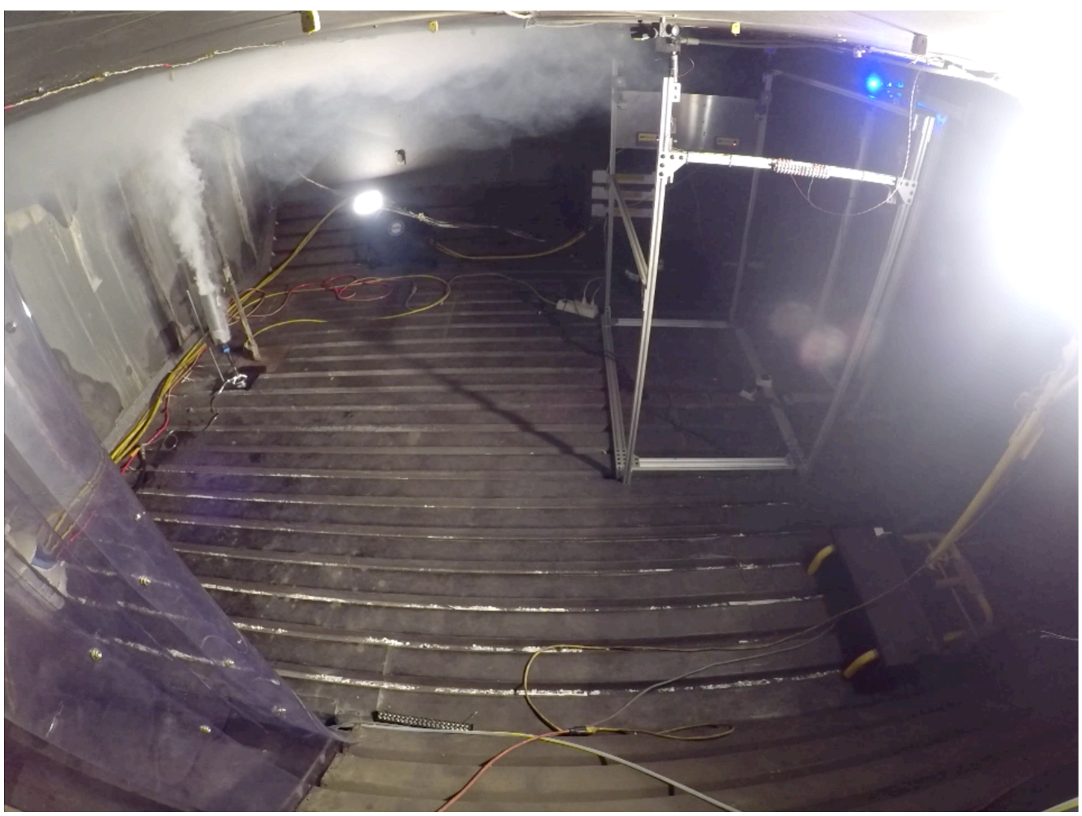


Figure A.7: Photo from FAATC cargo compartment shredded paper test.

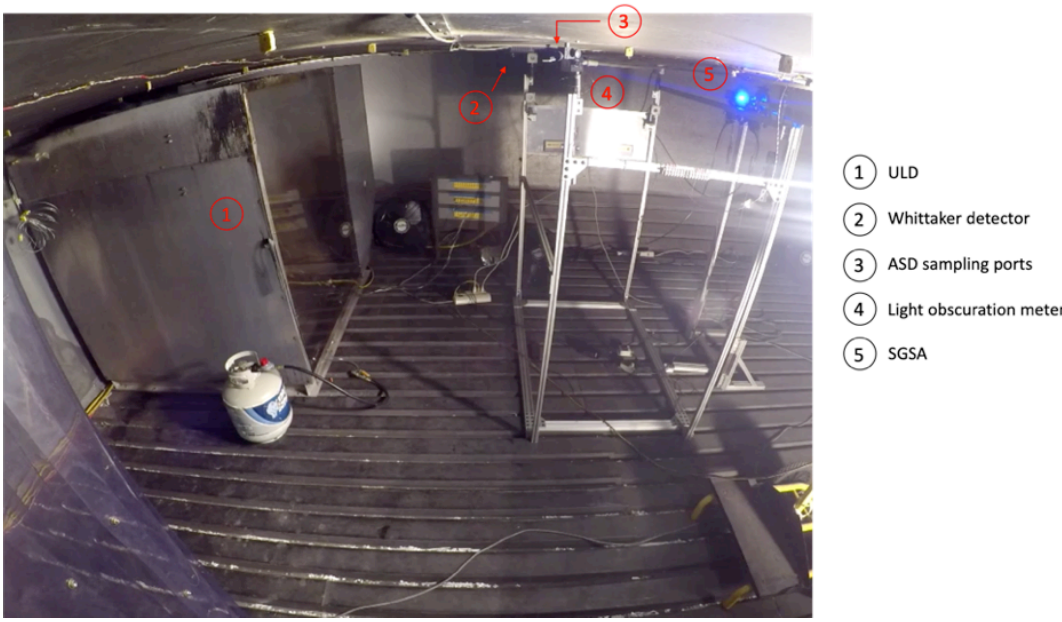


Figure A.8: Photo from FAATC ULD in cargo compartment testing.

Figure A.9: Whittaker photoelectric spot detector.

Appendix B

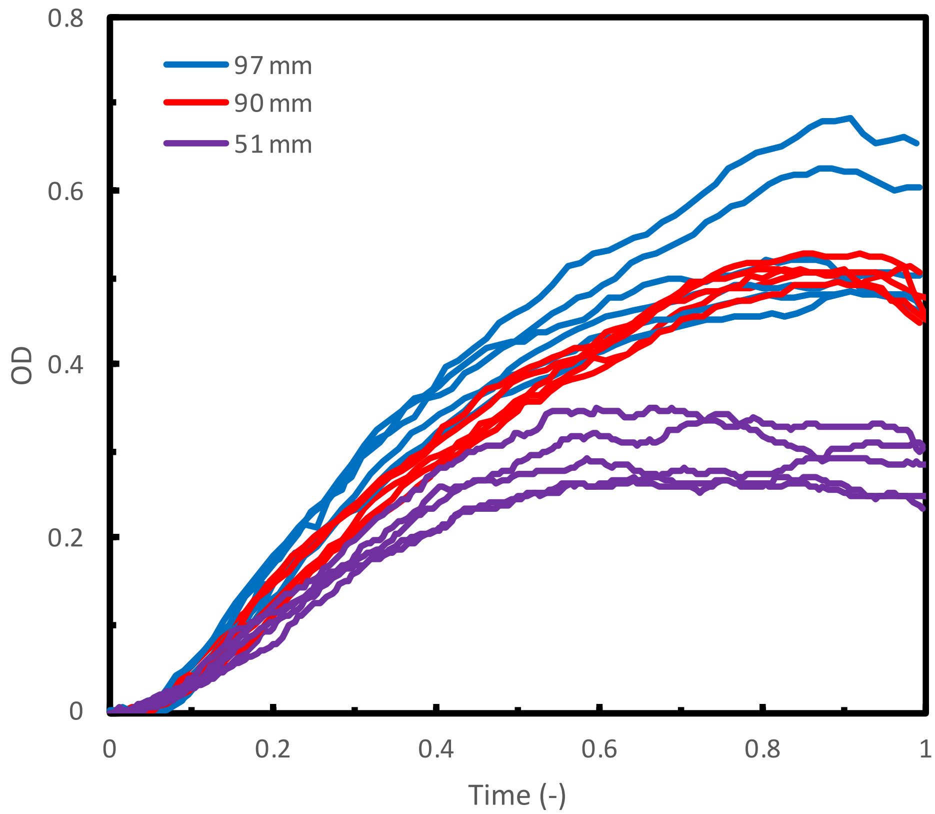


Figure B.1. Raw OD measurements from heptane fires when V=1 m^3.

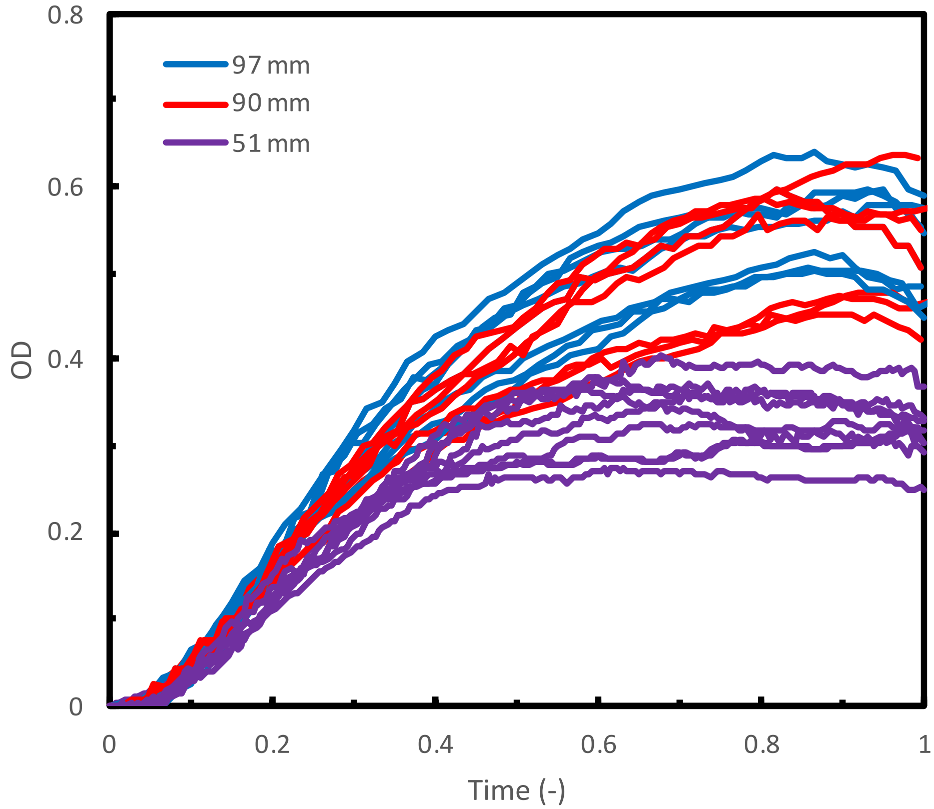
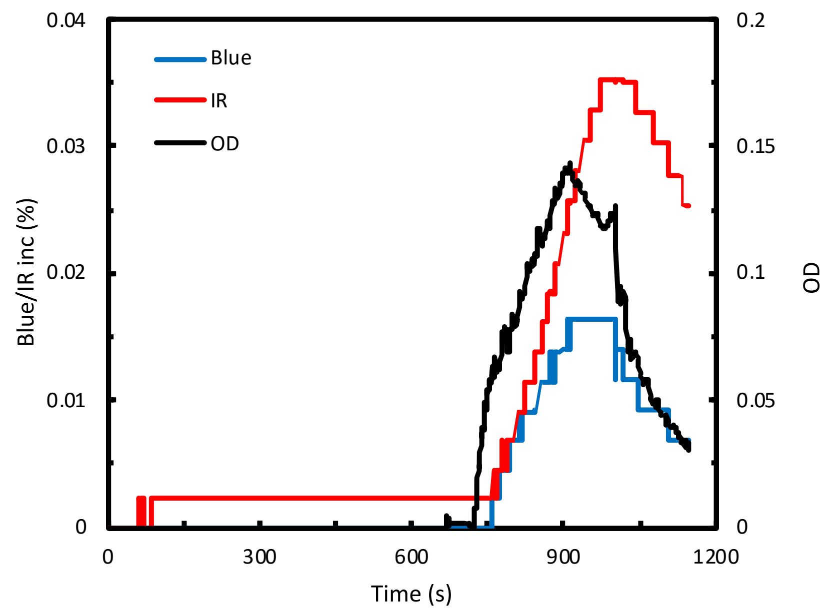


Figure B.2. Raw OD measurements from heptane fires when V=0.7 m^3.



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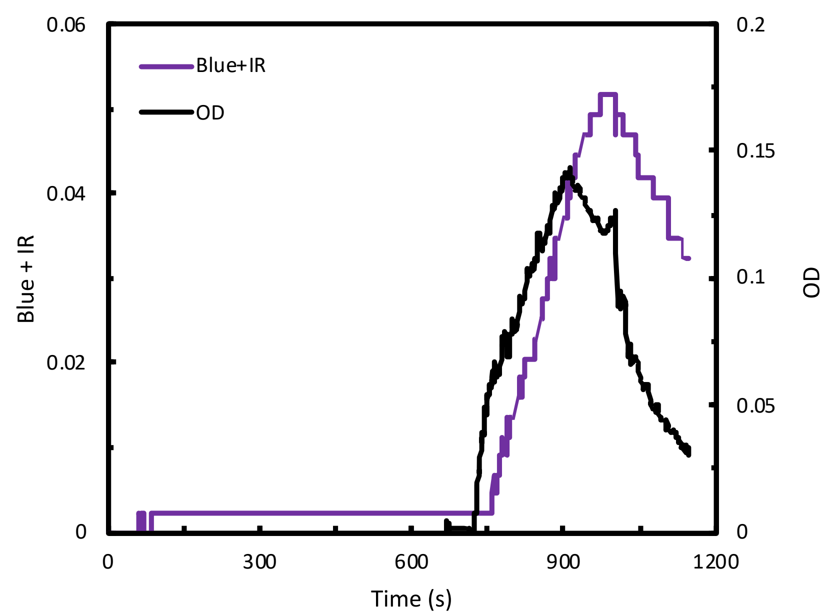
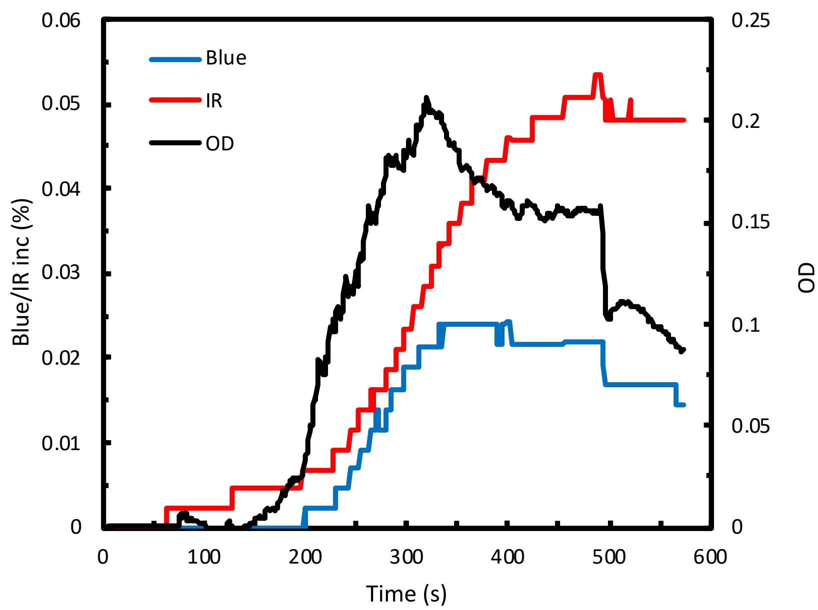


(b)

Figure B.3: (a) Heptane OD and blue/IR measurements. shown individually as percentage increases from a baseline. (b) Heptane OD and blue/IR measurements added together as percentage increases from a baseline.



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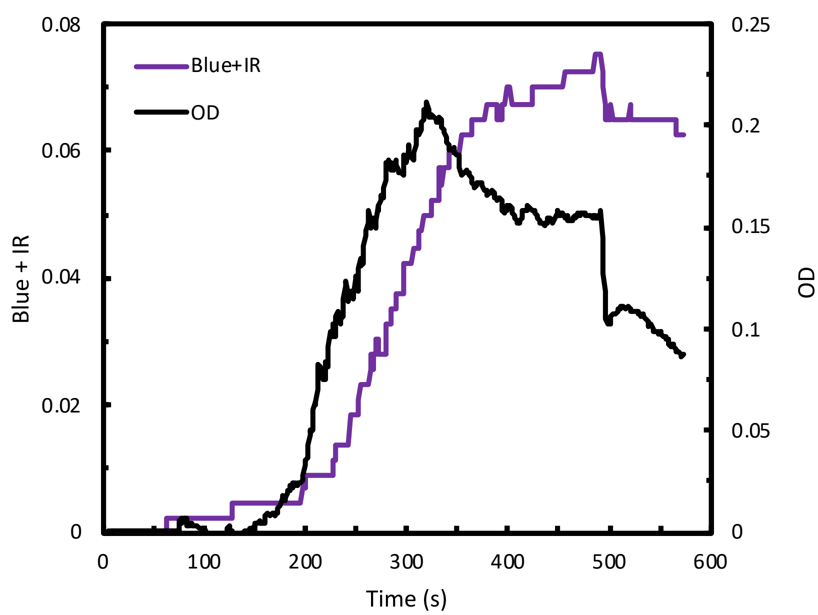
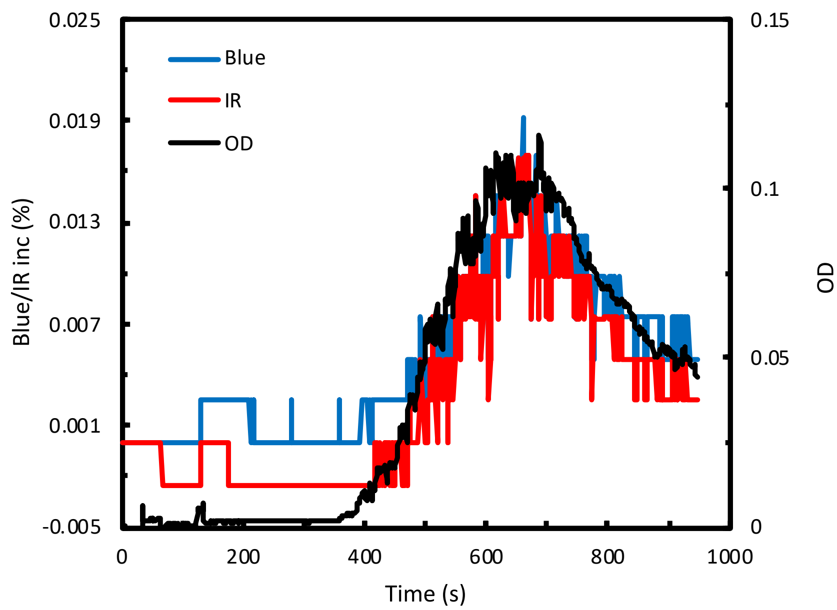
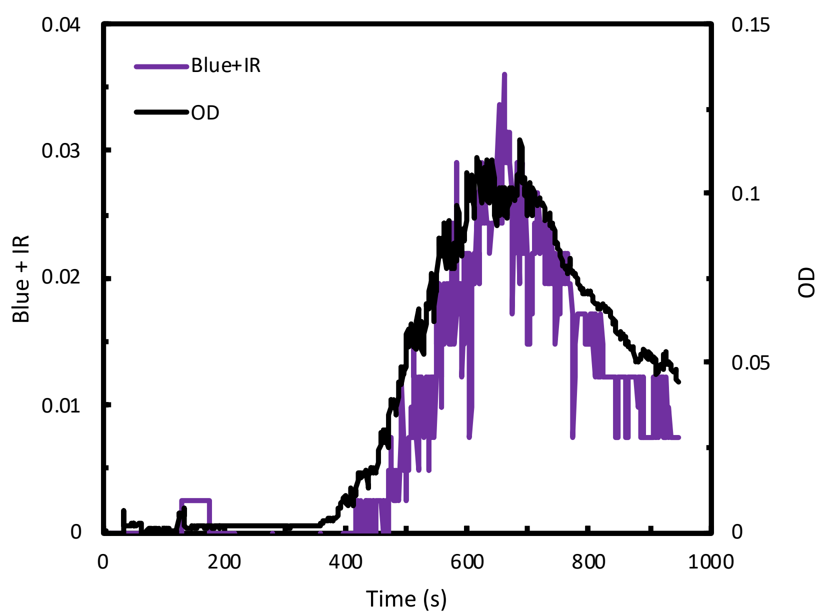


(b)

Figure B.4: (a) Flaming PU OD and blue/IR measurements. shown individually as percentage increases from a baseline. (b) Flaming PU OD and blue/IR measurements added together as percentage increases from a baseline.

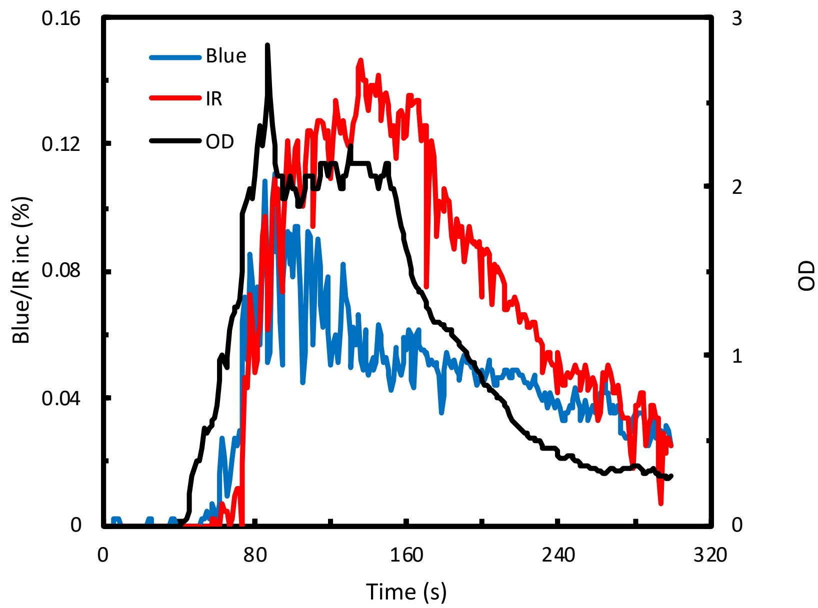


(a)

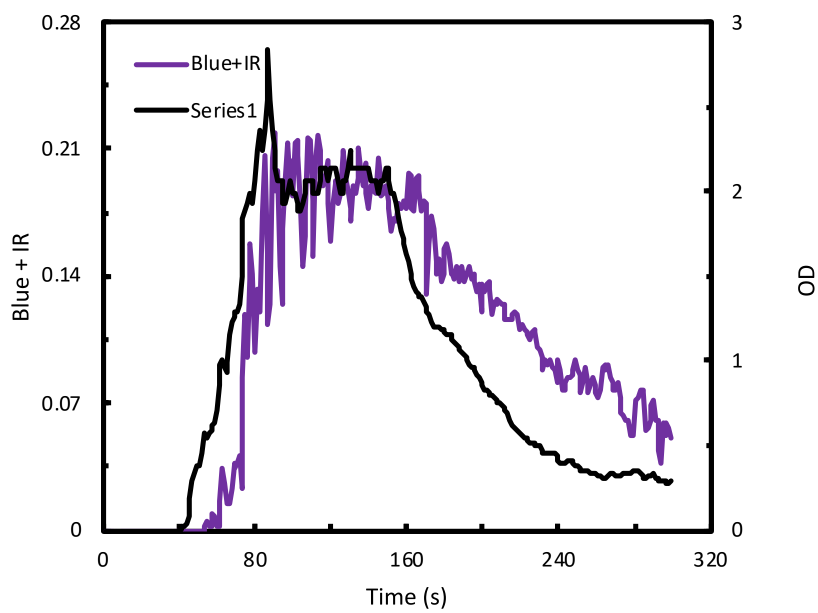


(b)

Figure B.5: (a) Suitcase OD and blue/IR measurements. shown individually as percentage increases from a baseline. (b) Suitcase OD and blue/IR measurements added together as percentage increases from a baseline.

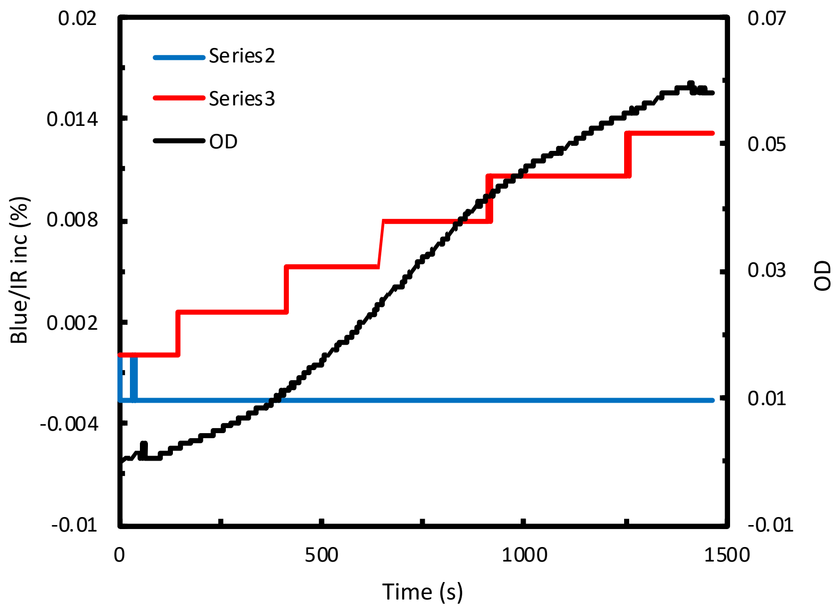


(a)

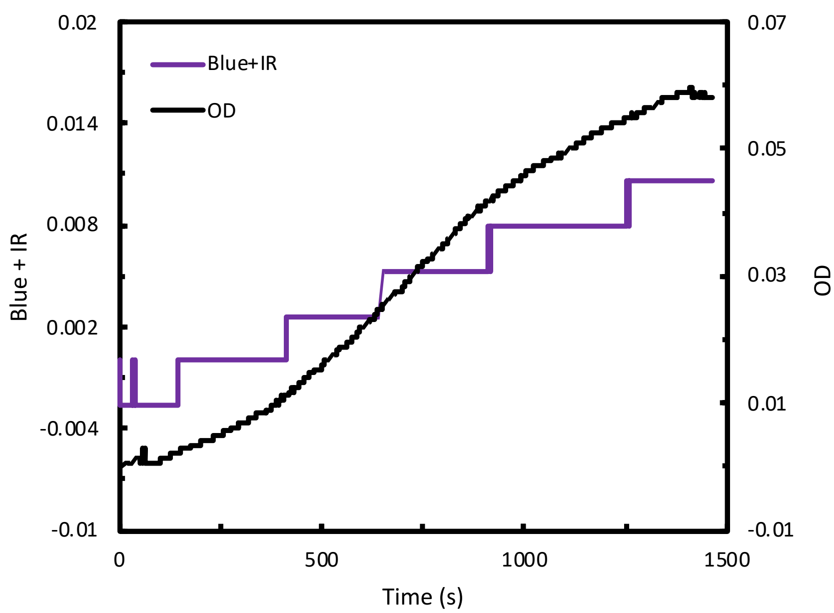


(b)

Figure B.6: (a) Shredded paper OD and blue/IR measurements. shown individually as percentage increases from a baseline. (b) Shredded paper OD and blue/IR measurements added together as percentage increases from a baseline.

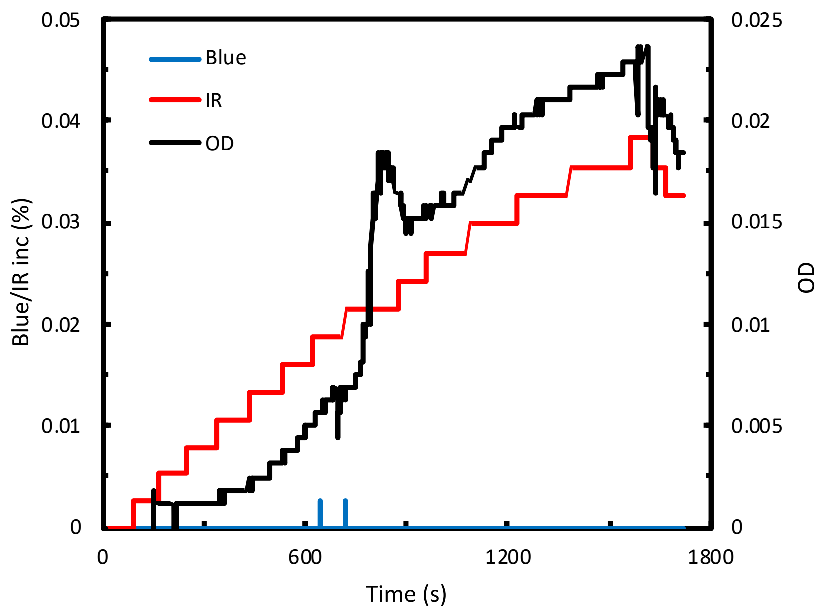


(a)

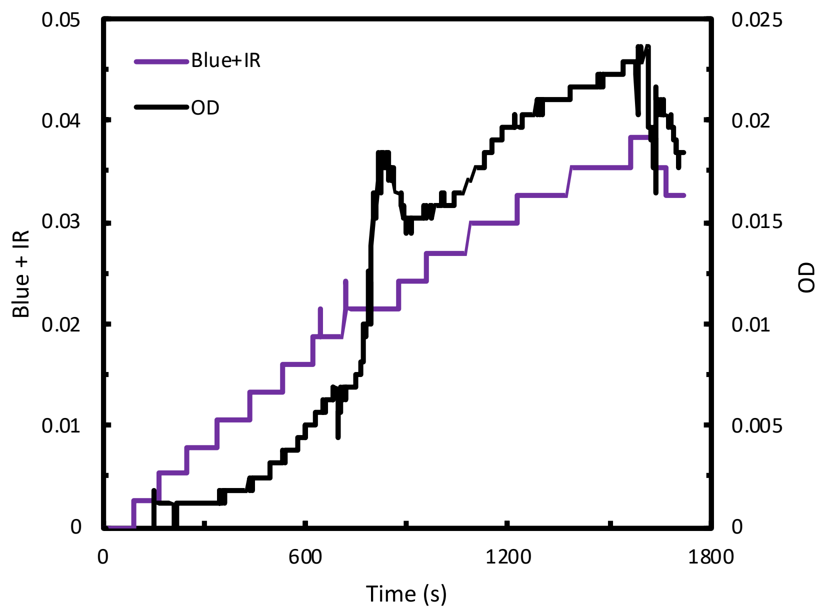


(b)

Figure B.7: (a) Wood OD and blue/IR measurements. shown individually as percentage increases from a baseline. (b) Wood OD and blue/IR measurements added together as percentage increases from a baseline.



(a)



(b)

Figure B.8: (a) Baled cotton OD and blue/IR measurements. shown individually as percentage increases from a baseline. (b) Baled cotton OD and blue/IR measurements added together as percentage increases from a baseline.

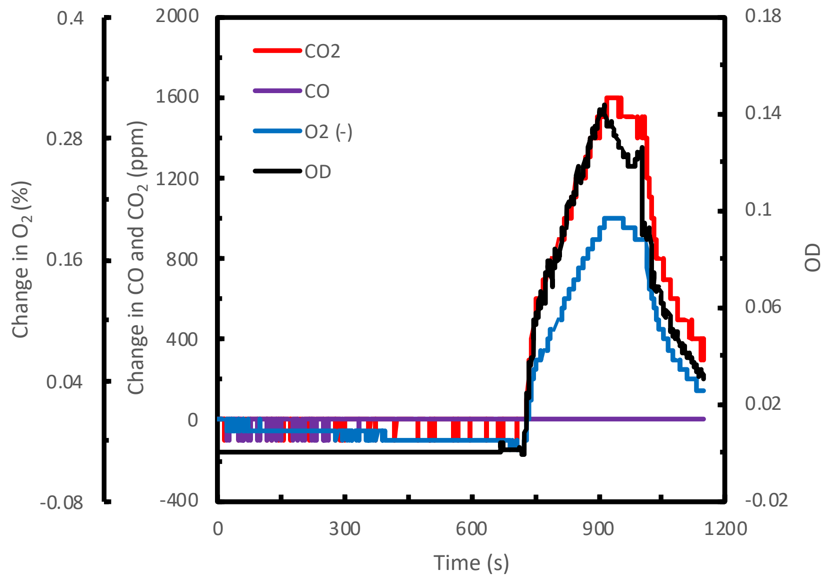


Figure B.9: Heptane gas measurements compared to OD.

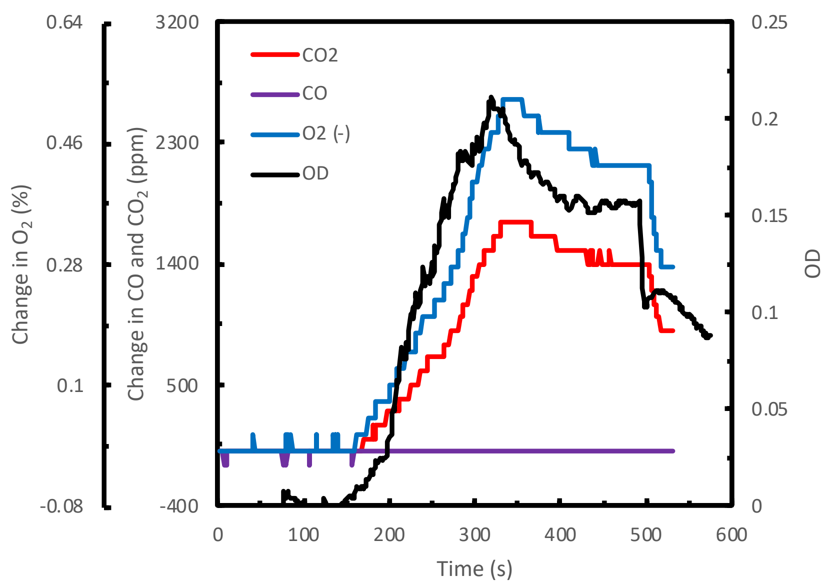


Figure B.10: Flaming PU gas measurements compared to OD.

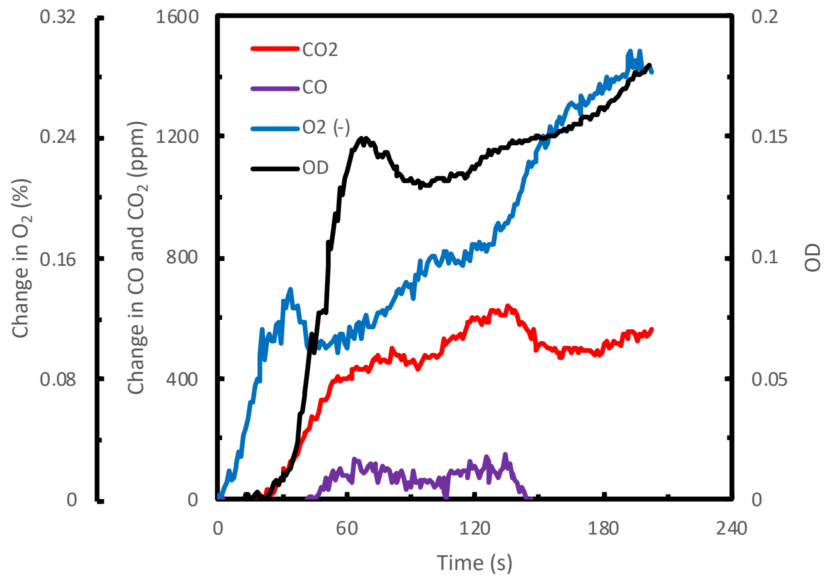


Figure B.11: Suitcase gas measurements compared to OD.

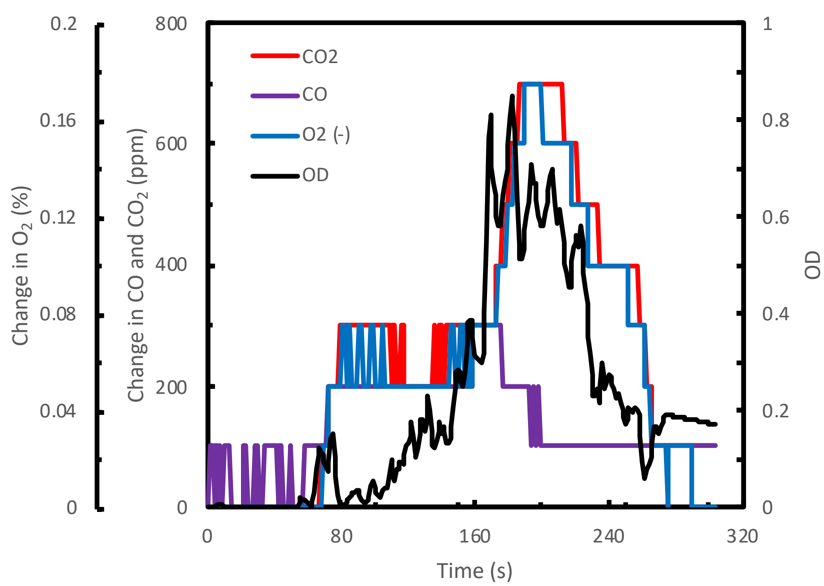


Figure B.12: Shredded paper gas measurements compared to OD.

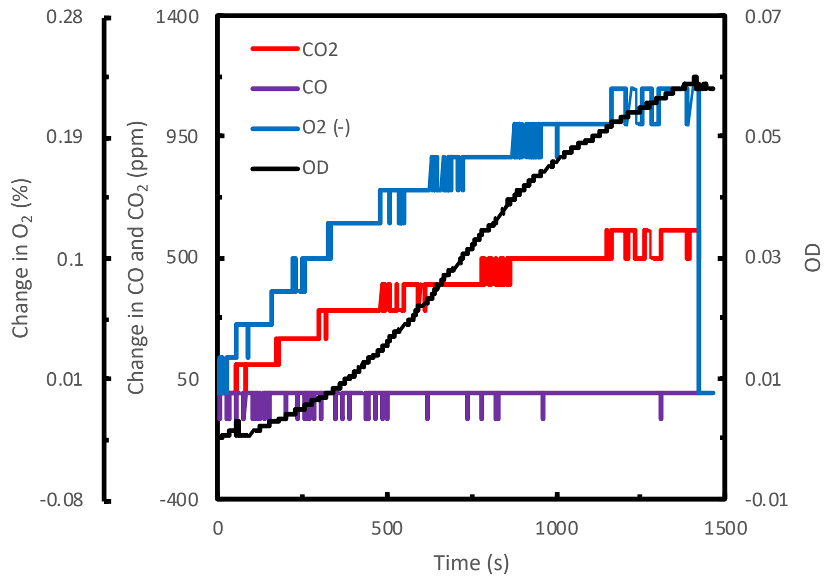


Figure B.13: Wood gas measurements compared to OD.

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