DOT/FAA/TC-TT18/9

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Characterization of Smoke Machines in Testing Aircraft Smoke Detectors

April 2018

Technical Thesis

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Page

1. Report No.
DOT/FAA/TC-TT18/9

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
CHARACTERIZATION OF SMOKE MACHINES IN TESTING AIRCRAFT SMOKE DETECTORS

5. Report Date
April 2018

6. Performing Organization Code
ANG-E21

7. Author(s)
Tina Emami

8. Performing Organization Report No.

9. Performing Organization Name and Address
Rutgers, The State University of New Jersey
Department of Mechanical and Aerospace Engineering
98 Brett Rd.
Piscataway, NJ, 08854

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
14-G-004

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Fire Safety Branch
Atlantic City International Airport, NJ 08405

13. Type of Report and Period Covered
Technical Thesis

14. Sponsoring Agency Code

15. Supplementary Notes
The FAA William J. Hughes Technical Center Aviation Research Technical Monitor was Robert Ochs. This work was conducted in partial fulfillment of the degree requirements for a Masters in Mechanical Engineering, which was awarded to the author by the Rutgers University, New Brunswick NJ in October 2017. The FAA has not edited or modified the contents of the report in any manner.

16. Abstract
To improve the accuracy of aircraft fire detection, new smoke detectors have been produced to differentiate between what is a real fire and what is a false alarm. Nontoxic theatrical smoke machines are used to test these new false resistant smoke detectors in flight. This research is based on characterizing the smoke from the machines to understand what alerts different types of smoke detectors, and what would best be used for testing them.

Two smoke detectors were utilized in testing. One was a Whittaker Model 601 smoke detector which is an optical beam smoke detector; the second is a Kidde Aerospace & Defense Smoke Detector Type II which is a prototype of the new false alarm resistant detector. Two smoke machines were also used: one using fluid that is oil-based (the Concept Smoke Systems Aviator UL 440) and one using fluid that is water-based (the Rosco 1700). The particle size and percent obscuration of the smoke from these machines have been determined and used to understand the requirements of alarm for the detectors.

By using the Phase Doppler Particle Analyzer (PDPA) to measure the particle size of the smoke leaving each machine, it was found that the smoke from the Aviator UL had much smaller particles than that of the Rosco. Optical density meters were used to measure the percent obscuration per foot of the smoke entering the detectors. Along with the smaller particle sizes recorded, the Aviator UL also alarmed at a significantly lower percent obscuration per foot. It is hypothesized to be that because of this smaller particle size, the Aviator UL was able to alarm the “false alarm resistant” Kidde detector whereas the Rosco, with the larger particle sizes was unable to force the alarm into detection until the level of obscuration was significantly higher than the Aviator UL.

17. Key Words
Smoke detector, detection, phase Doppler particle analyzer, PDPA, particle sizing, smoke generator, theatrical smoke, false alarm, optical density

18. Distribution Statement
This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	93	

CHARACTERIZATION OF SMOKE MACHINES IN TESTING AIRCRAFT SMOKE DETECTORS

By

TINA EMAMI

A thesis submitted to the

Graduate School – New Brunswick

Rutgers, The State University of New Jersey

In partial fulfillment of the requirements

For the degree of

Master of Science

Graduate Program in Mechanical and Aerospace Engineering

Written under the direction of

Francisco Javier Diez

And approved by

New Brunswick, New Jersey

October, 2017

ABSTRACT OF THE THESIS

Characterization of Smoke Machines in Testing Aircraft Smoke Detectors

By TINA EMAMI

Thesis Director:
Francisco Javier Diez

To improve the accuracy of aircraft fire detection, new smoke detectors have been produced to differentiate between what is a real fire and what is a false alarm. Nontoxic theatrical smoke machines are used to test these new false resistant smoke detectors in flight. This research is based on characterizing the smoke from the machines to understand what alerts different types of smoke detectors, and what would best be used for testing them.

Two smoke detectors were utilized in testing. One was a Whittaker Model 601 smoke detector which is an optical beam smoke detector; the second is a Kidde Aerospace & Defense Smoke Detector Type II which is a prototype of the new false alarm resistant detector. Two smoke machines were also used: one using fluid that is oil-based (the Concept Smoke Systems Aviator UL 440) and one using fluid that is water-based (the Rosco 1700). The particle size and percent obscuration of the smoke from these machines have been determined and used to understand the requirements of alarm for the detectors.

By using the Phase Doppler Particle Analyzer (PDPA) to measure the particle size of the smoke leaving each machine, it was found that the smoke from the Aviator UL had much smaller particles than that of the Rosco. Optical density meters

were used to measure the percent obscuration per foot of the smoke entering the detectors. Along with the smaller particle sizes recorded, the Aviator UL also alarmed at a significantly lower percent obscuration per foot. It is hypothesized to be that because of this smaller particle size, the Aviator UL was able to alarm the “false alarm resistant” Kidde detector whereas the Rosco, with the larger particle sizes was unable to force the alarm into detection until the level of obscuration was significantly higher than the Aviator UL.

II. Acknowledgements

I would like to thank Professor Diez, Robert Ochs, Dick Hill, and Dave Blake for giving me the opportunity to work towards my Master's Degree through the Federal Aviation Administration. I would like to again thank Professor Diez, Rob, Dick, and Dave as well as Paul Scrofani and Joey DeFalco for their immense knowledge, patience, and guidance through helping me with all of my research. Thanks to them and everyone else at the FAA Technical Center that was always ready and willing to help me, I am able to apply what I learned at Rutgers hands on and practically. My research would not have been possible without their help.

I would also like to thank my friends and family for supporting me through my studies. I would especially like to thank my parents who constantly support me with love, guidance and encouragement.

III. Contents

IV. List of Tables

V. List of Figures

Chapter 1: Introduction

Detection of fires in aircraft cargo compartments is extremely important. The flight crew aboard UPS flight 6 leaving Hong Kong in 2010 did not survive a fatal crash caused by an uncontained cargo fire which lead to the loss of control during flight [1]. On a different flight, the flight attendants of Philippine Air Lines flight PR512 from Singapore to Manila in 2013 were alerted of a fire in the aft cargo compartment, which lead the cabin crew to discharge fire extinguishing bottles and the flight crew to land immediately. No one was hurt in this accident [2].

Early detection can prevent disasters from happening during flight. This is why the FAA requires smoke detectors in cargo compartments as seen in the code of Federal Regulations, Amendment 25-142 Section 25.857; there must be approved smoke detectors to give warning to the pilot or flight engineer [3]. The Philippine Airlines aircraft fire was due to the mixing of two dangerous chemicals glycerin and potassium permanganate [2]. This could have been better prevented if baggage was more thoroughly checked prior to the flight, but the smoke detectors were at least alerting the crew to land immediately and discharge the fire extinguishing bottles in the cargo compartment. Through early detection, lives were saved as a result of quick and accurate smoke detection and fire suppression.

Having smoke detectors in cargo compartments is just as important as having them in aircraft lavatories. This is a location that is not easily occupied or accessible during flight, so a fire could grow and spread, possibly affecting critical flight systems. Early detection of smoke in the cargo compartments gives the crew the opportunity to suppress the fire quickly before serious damage is done to critical flight systems.

The federal regulations requiring smoke detectors to be installed in cargo compartments also require that the detectors be tested in flight [4]. The tests are intended to detect the toxic smoke before reaching compartments with crew and passengers. The tests must be done in flight because both the detector sensitivity and the internal airplane airflows during flight are different than when on the ground [4].

Ensuring the smoke detector is operating properly brings up the difficulty of testing it. Typically, using safe and nontoxic theatrical smoke machines to simulate cargo compartment fire-generated smoke in flight was adequate to cause smoke detectors to alarm quickly [5]. These same smoke machines need to be used to evaluate the performance of the new false alarm resistant detectors to ensure they can alarm when exposed to the same levels of simulated smoke. False alarms include an alarm that is not due to smoke from a fire, this includes the detectors alarming due to gasses or fumes, water mists, and further unknown sources. Because of the safety hazards of testing with fire while in flight, the exact criteria of what alerts the detectors needs to be found to find a safe testing alternative.

The objective of this study is to understand the characteristics of theatrical smoke that alarm two specific smoke detectors. There are different characteristics of the smoke to be measured. Measuring the particle sizes of the theatrical smoke that alarm the smoke detectors can help to classify the smoke. Comparing this with the density of the measured smoke can give a better understanding of what will alert the smoke detectors. This can help to further identify what method is best used to evaluate the performance of the new false alarm smoke detectors.

Chapter 2: Instrumentation

2.1 Introduction

In this section, the theory behind the PDPA, smoke detectors, theatrical smoke machines, and optical density meters are explained.

2.2 Theatrical Smoke Machines

Theatrical smoke is originally designed for stages, visually creating a safe and nontoxic form of smoke from fires. There were two theatrical smoke machines used in this study; the Rosco 1700 model smoke machine shown in Figure 1 and the Concept Aviator SDT Ultra Low smoke machine shown in Figure 2. Both smoke machines create smoke that is very buoyant. Rosco smoke produces thick, white, nearly opaque clouds of smoke where the Aviator UL at its original state outputs smoke that is much lighter in comparison.

Figure 1 - Rosco 1700 Smoke Machine

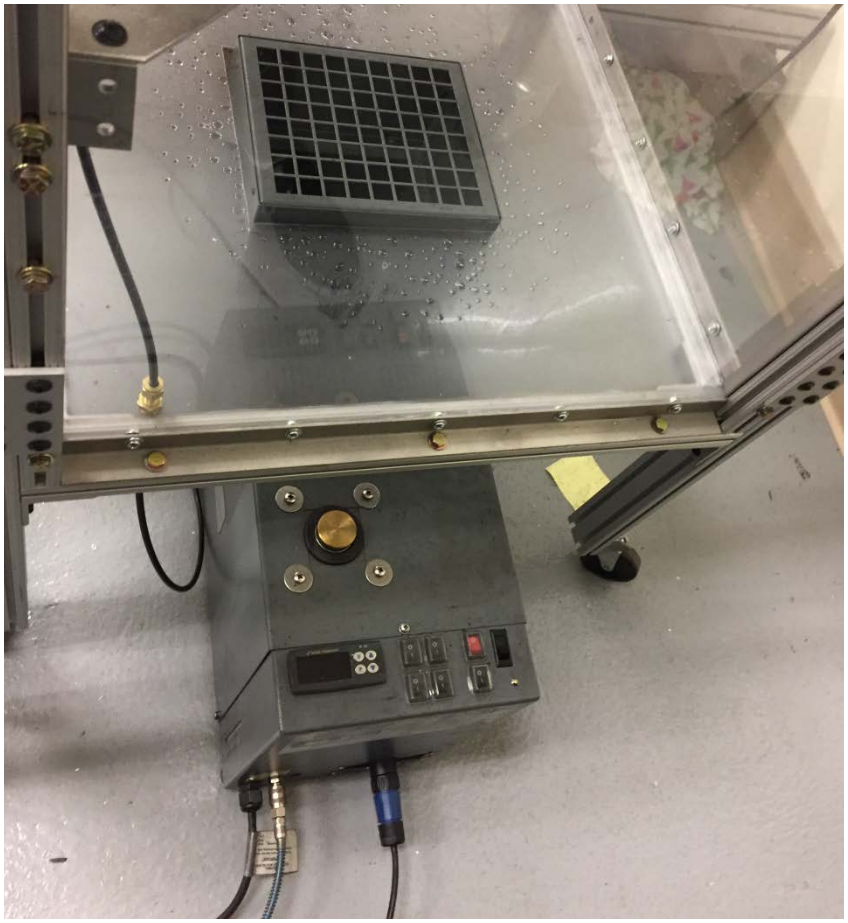

Figure 2 - Concept Aviator SDT UL Smoke Machine

The Rosco 1700 machine is a variable output smoke machine. This smoke machine works by drawing fluid from an external reservoir and into a heat exchanger. It is here where the fluid is heated very quickly and vaporized. The vaporized fluid is ejected through its nozzle and into the atmosphere. When it reaches cool air, it turns into an aerosol with millions of small particles [6].

Rosco manufactures its own brand of smoke fluid, two of which were used, the Rosco Clear Smoke Fluid and the Rosco Light Smoke Fluid. The Clear Smoke Fluid is made of Triethylene glycol, 1,3-Butylene glycol, Propylene glycol, and deionized water. This is the standard formula, and it puffs out thick white clouds of smoke. The Rosco light smoke fluid has all the same ingredients minus the 1,3-Butylene glycol [7]. With this fluid, the machine puffs out much lighter clouds of smoke, appearing less opaque than the Rosco Clear Smoke Fluid.

The Concept Aviator Ultra Low smoke machine uses an oil based fluid which makes it resistant to extremely high temperatures. Contrary to the Rosco smoke machine, the Aviator UL is not made for theatrical stages, it is made to represent actual fires from small to larger quantities to specifically be used for testing smoke detectors. The machine uses an inert gas, which was nitrogen in this study, to propel the food grade mineral oil into a heat exchanger which vaporizes it into smoke. The heated gas in the machine rises, carrying the temperature resistant smoke particles vertically out of the smoke machine and upwards [8].

The Concept Aviator UL also manufactures their own smoke fluid which is an oil-based smoke fluid called Concept Oil 135 which is a white mineral oil. This is the main difference between the Rosco and Aviator UL smoke machines, and the fluids are not interchangeable between the two. The Aviator UL has the capability to adjust the smoke density to a desired level, but the “original” setting puffs smoke to appear similar to that of the Rosco Light fluid.

2.3 Smoke Detectors

Accuracy in the detection of fires is a necessity, and with the growth of technology more accurate smoke detectors have been developed. The most common type of detector employs photoelectric sensors, which can alarm with any particle in the detector including cigarette smoke, water steam, and dust, often resulting in alarms that were not caused by smoke from fires [9]. This can be demonstrated by the high frequency of false alarms seen with household detectors [10].

Photoelectric smoke detectors have two main components; a light source and a photosensitive receiver. When the smoke particles enter the detector, they scatter some of the laser light, which refracts into the receiver. This can be seen in Figure 3 where A is the light source and B is the receiver. If the amount of light refracted into the receiver exceeds a set value, the detector responds by alerting of a fire [11].

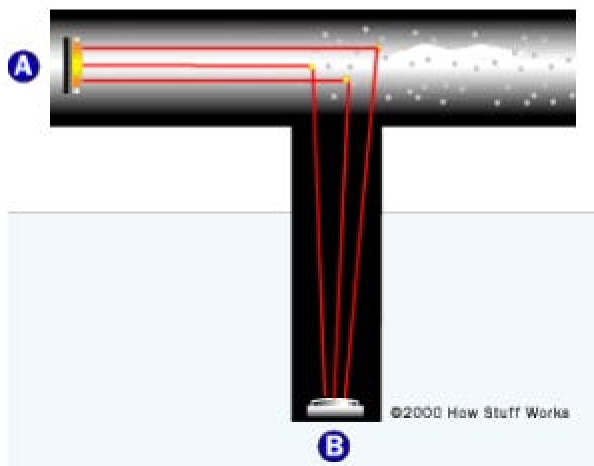

Figure 3 - Photoelectric Smoke Detector Schematic [12]

The smoke detectors used in this testing are the Whittaker Model 601 Smoke Detector and the Kidde Aerospace & Defense Smoke Detector Type II. The Whittaker model is representative of what is currently installed in airplane cargo compartments while the Kidde smoke detector is a prototype of a newer, more advanced model with enhanced technology. Both smoke detectors are claimed by the manufacturers to alarm at a 96% ± 1.0% light transmission.

New false alarm resistant smoke detectors are installed in airplane cargo compartments and are required to be tested regularly. The false alarm rejection criteria for these new alarms include dust, insecticide, ambient light, and a combination of temperature, pressure, and humidity cycling [13]. A majority of the new technology used in the Kidde smoke detector is proprietary to the company and was not available during this study.

2.4 Optical Density Meters

One characteristic of the theatrical smoke that was measured is the percent obscuration of light that the smoke was creating while alarming the smoke detectors. This was accomplished with an optical density meter, which is a 670 nm wavelength, 0.9 mW laser paired with an optical light receiver. The laser sends energy through photons to the receiver, which receives the light and converts it into electrical current [14]. This current is then sent to an optical amplifier to magnify the signal that is sent to the computer to be recorded. To calculate the percent obscuration per foot between the laser and the receiver using the signals recorded, Equation 1 is used.

$$O_u = \left[1 - \left(\frac{T_s}{T_c}\right)^{1/d}\right] * 100 \tag{1}$$

In Equation 1, O_u is the percent obscuration per foot, T_s is the density meter reading with smoke, T_c is the density meter reading with clear air, and d is the distance between the laser and the receiver [15]. Normalizing the obscuration by length in feet is better for comparison to the different settings chosen. Mathematically, the percent obscuration O_u is a ratio of the recording with smoke and recording without. Since the receiver is receiving light in general and not just the specific wavelength of the laser, a cloudy day versus a sunny day would affect this. To counteract this, the value of the density meter reading with clear air is updated before each test to compensate for daily fluctuations in ambient laboratory lighting.

2.5 Phase Doppler Particle Analyzer

To measure the particle sizes of theatrical smoke, a Phase Doppler Particle Analyzer (PDPA) was used. PDPA is frequently used to precisely measure particle sizes for a wide variety of applications. The Institute of Chemical Technology in Mumbai used PDPA to accurately measure the drop size characteristics in annular centrifugal extractors [16]. The PDPA was also used to understand the influence of spinning cup and disk atomizer on droplet sizes [17]. The PDPA was even used for successfully characterizing droplet spectrum characteristics of pesticide spray nozzles, [18] [19] and continued to understand the characterization of splash droplets from different surfaces [20].

PDPA can also be used to measure particle velocities, even at high speeds. Sun and Huang of Lanzhou University utilized the PDPA to measure the velocity of sand in a wind tunnel [21]. It has also been used to measure size, as well as axial and transversal velocities of the gas-particle flow in a circulating fluidized bed [22].

The PDPA measures flow velocities and particle sizes by processing scattered light from small inhomogeneities in the flow [23]. The PDPA has four separate lasers are fired at two different wavelengths, one at 532 nm (green) and one at 561 nm (yellow). The yellow laser records particle size measurements as well as the vertical velocity component, where the green laser measures the horizontal velocity component. Since the particle size and vertical velocity component are the only measurements needed in this study, the yellow laser was the only one utilized. The measurements are found at the intersection of the laser beams. When a particle passes through this intersection area, it scatters the light of the beams into a receiving probe. The size of the particle being measured is proportional to the phase shift between the Doppler burst signals that the detectors received [24].

The Doppler shift can be understood by listening to a car moving towards and away from a point, the faster the car is moving the greater the shift in the frequency that is heard. The effect works similarly with light. The speed of the particle is measured by noting the frequency shift. The Doppler shift, f_D, is shown in Equation 2.

$$f_D = \frac{2V}{\lambda} cos\beta \; sin\frac{\alpha}{2} \tag{2}$$

In Equation 2, V is the particle speed, λ is the wavelength of the light, α is the orientation of the observer and β is the direction of the particle motion [25].

The PDPA has different components. It has a transmitting probe, a receiver, a Photo Detector Module (PDM), and the Flow Size Analyzer (FSA) signal processor. The configuration is seen in Figure 4. Scattered light is collected by the probes in the receiver and into the PDM. In here the light is sent through color separating optics. The signal is then sent through high pass filters. The filtered signal is then sent to the FSA as an electrical signal which processes it and sends it to the computer [26].

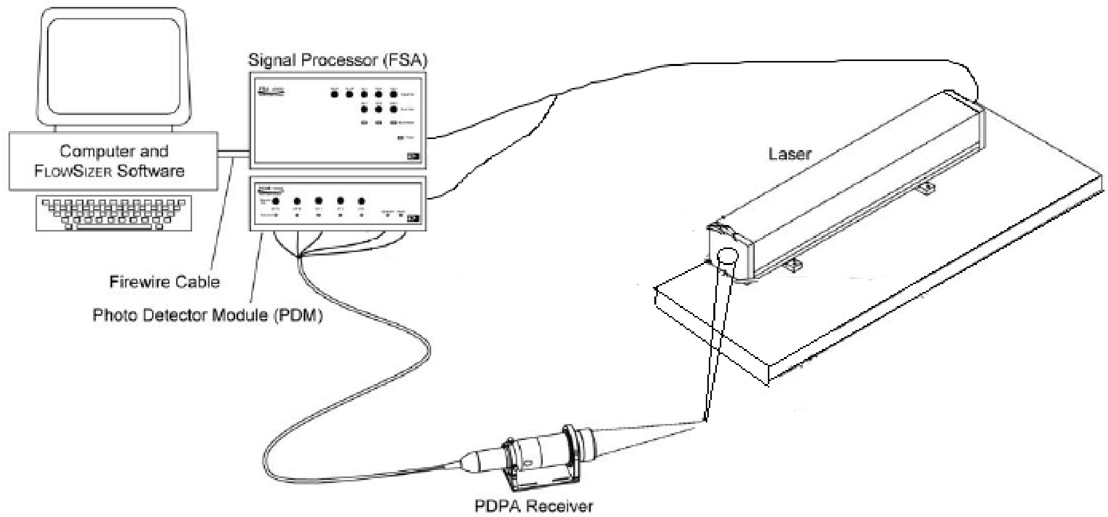

Figure 4 - PDPA Components [26]

The FSA receives the signals from the PDM and extracts information such as frequency, phase, burst transmit time and burst arrival time and sends it to the computer. The FSA has different signal processing stages. It first goes through the downmixer which changes the frequency shift from the multicolor beam generator at any value between 0 and 40 MHz. This process is equivalent to multiplying the input signal with the downmix frequency that is selected by the user through the software [26].

It then goes through one of twenty bandpass filters. This process removes noise. Then the signal splits into two; one goes to the burst detector and the other goes to the burst sampler. The burst detector discriminates between the Doppler signal and background noise. It does this by constantly monitoring the signal to noise ratio (SNR) of the signal and detecting the signal when it exceeds that set SNR value. The burst detector then measures the duration of the burst [26].

The signals are also sampled in parallel with the burst detector. This is done using high speed A/D converters. This frequency estimate determines the best multi-bit sampler for the actual burst frequency, and also determines the best part of the burst to collect samples from. It takes the best samples and sends them to the burst processor. This determines the frequency using an autocorrelation technique. The processed burst is sent to the computer with its frequency, time stamp, transit time, and channel number [26].

The transmitting probe and receiver of the PDPA need to be placed at a certain off-axis angle for proper measurement. There are a few steps to determine this. First it is necessary to know the refractive index of the particles. The theatrical smoke used is from a Rosco Smoke Machine 1700. According to the manufacturer, the machine outputs smoke at particle sizes ranging from 0.25 – 60 microns [27]. This measurement can be read differently in varying situations. Through the Rosco website the composition of the smoke fluid was found, so the refractive index of the fluid was used with the assumption that it would be equal to the refractive index of the smoke. It is an aqueous glycol solution composed of triethylene glycol, 1,3-Butylene glycol, Propylene glycol and deionized water [28]. The refractive index of triethylene glycol is 1.4531, the refractive index of 1,3-Butylene glycol is 1.4401, and the refractive index of propylene glycol is 1.4324 [29]. The weight percentage of each component is not provided by the manufacturer, but with these values an estimate was made of a refractive index of 1.439. The Concept Smoke Oil 135, used by the Aviator UL smoke machine., is a white mineral oil and has a refractive index of 1.475 [30]. These values are entered into the PDPA's program called Flow Sizer.

The off-axis angle is found from the chart in Figure 5. In order to find the off-axis angle on the y-axis the domain number must be determined. The domain number is found from the chart in Figure 7, using the attenuation coefficient.

Under the "Polarization Perpendicular to Beam Plane" it can be seen that the Domain number is 11 since our Attenuation level is 1. The attenuation level is found by inputting the attenuation coefficient into the FlowSizer program which finds the attenuation level. The attenuation coefficient is found in the chart in Figure 6. Because the smoke fluids are water based, an attenuation coefficient of 0 was chosen and the attenuation level of 1 was calculated by the FlowSizer program.

Refraction will be used to measure the droplet sizes of the smoke because its particles are transparent. Back scatter, or reflection, is used when the particle droplets are opaque. This can be seen in Figure 8.

In Figure 5, it can be seen that with a refractive index of 1.4559 and a domain number of 11, the off axis angle should be between 30 and 90 degrees. It is best to be well inside the section and not too close to the boundaries. In Figure 9, Domain 12 would also work but with less confidence but Domain 10 would not work at all. It is best to stay further away from Domain 10.

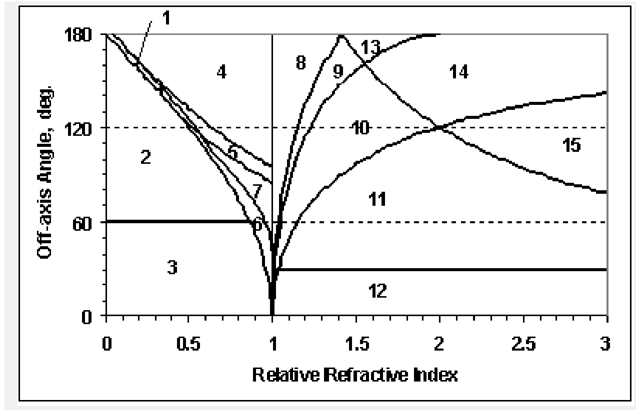

Figure 5 - Scattering Domain Chart [31]

Particle Material	Refractive Index	Attenuation Coefficient (1/mm)
Air	1	0
Water	1.33	0
Glass	1.52	0
Jet-A Fuel	1.45	50
Mil-C Fuel	1.45	0.05
Silver	0.2	84,000
Aluminum	1.44	128,000
Copper	0.62	63,000

Figure 6 - Attenuation Coefficient Chart [31]

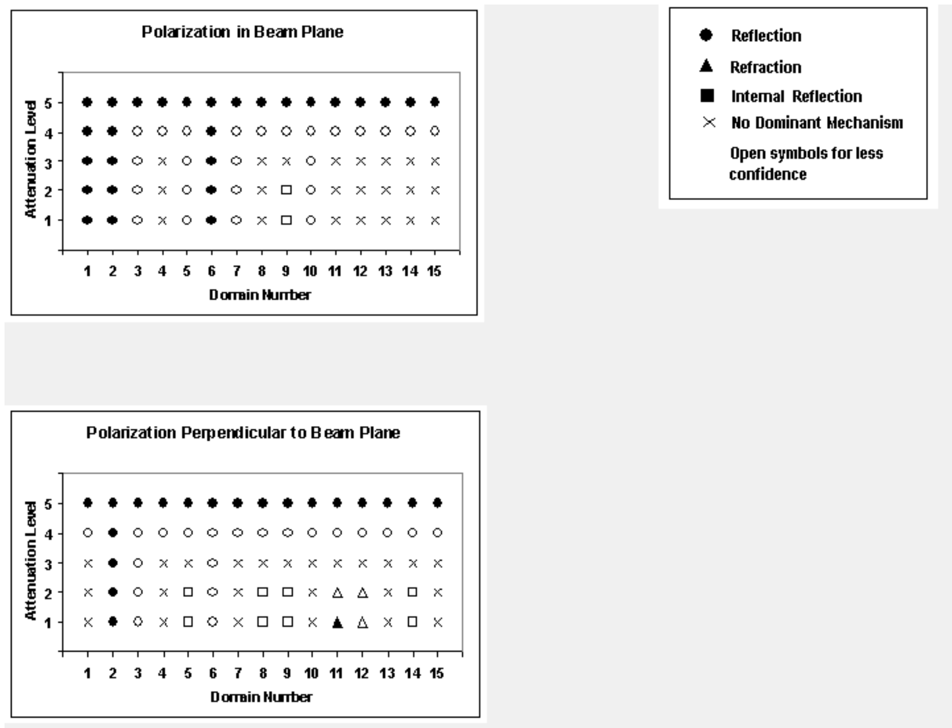

Figure 7 - Scattering Mode Charts [31]

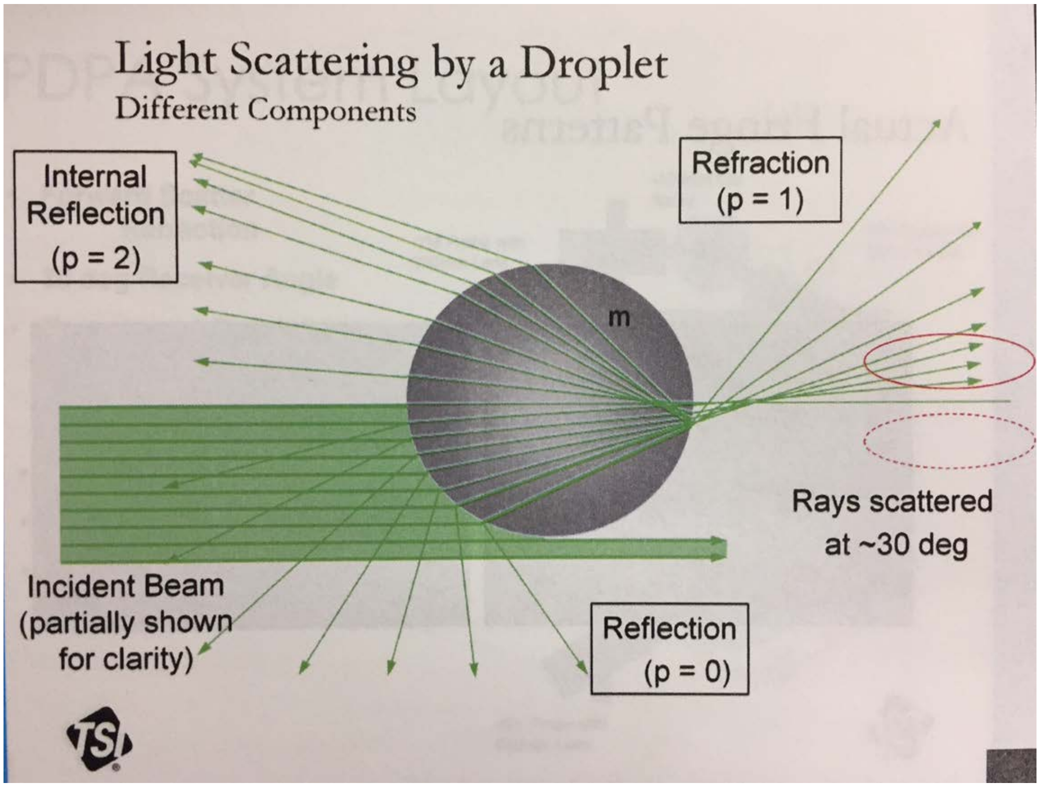

Figure 8 - Droplet Light Scattering Diagram [31]

The variation of scattered light intensity also needs to be considered. This can be seen in Figure 9 where the scattered light intensity as a function of receiver position is shown. It can be seen in the chart that the scattered light intensity dips low at 60 degrees. There is a small peak afterwards but there is a much higher intensity in the angles under 60 degrees. Because of the strong peak at 30 degrees as well as the fact that it is the smallest angle that can be physically achieved with this setup, the transmitter and receiver were chosen to be set at this angle.

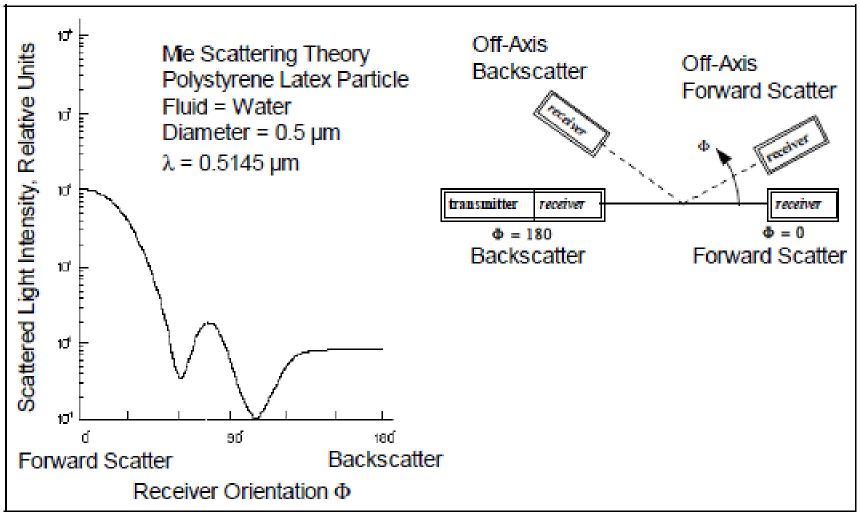

Figure 9 – Scattered light intensity Graph [31]

The PDPA outputs extensive data about the particles that pass through the beam intersection. The main characteristic to be found is the particle diameters. The diameters are shown in average values recorded. The Diameter number mean (D10) is the average of the diameters of all droplets in the sample. The Surface area mean (D20) is where the mean of the surface area is first calculated and the average diameter is found from that value, the Volume mean (D30) where the mean particle volume is first calculated and the diameter is found from that value, and the Sauter mean (D32) where the diameter is of the droplet whose ratio of volume to surface area is equal to that of the complete sample.

2.6 Instrumentation Error

Both the Whittaker smoke detector and the Kidde smoke detector note an error of ±1% light transmission. The optical density receiver used was made by Edmund Optics, which claims a noise equivalent power of 3.9x10^{-14} W/$Hz^{-1/2}$ [31].

The PDPA manufacturer states that it has a velocity accuracy of 0.1% of the maximum velocity which is calculated by the FlowSizer program [33]. The accuracy of arithmetic mean diameter (D10) of a large number of samples can be found by using Equation 3.

$$Accuracy\ of\ D10 < \ 1\% \ \times \ D_{max} + 1\% \ \times \ D_{measured} \quad (3)$$

In Equation 3, D_{max} is the maximum diameter that the program calculates with its current settings and $D_{measured}$is the measured droplet diameter [33].

Chapter 3: Experimental Set Up

3.1 Introduction

In the following chapter, the theory of optical density meters is discussed as well as describing the smoke detectors and smoke machines used in testing. The characteristics to be measured are particle size and percent obscuration of smoke entering the smoke detectors. To make these measurements, PDPA and optical density meters are used. The configuration for these measurements is discussed in detail in this chapter as well as the different positioning of instrumentation.

Understanding the particle size and percent obscuration of smoke that enters the detectors would ideally be done in the cargo compartment itself. For the PDPA to read accurate data, it requires particles that are concentrated near its beam's intersection point only. With clear air surrounding the particles at its beam's intersection point, the refracted light containing particle size information has perfect access to the PDPA's receiver. To reduce noise, a testing chamber has been created and described in this section.

3.2 Experiment Assembly

The experimental setup was built around the PDPA. Using the charts explained in previous section, the PDPA laser was mounted at 30 degrees away from its receiver. It is mounted on a traverse at this fixed angle so that the measurement point can be precisely moved in all directions without the need to readjust the laser-receiver angle.

The PDPA collects data from particles that flow through the lasers' intersection point, which then refract light into the PDPA's receiver. If there are too many particles surrounding this point especially in between that point and the receiver, the surrounding particles will reflect and refract that light as well, distorting data or making it unreadable. A testing chamber was made to ensure the smoke is directed to the laser intersection point to record the most accurate data possible. This test chamber along with its dimensions can be seen in Figure 10.

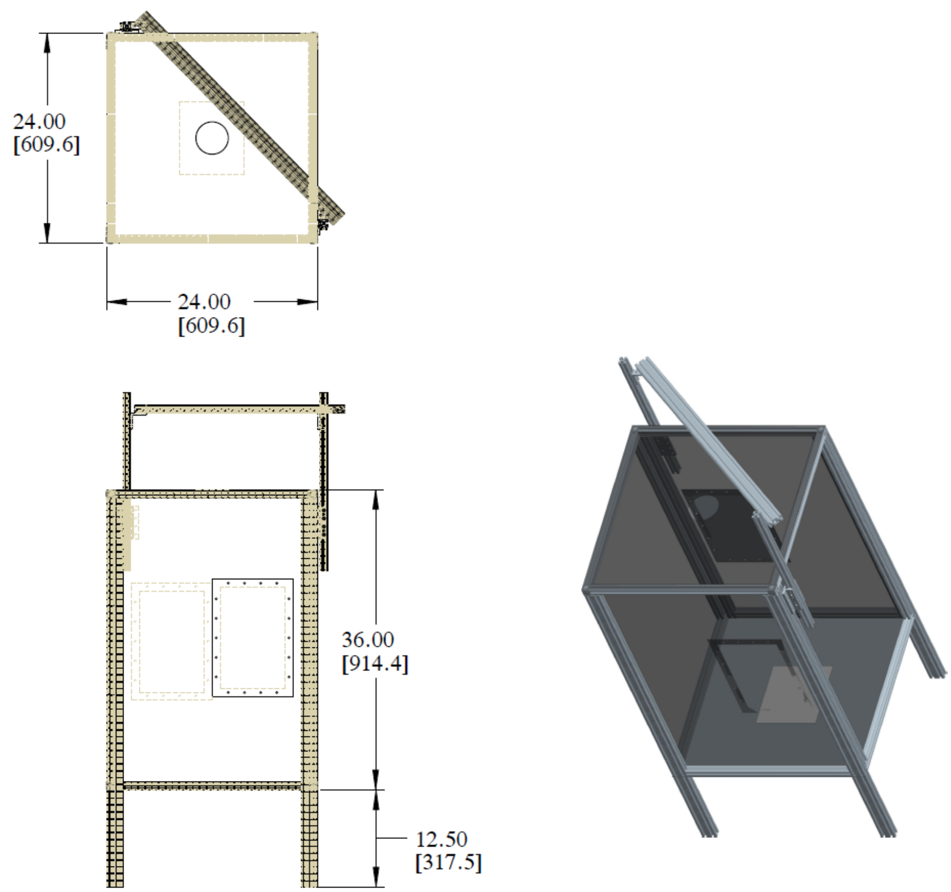

Figure 10 - Lexan Testing Chamber and Dimensions

The testing chamber is completely sealed shut except for two locations; the bottom of the chamber which is the inlet for the smoke and the top of the chamber which is the outlet for the smoke. This is done so that the location of the smoke entering the measurement instrumentation and smoke detectors are controlled and precise. The bottom of the chamber is shaped to fit the exit of the smoke machines exactly, to make sure all the smoke is entering the testing chamber. The top of the testing chamber has a 4-inch (101.6 mm) diameter fan mounted in its center. This acts as the smoke exit of the test chamber. This fan can be seen in Figure 11.

The fan is secured so that half of it is inside the test chamber and half of it is outside. Its edges are completely secured to be leak proof, so the only smoke exiting the top of the chamber is through the fan only. The fan is aimed towards the intersection of the PDPA lasers to direct the smoke to the measurement location.

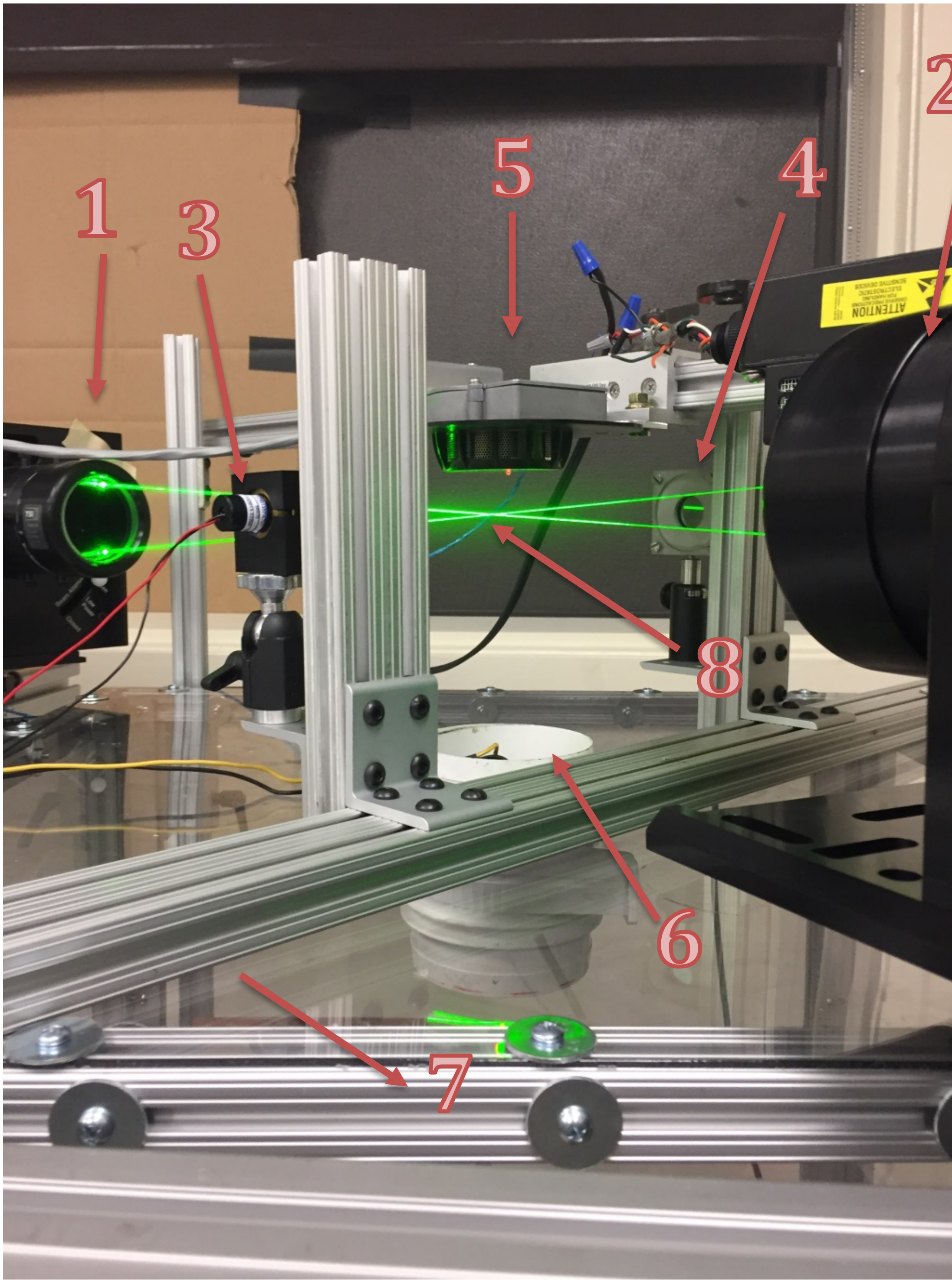

Figure 11 - Equipment Above Testing Chamber Including: PDPA Laser(1) and its Receiver (2), Optical Density Laser (3) and its Receiver (4), Kidde Detector in Alarm (5), Exit Fan (6) on top of Testing Chamber (7), and the Measurement Point (8)

The testing chamber has dimensions of 24 x 24 x 36 inches (609 x 609 x 914 mm) and is framed with extruded Aluminum T-slot rails and enclosed with clear Lexan. The legs are 12.5 inches (317 mm) high, which holds the test chamber at an exact height for its bottom to be level with the exit of the Aviator UL smoke machine. The bottom of the chamber has a square hole that is the same dimension as the exit of the Aviator UL, in order to capture all of the smoke leaving the smoke machine in the chamber. This is shown in Figure 12.

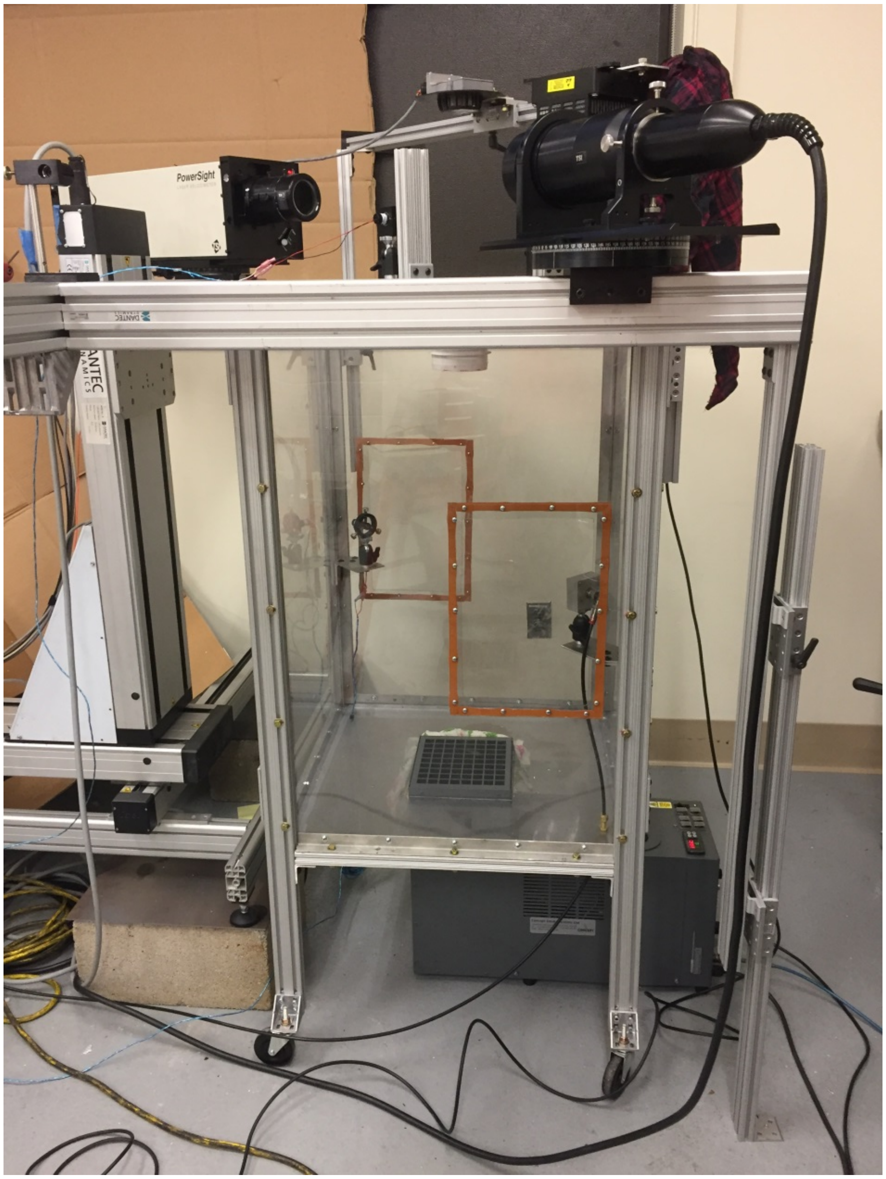

Figure 12 - Full Experimental Setup with Aviator UL in Testing Position

This is simpler with the Aviator UL because this machine outputs smoke upwards. The Rosco sprays smoke horizontally, so a 4 inch (101.6 mm) diameter tube is connected to the Rosco and bent up 90 degrees to force the smoke into the chamber. There is a Lexan adaptor that is attached to the bottom of the chamber with a circular hole to fit the tube connected to the Rosco. This can be seen in Figure 13.

On the inside of the chamber along its center, 18 inches (457.2 mm) down from the top of the box, an optical density meter is mounted two feet apart as seen in Figure 13. This is placed here to measure the density of smoke inside the chamber.

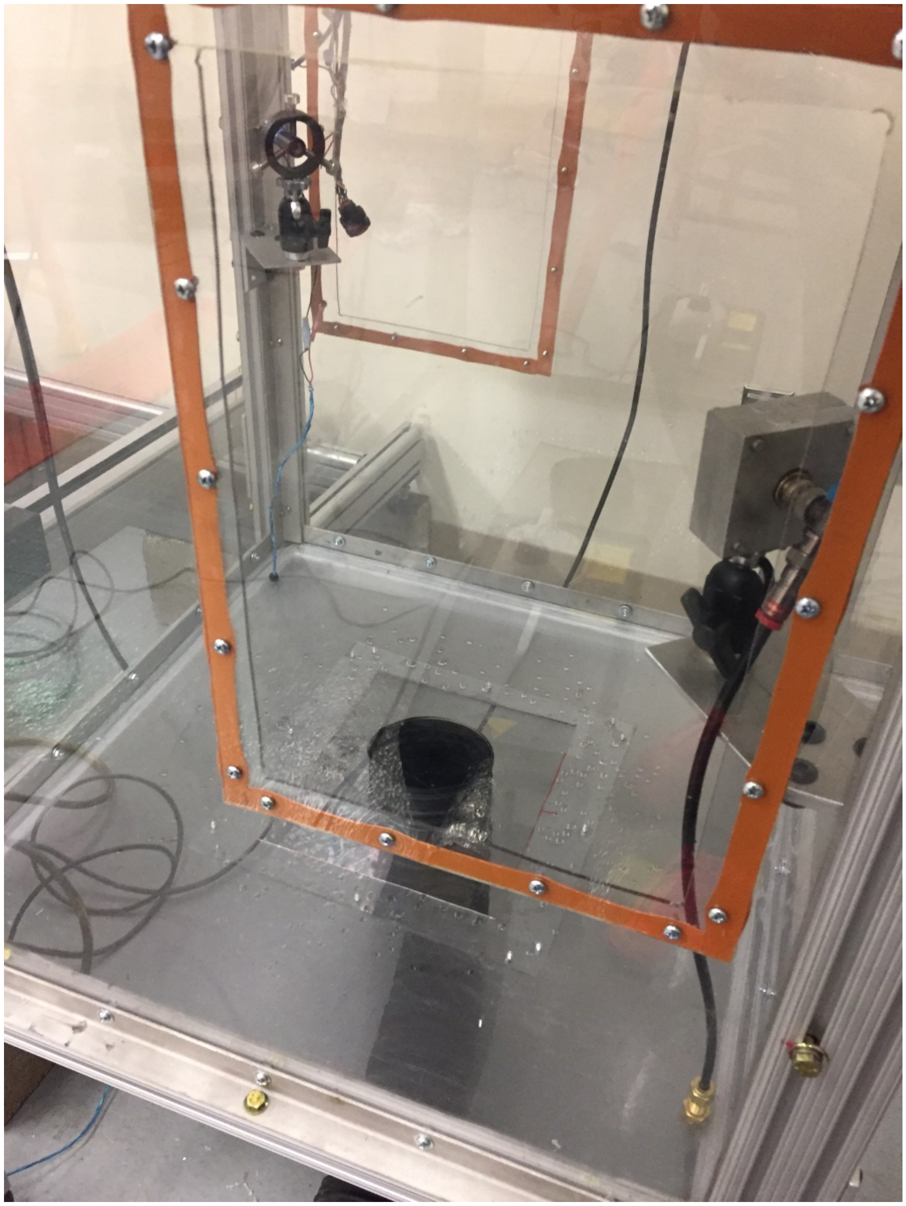

Figure 13 - Inside View of Testing Chamber with Optical Density Meters and Rosco Smoke Exit Tube

Above the fan is another optical density meter mounted around its exit. The optical density laser is mounted 6 inches (152.4 mm) apart from the receiver at a location near the smoke detector surface in order to measure the density of smoke entering the smoke detectors.

The PDPA laser beams intersect with the optical density meter laser, such that the PDPA measurement point is in the same plane as the optical density measurement. The optical density meters are connected to optical amplifiers to magnify the signal that they are reading. The optical amplifier is then connected to a data acquisition Board, the P-Daq/56 which measures the signal from the amplifiers and sends it to the computer through USB. The data acquisition software in the computer records the measurements it receives for every second.

The brightness of the PDPA lasers are not to be worried about here because the value for the optical density reading before smoke is introduced is recorded before starting the smoke machines and plugged into Equation 1. This value increases compared to when the two lasers are not aligned but it is accounted for when finding the percent obscuration per foot. This is accounted for by the value recorded for “clear air” before beginning to test. The light from the PDPA lasers stays uniform so by using this value, it is accounted for.

Mounted around the chamber are beams holding the two smoke detectors. The center beam holds the detectors above the fan exit and above the optical density meters. Both detectors are on the same horizontal beam so that each detector is tested separately. When testing each detector, it is centered above the fan exit as seen in Figure 11.

The Whittaker Smoke detector is connected to a 28 V power source and the same data acquisition board and program as the optical density meters. The Whittaker detector is either off or alarming and has a red light that turns on when it is detecting smoke. When the detector is alarming, it sends the 28V to the Data

Acquisition board, which sends that signal to the computer and is recorded alongside the optical density data. This way, the exact time and optical density can easily be seen when the detector alarms. An example of the Whittaker alarm is shown in Figure 14 where the detector is either not alarming (0 Volts) or alarming (28 Volts) as shown.

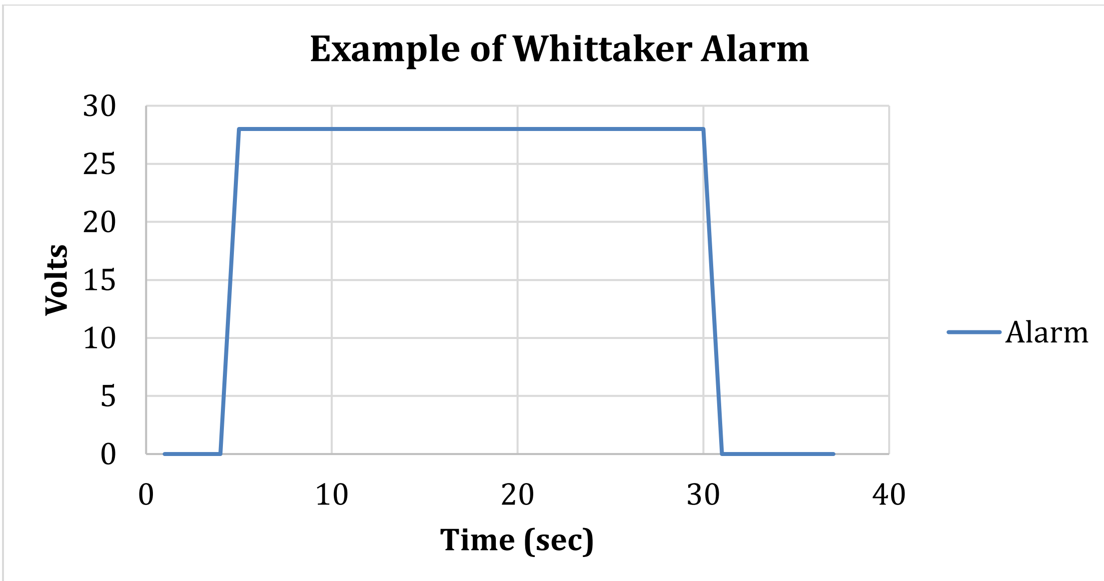

Figure 14 - Example of Whittaker Alarm

The Kidde smoke detector needs to be connected to a 28 V power source as well as a Microchip Controller Area Network (CAN bus). A CAN bus allows microcontrollers and devices to communicate with each other in applications without needing a host computer [34]. Through the CAN bus, the different types of readings that Kidde has programmed into the detector can be translated and understood. This CAN BUS Analyzer is connected to the computer and through

Microchip's Analyzer Software it records the different types of alarms that the Kidde detector is seeing.

The Kidde detector outputs different values from the Whittaker such as: temperature alarm, pre alarm, low alarm, medium alarm, and high alarm in that order. This can be seen in Figure 15. They do not have an exact output magnitude, they just state their level of alarm and are shown in the graphs in this way. These threshold values can be set by the user, but the values that the manufacturer originally set were used in this study.

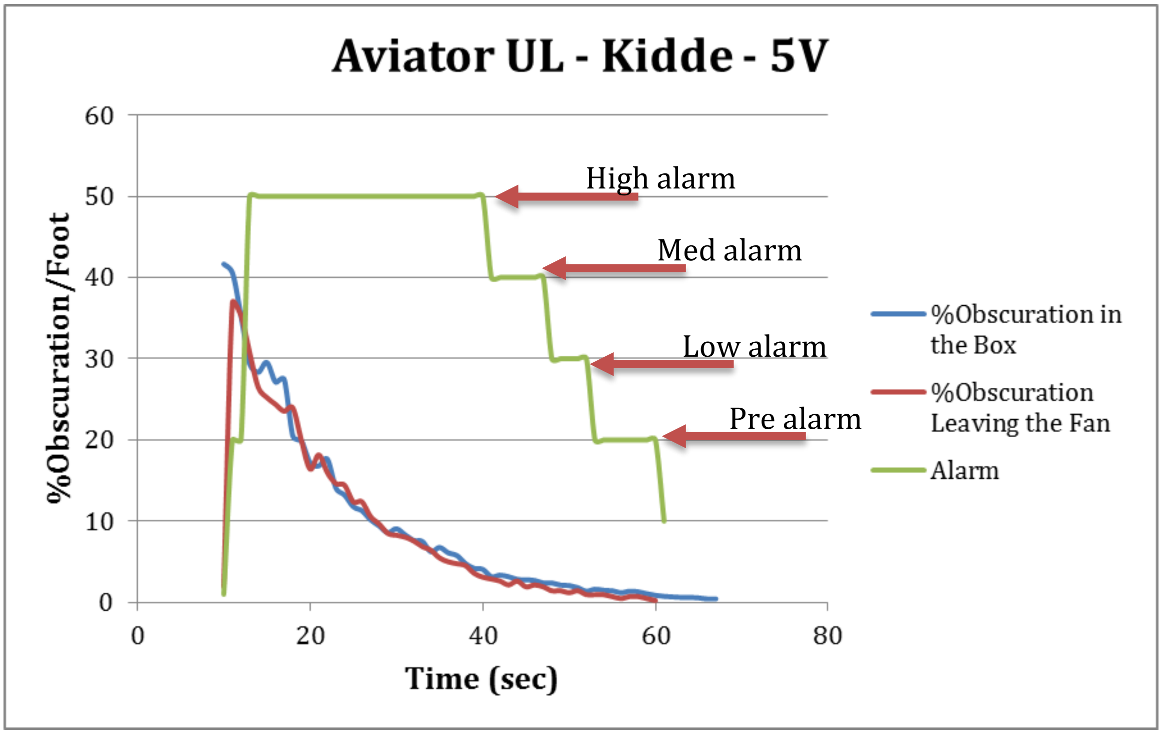

Figure 15 - Kidde Detector Test Example Showing Different Levels of Alarm

The Rosco smoke machine just needs to be plugged into a power outlet. The Aviator UL uses Nitrogen gas as a propellant in this study at 30 psi as well as plugged into a power outlet. The pressure of the inert gas is crucial for the Aviator

UL to work, as explained in the previous chapter. The smoke machine being tested is placed underneath the test chamber and is switched out when the other is needed.

3.3 Exit Fan Speeds

The fan attached to the top of the Lexan testing chamber is connected to a power source. For half of the testing done, it is connected to a 2.5V power source and for the other half of testing it is connected to a 5V power source. The PDPA is able to measure particle velocity and diameter, so the fan exit velocities as a function of applied DC voltage have been measured and shown in Figure 16.

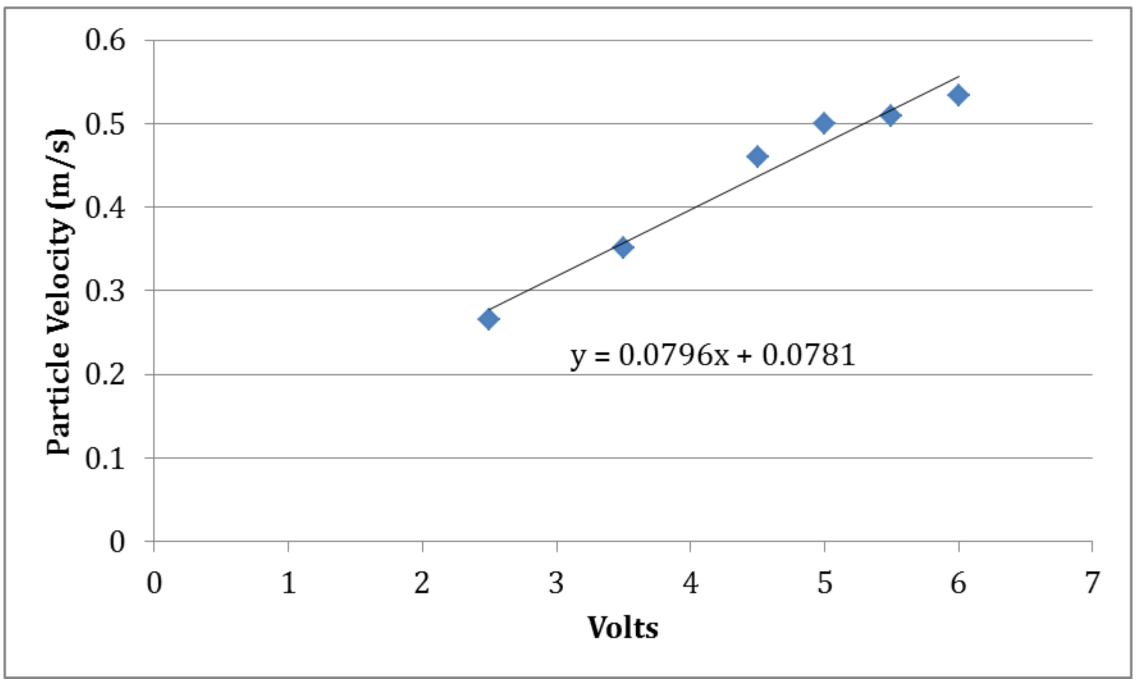

Figure 16 - Particle Velocity Recorded Versus Fan Voltage

From the data taken with the Rosco smoke machine, it is found that the mean vertical component of velocity of particles when the fan is connected to the 2.5V power source is 0.2654 m/s. When the fan is connected to the 5V power source the mean velocity of the particles is 0.4999 m/s. In the range of applied fan voltages measured, 2.5 – 5 V, a linear relationship was found between fan exit vertical velocity component and applied fan voltage shown in Equation 4.

$$v_y = 0.076 \times (voltage) + 0.0781 \tag{4}$$

In this setup, the maximum velocity is 1.22 m/s and the error is calculated to be 0.00122 m/s as explained in section 2.6. This is an extremely small error relative to the data found.

3.4 Detector Positioning

Several different configurations were tested in this study. The first is shown in Figure 17 which is called Configuration 1. The PDPA lasers and optical density lasers are initially not aligned here in fear of corrupting either of the data. The intersection point of the PDPA is 2.25 inches above that of the optical density lasers. The PDPA intersection point is 7.25 inches above the exit fan. The Whittaker detector is 9.75 inches above the exit of the fan and the Kidde detector is 11.75 inches above the exit of the fan. The Kidde detector is held higher here than the Whittaker simply because of the way their mounting was designed. The optical density laser is mounted a foot away from its receiver.

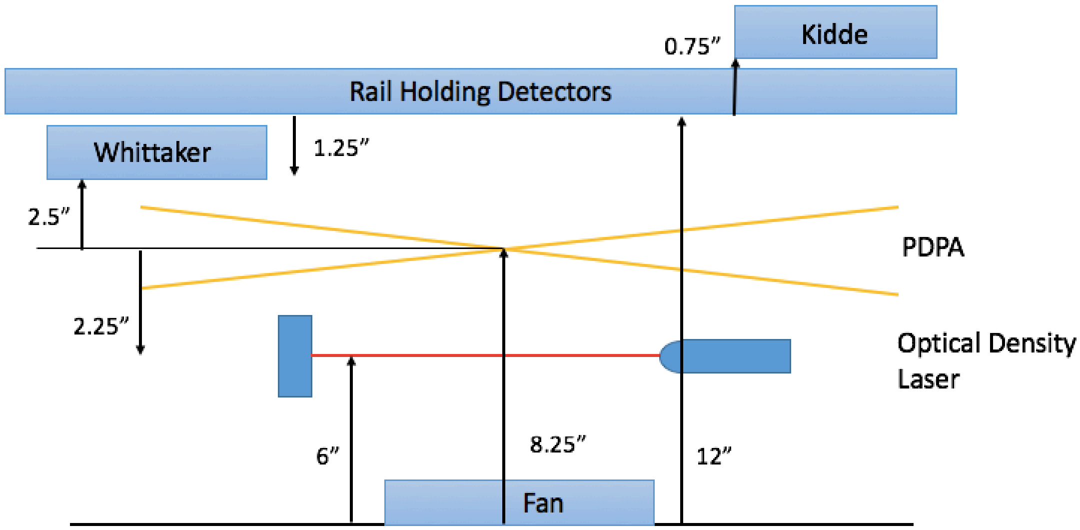

Figure 17 - Configuration 1 of Test Setup

Configuration 2 is shown in Figure 18. The Optical density lasers are now intersecting with the PDPA lasers and are both 5 inches above the exit of the fan. The railing holding the detectors was also brought down a lot so the Whittaker detector is now 6 inches above the exit fan and the Kidde detector is 8 inches above the exit fan. The optical density laser is still held a foot away from its receiver.

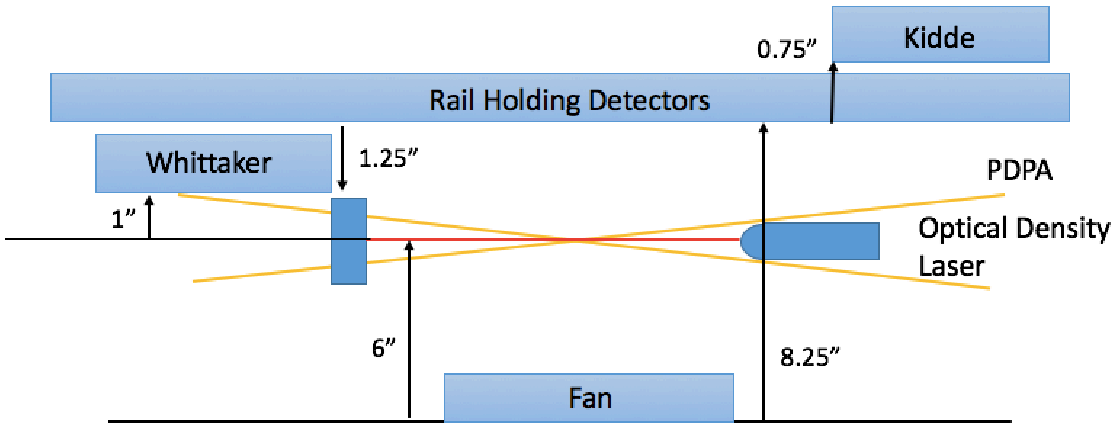

Figure 18 - Configuration 2 of Test Setup

In Configuration 3, everything is held the same except the optical density laser is now mounted 6 inches away from its receiver to closely wrap around the edges of the detectors and aim for a more accurate optical density reading. Also, the Kidde detector is forcibly mounted underneath the rail holding the detectors to match the height of the Whittaker. This can be seen in Figure 19.

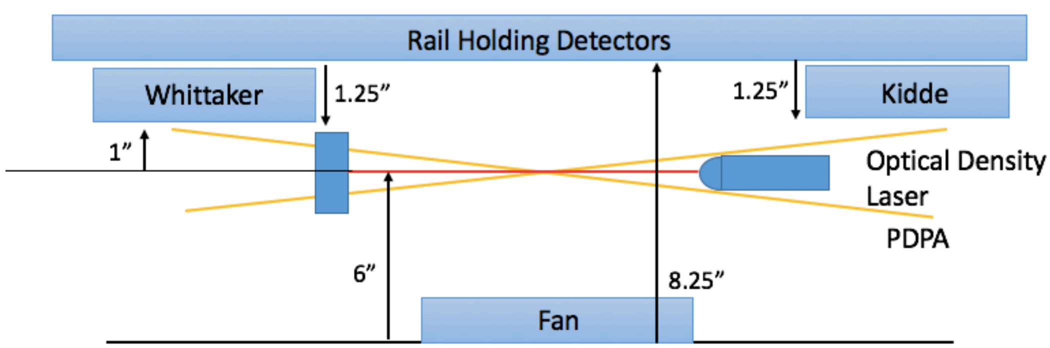

Figure 19 - Configuration 3 of Test Setup

Chapter 4: Calibration and Experimental Procedure

4.1 Calibration

In this section, the calibration procedures for the PDPA and optical density lasers are explained.

4.1.1 Optical Density Lasers

The optical density laser must be mounted so that its beam is directly aligned with the center of its receiver. The laser is connected to a 3V power source, and its red beam projection is then visible. The projected diameter of the laser is able to be changed and focused to a desired size or concentration through a focusing lens. The smaller the projected beam appears, the more concentrated it is. The size of the diameter of the laser is focused so that it matches the diameter of the receiver. Because the optical receiver is connected to an optical amplifier, the signal that is read is higher than that of the laser. The computer software reads 8V. The laser is moved and focused until the computer software reads the highest voltage possible. It is then confirmed that the laser is aligned with its receiver.

4.1.2 Phase Doppler Particle Analyzer

The PDPA laser has different calibrations that need to be done. The first and main calibration is the lasers beam alignment which is the main factor of measurement. A laser beam magnifier, that enlarges the beams 40 times, is placed at their intersection and projected on a sheet a few feet away as shown in Figure 20.

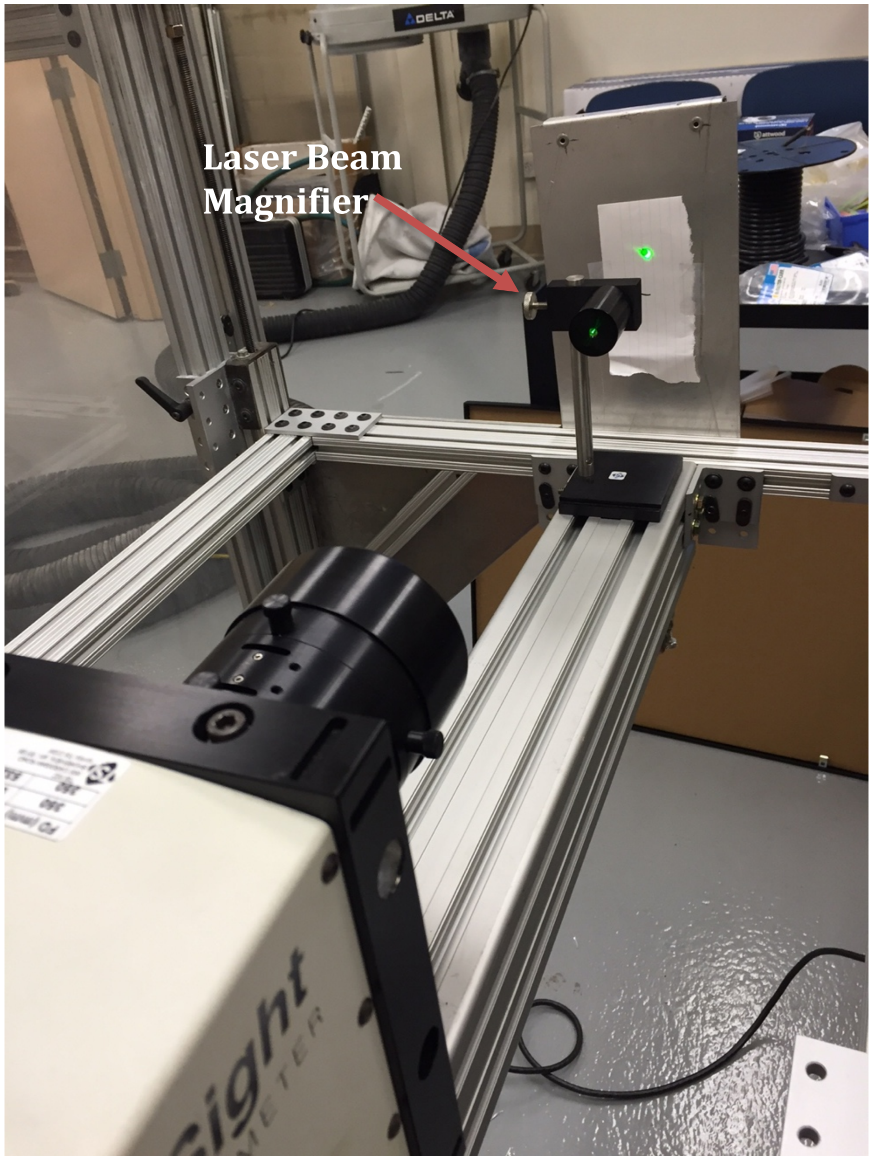

Figure 20 - PDPA Lasers and Laser Beam Magnifier

In Figure 21, an example of the four laser beams unaligned is shown while Figure 22 shows the beams aligned.

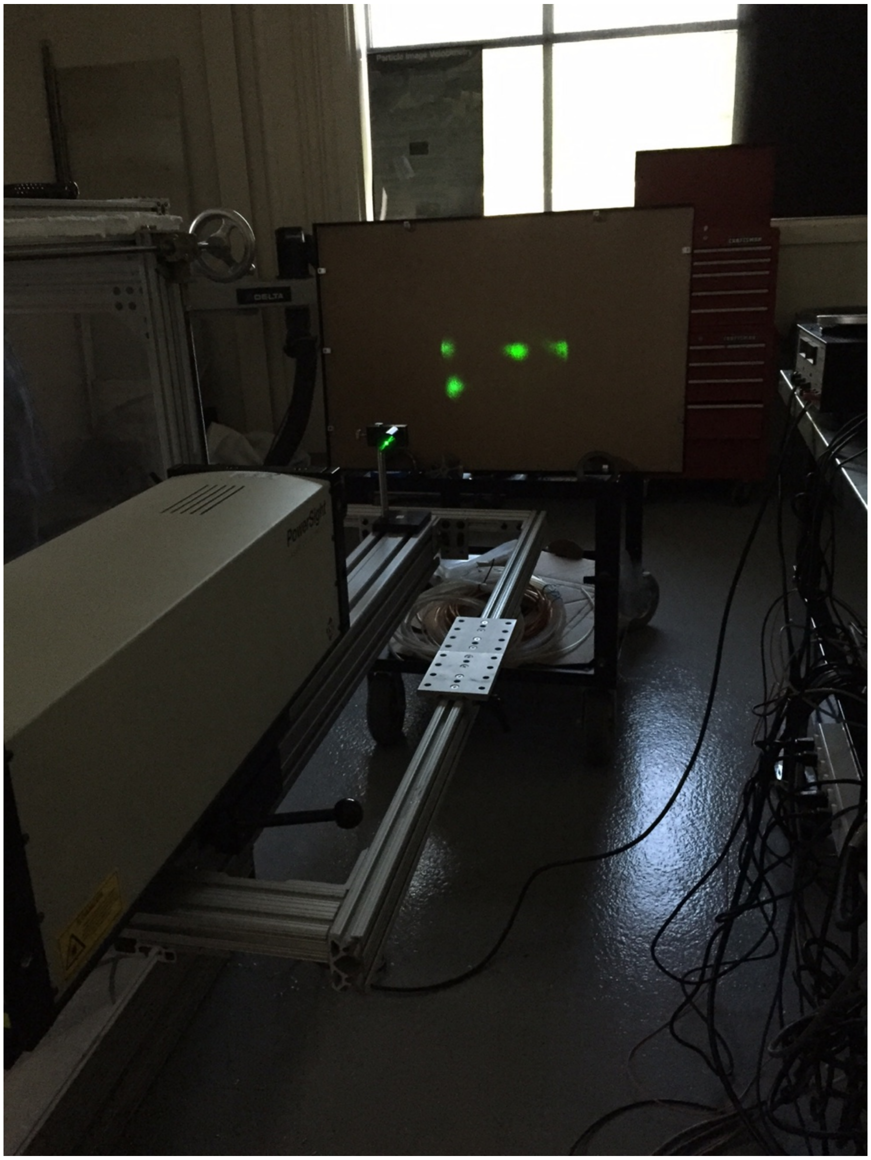

Figure 21 - Example of PDPA Laser Beams Unaligned

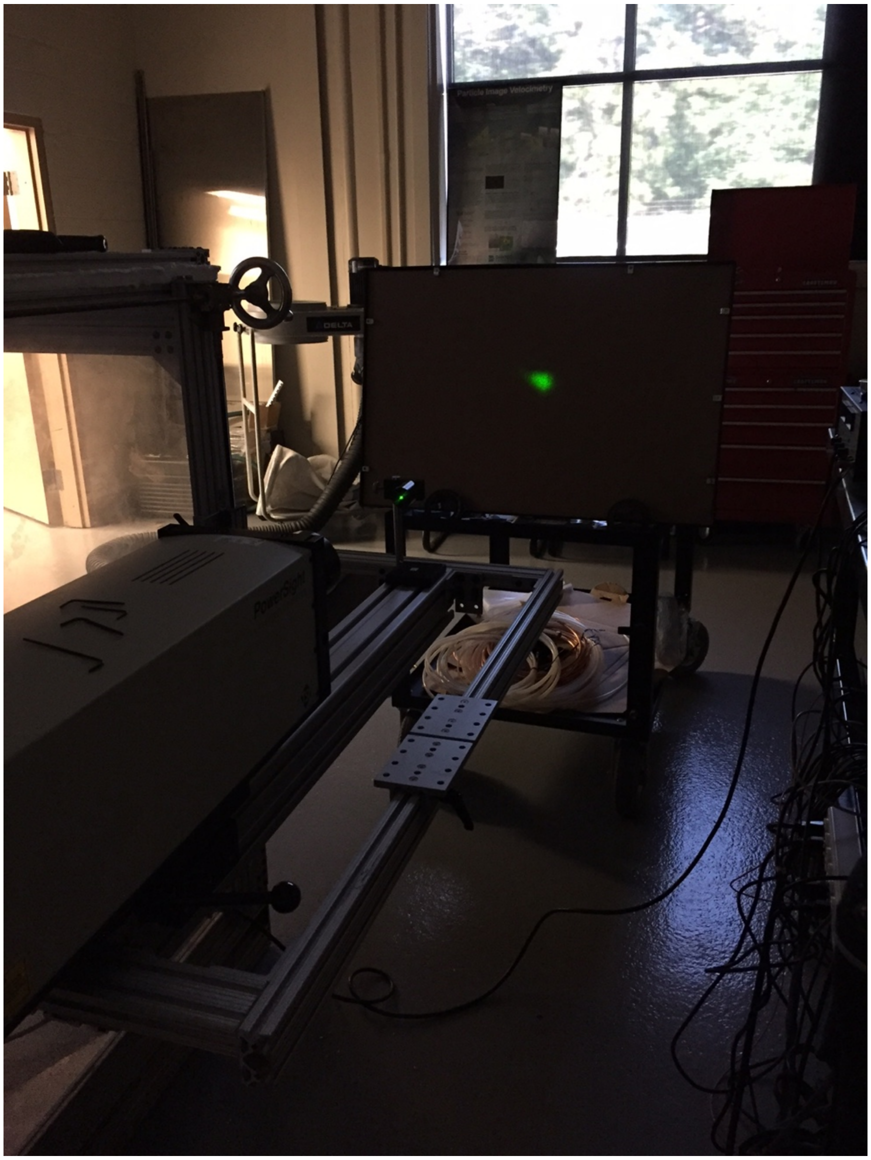

Figure 22 - Example of PDPA Laser Beams Aligned

The correct placement for the beams to be aligned to is at a very faint red calibration laser point that can be seen through the beam magnifier as well. The beam magnifier is moved towards and away from the laser source until the red laser point is seen strongest. The lasers are then moved with steering modules to meet at this point.

Once the beams are aligned, the receiver is then aligned to the intersection point of the lasers. The receiver is mounted at 30-degrees off-axis from the laser and is fine-tuned until the program can view the maximum amount of particles possible. Once the maximum amount of particles is found, the quality of the data read from those particles is fine-tuned through changing settings in the FlowSizer software.

Once the correct band-pass filter is chosen for the test, a phase calibration must also be done. The phase calibration is performed to eliminate the influence of the PMT's and processing electronics on the phase shift measurement [31]. Here, the calibration diode is enabled and the receiver is covered before taking data. From here the phase mean is found in degrees which is the new phase calibration value.

4.2 Experimental Procedure

In this section, the experimental procedures are explained in detail. The procedure of analyzing the effects of detector positioning are explained as well as the characteristics to measure such as the percent obscuration of the smoke "going into alarm" and "leaving alarm".

Since the smoke exited each machine differently, the experimental method slightly changed between the two to achieve the same output. In order to start each test with a pre-determined amount of smoke in the chamber, optical density meters were installed inside the test chamber to measure the density of smoke inside. The Aviator UL was very easy to control densities of smoke entering the box, so this was easily done by turning on the machine and filling the box to the desired percent obscuration. However, with the Rosco, it was more difficult to achieve a desired smoke density in the chamber, since the output is very heavy, fast, and uncontrollable, so the Rosco machine was turned on and the box was filled near the desired percent obscuration, either exact value or higher if not achievable. When the box was filled above the desired amount, the top of the box was opened to slowly let out smoke until the desired percent obscuration was reached. The lid was then closed to prepare for testing.

4.2.1 Detectors Leaving Alarm

Testing began by measuring when the detector “left alarm”. The detector is introduced to a large amount of smoke where it begins to alarm. The smoke entering the detector is decreased until the detector stops alarming. The percent obscuration where the detector stops alarming is the sought value for the detector “leaving alarm”.

To find these values, the exit fan is closed shut and the test chamber was first filled with smoke to a desired percent obscuration. The four different levels of percent obscurations were chosen at an even range from around 15 percent obscuration per foot to up to 50 percent obscuration per foot. This 50 percent obscuration per foot value seems low, but that is because of the calculations done. When looking at percent obscuration for the length of the laser beam and not per foot, it is around 75 percent full with smoke. Because the smoke is white and not completely opaque, even when filling the box as much as possible it won’t read 100% obscuration per foot unless a black sheet is covering the receiver completely.

The box is filled with a lid on top of the exit fan, while the fan is still running, enclosing all the smoke inside. When the smoke first enters the test chamber, it is not completely spread throughout. The closed lid on the fan helps mix the smoke inside the box. Once the smoke is evenly filled in the box, the fan lid is lifted and the recording of percent obscuration began. To know exactly what is happening while looking at raw data, the lid was lifted off of the fan 10 seconds after starting the program, this is why all data charts start at 10 seconds. The program then measured the percent obscuration of smoke right underneath the smoke machine every second and was left running until the detector no longer alarmed.

4.2.3 Detectors Going Into Alarm

Another characteristic to look into is when the detector begins alarming while slowly introduced to increasing amounts of smoke. Because the two smoke machines are built differently and use different smoke fluid, there are two different methods for each smoke machine to find these values.

The Aviator UL is actually designed to output the user's desired thickness of smoke. There is a micrometer on the machine that allows for very exact changes in the machine's output density. The manufacturer provided instructions to turn the micrometer 4 turns outwards from fully closed to output a consistent low amount of smoke. The different settings for this are shown in Table 1. Throughout the testing of the detectors leaving alarm, it was at setting A. Since it is desired to obtain a gradual alarm it is best to use the lowest possible smoke density output. With configuration C testing freely through the chamber and into the detector, the

Whittaker never alarmed. With Configuration B, however, the detector alarmed easily so this setting was used for these tests.

Configuration	Aviator UL Micrometer Turns from Closed
A	4
B	3.5
C	3
D	2.5

Table 1 - Configurations for Aviator UL Micrometer Valve

The Rosco smoke machine was difficult to use for these tests. It had a range of output intensity from one through nine but even at the lowest level, the smoke quantity of it produced was far too great to create a gradual increase to alarm. A filter was created to reduce the smoke amount. A tight knit scotch pad was placed inside the fan, through the inside of the test chamber, to filter the smoke leaving the fan and entering the smoke detectors. This was found to reduce the amount of smoke leaving the fan.

For testing when the detectors “go into alarm”, the previous method for leaving alarm would not work out well. Collecting smoke in the chamber first and releasing it all at once will always give a quick thick burst of smoke which is not what is desired. So for these tests, the lid was never placed on the fan to collect smoke. Data collection begins the instant the smoke machine turns on, pushing the smoke directly through the testing chamber and up through the fan. This keeps the smoke that is leaving the fan thin enough to understand when exactly the detector alarms. Once the detector begins alarming, the smoke machine is then turned off. Data collection continues until the detector is no longer alarming.

Taking data with the Rosco machine was very different. Even with the scotch pad, the smoke was still very dense and difficult to see where exactly the detector goes “into alarm” here. To have the smoke leave the test chamber as thin as possible, the fan was connected to an 8V power source which was very high speeds and a tight knit scotch pad was placed inside the fan on the inside of the testing chamber.

4.2.4 Particle Size Measurement

The particle size of the smoke was also measured while each detector was alarming. This was done because each detector can alarm at different times, so the possibility of the particle size changing at different times is taken into account as well. Tests were done with the Aviator UL, and the Rosco smoke machine with both Normal smoke fluid and Light smoke fluid.

First, a fan speed was chosen for the tests conducted. The Rosco smoke machine was chosen to test with, the fan was first connected to a 2.5V power source and the test chamber was filled to a desired percent obscuration per foot. The smoke was released and the particle size of the smoke was measured. This was repeated for various percent obscurations per foot. The entire testing was repeated for the fan connected to a 5V power source.

The Kidde detector measurements were taken at any level alarm of the Kidde because the alarms were so short compared to the Whittaker.

The PDPA has limitations on what it can and cannot measure. The lowest diameter size that it can measure is 0.4 microns and for the configuration that was used, 0.5 microns. The minimum and maximum particle size bounds depend on the transmitter fringe spacing, the PDPA receiver focal length, the off axis angle of the receiver to the transmitter and the refractive index of the particle that is to be measured.

When testing with the Rosco Light Fluid, to make the smoke as dense as possible to have the detectors alarm, there was no lid placed on the fan's exit. Instead, the smoke was pushed straight through the test chamber and out, collecting to be as dense as possible. For particle size testing, the PDPA recorded data once the smoke machine was on.

As a comparison for false alarms, an electric kettle was used to find the particle size of water steam. The electric kettle was set underneath the testing chamber and the steam it produced was led through the box and up through the fan and into the detectors. The fan was kept off as to not cool the steam back into water droplets.

Chapter 5: Results

5.1 Introduction

In this chapter, the percent obscurations for when the detectors go into alarm are given as well as the percent obscuration when the leave alarm. The particle size of the smoke from the Aviator UL, Rosco Clear Smoke, and Rosco Light smoke are provided as well.

5.2 Effects of Detector Positioning

The effect of detector positioning (Configurations 1-3) was evaluated with the Aviator UL and Kidde detector by varying the height of detector relative to measurement point. They were tested for the detectors leaving alarm and shown in Tables 2, 3, and 4.

Aviator UL – Kidde – 2.5V Fan			
Configuration 1			
	Fan Exit Meter		**Chamber Meter**
RUN	**Min % Obsc**	**Max % Obsc**	**%Obsc before test**
1	1.7	8.6	24.1
2	2.2	10.2	35.6
3	3.0	14.2	51.4
4	2.8	32.2	69.9
5	1.8	7.4	17.0
Average	2.3		

Table 2 – Percent Obscuration Testing for Configuration 1

Aviator UL – Kidde – 2.5V Fan			
Configuration 2			
	Fan Exit Meter		**Chamber Meter**
RUN	**Min % Obsc**	**Max % Obsc**	**%Obsc before test**
3	3.7	26.6	56.6
4	3.9	38.4	63.9
5	2.4	13.4	28.4
6	2.5	3.6	8.8
Average	3.1		

Table 3 – Percent Obscuration Testing for Configuration 2

Aviator UL - Kidde - Fan 2.5V			
Configuration 3			
	Fan Exit Meter		**Chamber Meter**
RUN	**Min % Obsc**	**Max % Obsc**	**%Obsc before test**
Feb6 005	6.2	41.7	45.3
Feb6 006	5.8	30.9	33.9
Feb6 007	3.8	50.1	55.4
Feb6 008	5.0	16.7	15.6
Average	5.2		

Table 4 – Percent Obscuration Testing for Configuration 3

5.3 Smoke Detector Testing

5.3.1 The Detectors Leaving Alarm

Different tests were conducted. Both smoke detectors were tested with the Rosco smoke machine 4 times and with the Aviator UL smoke machine 4 times to get an average percent obscuration per foot leaving alarm. Each test was performed at two different fan input voltages, 2.5V and 5V.

5.3.1.a Whittaker Smoke Detector Results

Tables 5 and 6 display the values recorded while testing the Whittaker Smoke Detector with the Aviator and Rosco, respectively, with a 2.5V fan input voltage. Figure 23 displays the percent obscuration recorded leaving the fan at 5V with the Rosco smoke machine and Whittaker detector. The value to be observed is circled in purple in Figure 23. At this value the detector still recorded in alarm.

This test was repeated 4 times, at different starting percent obscurations to see if the value leaving alarm changed from the amount of smoke it is first introduced to. The Whittaker Smoke Detector was tested once with the Aviator UL smoke machine and once with the Rosco smoke machine.

Aviator UL - Whittaker - 2.5V Fan			
Configuration 3			
	Fan Exit Meter		Chamber Meter
RUN	**Min % Obsc/Foot**	**Max % Obsc/Foot**	**%Obsc/Foot before test**
Feb7 001	4.4	37.5	40.0
Feb7 002	2.8	46.8	50.8
Feb7 003	2.0	23.4	27.2
Feb7 004	2.5	19.2	21.3
Average	2.9		

Table 5 – Percent Obscuration Testing for "Leaving Alarm" with Aviator UL Smoke Machine and Whittaker Detector at a 2.5V Fan Speed

Rosco - Whittaker - 2.5V			
Configuration 3			
	Fan Exit Meter		Chamber Meter
RUN	**Min % Obsc/Foot**	**Max % Obsc/Foot**	**%Obsc/Foot before test**
Feb8 007	4.3	17.2	32.3
Feb8 008	3.4	13.6	28.3
Feb8 009	5.0	28.2	50.9
Feb8 010	5.8	29.1	63.2
Average	4.6		

Table 6 – Percent Obscuration Testing for “Leaving Alarm” with Rosco Smoke Machine and Whittaker Detector at a 2.5V Fan Speed

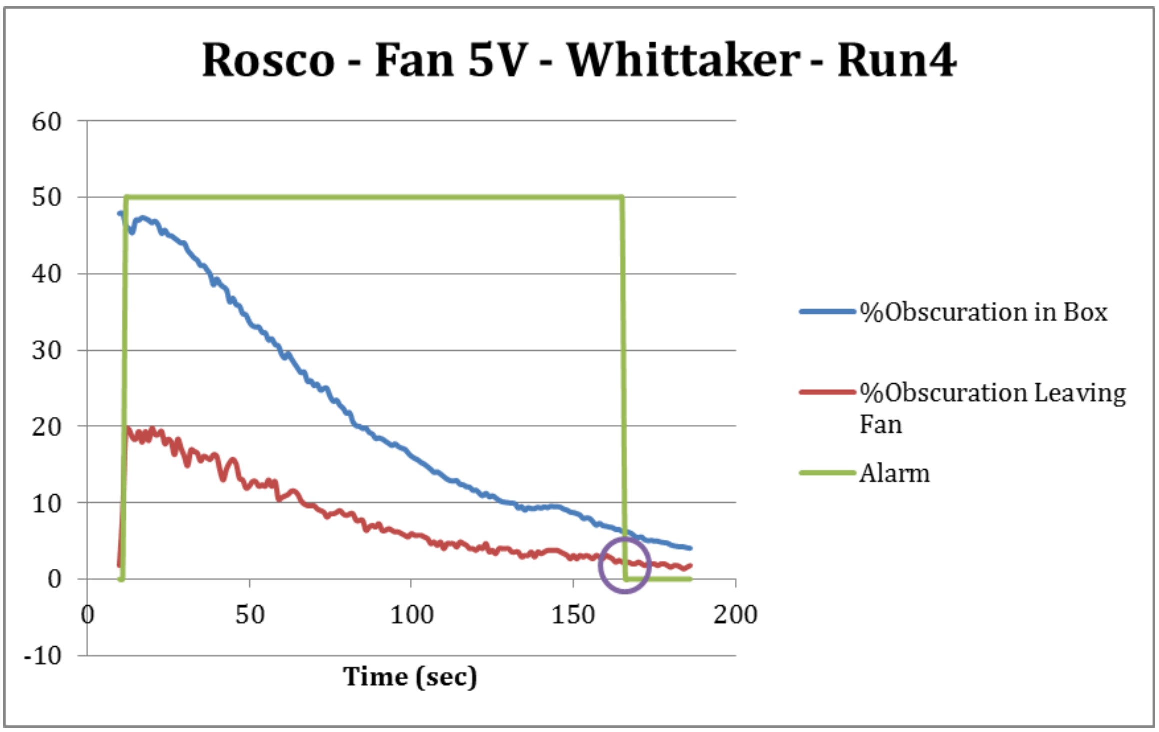

Figure 23 – Whittaker Detector Testing with Rosco Smoke Machine for Detector “Leaving Alarm”

In Tables 5 and 6, the column entitled "Chamber Optical Density Meter" displays the measured values of percent obscuration per foot inside the testing chamber before releasing the smoke into the detectors. The values displayed in the column entitled "Fan Exit Optical Density Meter" are the maximum and minimum percent obscuration per foot the optical density meters saw while the detector is alarming. The minimum percent obscuration per foot is the lowest value in which the detector is leaving alarm. These values do vary, but an average is found to understand where this happens in general. The Rosco smoke, as shown in Tables 5 and 6, has a higher average minimum percent obscuration per foot when alarming the Whittaker detector than the Aviator UL has.

Tables 7 and 8 display the percent obscuration values measured for the Aviator UL and Rosco, respectively, for the Whittaker detector at 5V fan input voltage.

Aviator UL - Whittaker - 5V			
Configuration 3			
	Fan Exit Meter		**Chamber Meter**
RUN	**Min % Obsc/Foot**	**Max % Obsc/Foot**	**%Obsc/Foot before test**
Feb7 005	1.5	18.0	19.0
Feb7 006	3.4	26.4	28.1
Feb7 007	1.7	32.9	35.7
Feb7 008	1.5	44.6	50.4
Average	2.0		

Table 7 – Percent Obscuration Testing for "Leaving Alarm" with Aviator UL Smoke Machine and Whittaker Detector at a 5V Fan Speed

Rosco – Whittaker – 5V			
Configuration 3			
	Fan Exit Meter		**Chamber Meter**
RUN	**Min % Obsc/Foot**	**Max % Obsc/Foot**	**%Obsc/Foot before test**
Feb8 003	1.4	12.0	25.5
Feb8 004	2.4	19.7	47.9
Feb8 005	2.5	7.5	19.6
Feb8 006	4.5	29.2	59.3
Average	2.7		

Table 8 – Percent Obscuration Testing for "Leaving Alarm" with Rosco Smoke Machine and Whittaker Detector at a 5V Fan Speed

5.3.1.b Kidde Smoke Detector Testing

The Rosco smoke machine had difficulty alarming the Kidde detector, regardless of the amount of smoke in the test chamber. It was only able to alarm when there was no lid on the fan and a lot of smoke was output continuously and directly into the box and immediately out without stopping. It was only able to alarm three times in total with both fan speeds. This is shown in Tables 9 and 11, Tables 10 and 12 show values for testing with the Aviator UL. There were many runs attempted with the Rosco smoke machine and Kidde detector but only one run was deemed acceptable and is shown in Table 10.

Rosco – Kidde – High Alarm - Fan 2.5V		
Configuration 3		
	Fan Exit Meter	
RUN	**Min % Obsc/Foot**	**Max % Obsc/Foot**
Feb16 003	48.5	56.5

Table 9 – Percent Obscuration Testing for "Leaving Alarm" with Rosco Smoke Machine and Kidde Detector at a 2.5V Fan Speed

Aviator UL - Kidde - High Alarm - Fan 2.5V			
Configuration 3			
	Fan Exit Meter		Chamber Meter
RUN	**Min % Obsc/Foot**	**Max % Obsc/Foot**	**%Obsc/Foot before test**
Feb6 005	6.2	41.7	45.3
Feb6 006	5.8	30.9	33.9
Feb6 007	3.8	50.1	55.4
Feb6 008	5.0	16.7	15.6
Average	5.2		

Table 10 – Percent Obscuration Testing for "Leaving Alarm" with Aviator UL Smoke Machine and Kidde Detector at a 2.5V Fan Speed

Rosco - Kidde - Fan 5V		
Configuration 3		
	Fan Exit Meter	
RUN	**Min % Obsc/Foot**	**Max % Obsc/Foot**
Feb16 001	56.4	85.8
Feb16 002	48.3	69.0
Average	52.4	77.4

Table 11 – Percent Obscuration Testing for "Leaving Alarm" with Rosco Smoke Machine and Kidde Detector at a 5V Fan Speed

Aviator UL - Kidde - High Alarm - Fan 5V			
Configuration 3			
	Fan Exit Meter		Chamber Meter
RUN	**Min % Obsc/Foot**	**Max % Obsc/Foot**	**%Obsc/Foot before test**
Feb7 009	2.2	15.7	24.3
Feb7 010	3.1	30.8	41.7
Feb7 011	3.1	37.0	49.8
Feb7 012	4.7	45.7	60.7
Average	3.3		

Table 12 – Percent Obscuration Testing for “Leaving Alarm” with Aviator UL Smoke Machine and Kidde Detector at a 5V Fan Speed

5.3.2 Detectors Going Into Alarm

5.3.2.a Whittaker Detector Testing

When testing with the Aviator UL, the machine is turned on and uniform amount of smoke is produced which can be seen in Figure 24. The data for all the runs testing the Whittaker detector with the Aviator UL smoke machine are shown in Table 13 for 2.5V fan speed and Table 14 for 5V fan speed.

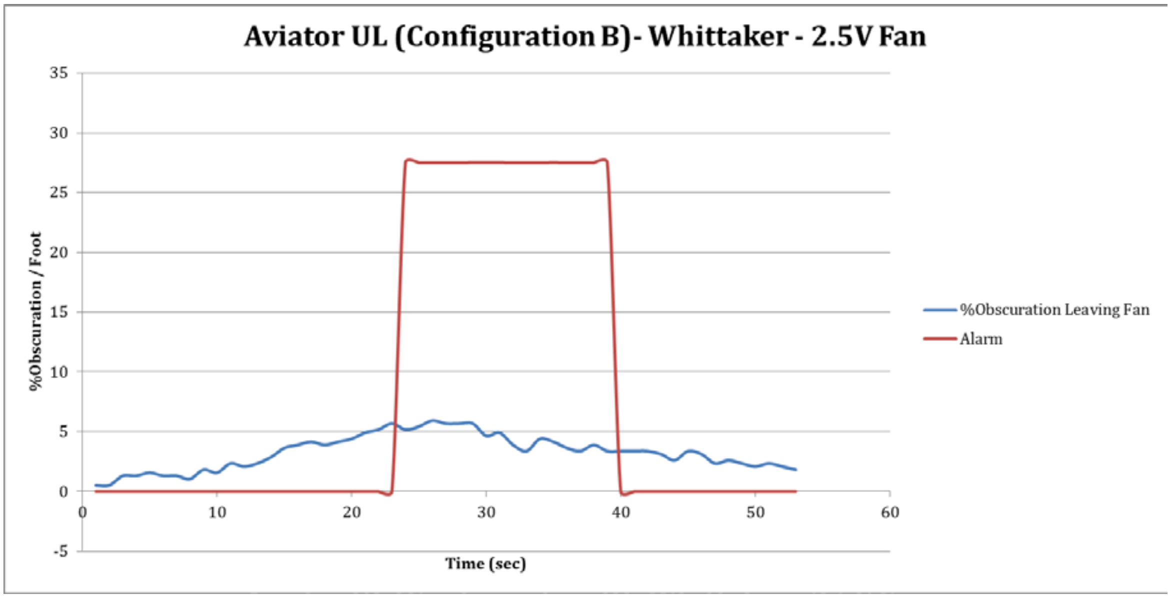

Figure 24 – Whittaker Detector Testing for Going "Into Alarm" with the Aviator UL Smoke Machine and a 2.5V Fan Speed

AviatorUL - Whittaker - 2.5V	
No Filter – Configuration B	
	Fan Exit Meter
RUN	**%Obsc/Foot Going Into Alarm**
March29 003	5.7
March29 004	5.5
March29 005	6.6
Average	5.9

Table 13 – Percent Obscuration Testing for Going "Into Alarm" with the Aviator UL Smoke Machine and Whittaker detector at a 2.5V Fan Speed

AviatorUL - Whittaker - 5V	
No Filter – Configuration B	
	Fan Exit Meter
RUN	**%Obsc/Foot Going Into Alarm**
March29 007	4.5
March29 008	4.5
March29 009	5.3
Average	4.8

Table 14 – Percent Obscuration Testing for Going “Into Alarm” with the Aviator UL Smoke Machine and Whittaker detector at a 5V Fan Speed

This test was repeated 6 times as shown in Table 15. The percent obscuration for when the detector went “into alarm” is shown as well as the slope of the graph right before it leads into alarm.

Figures 25 and 26 show example runs of the Rosco smoke machine alarming the Whittaker detector into alarm. Figure 27 compares the peaks of these two graphs.

Rosco with Scotch Pad		
Whittaker Smoke Detector		
	Fan Exit Meter	
RUN	**Going Into Alarm**	**Slope**
April5 001	8.4	4.45
April5 003	8.6	3.34
April5 004	5.4	5.35
April5 005	6.3	4.88
April5 007	8.4	9.46
April5 008	6.5	3.54

Table 15 – Percent Obscuration for Whittaker Detector Going “into Alarm” with 8V Fan

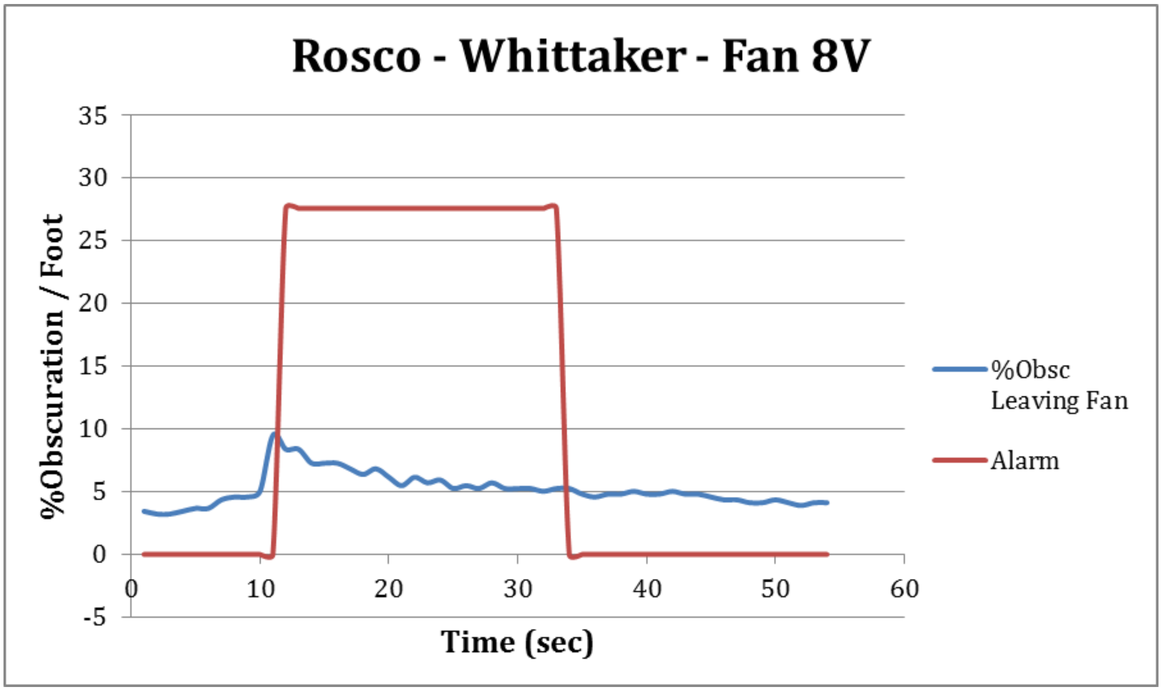

Figure 25 –Data for Whittaker Detector Going "Into Alarm" with Rosco Smoke Machine with 8V Fan

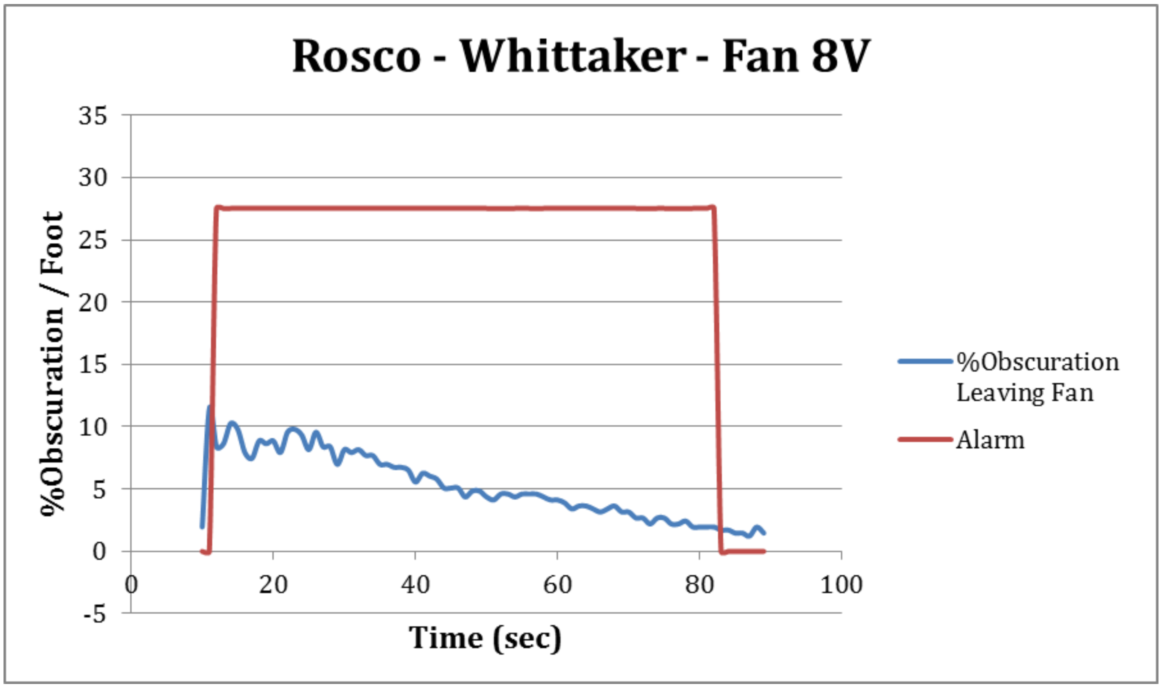

Figure 26 –Data for Whittaker Detector Going "Into Alarm" with Rosco Smoke Machine with 8V Fan

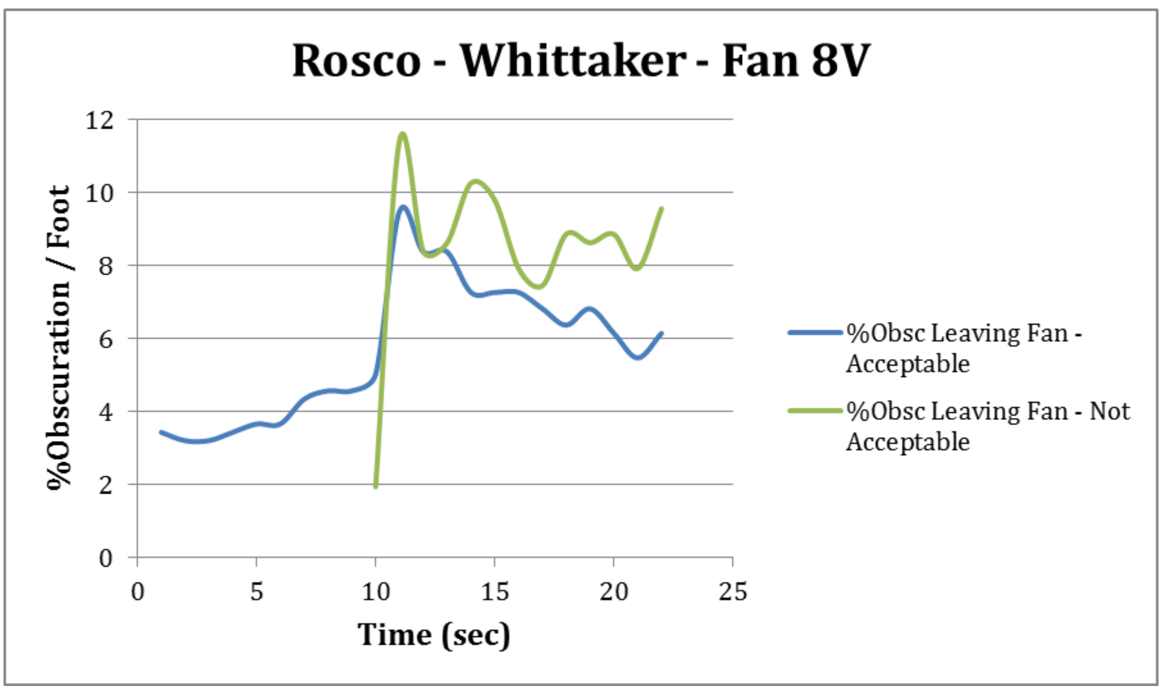

Figure 27 – Comparing Runs 'April5 001' and 'April5 007' introduction of peaks for two different runs with Rosco Smoke Machine and Whittaker detector

5.3.2.b Kidde Smoke Detector Testing

The same exact tests were done with the Kidde smoke detector, and the high alarm was observed while doing them. As shown in Figure 28, there is again a gradual increase in smoke when testing with the Aviator UL. This graph is an example of valid data. The 5V fan run is equally as acceptable, shown in Figure 29. The values found in these tests are shown in Tables 16 and 17.

An example of testing the Kidde detector with the Rosco smoke machine is shown in Figure 30.

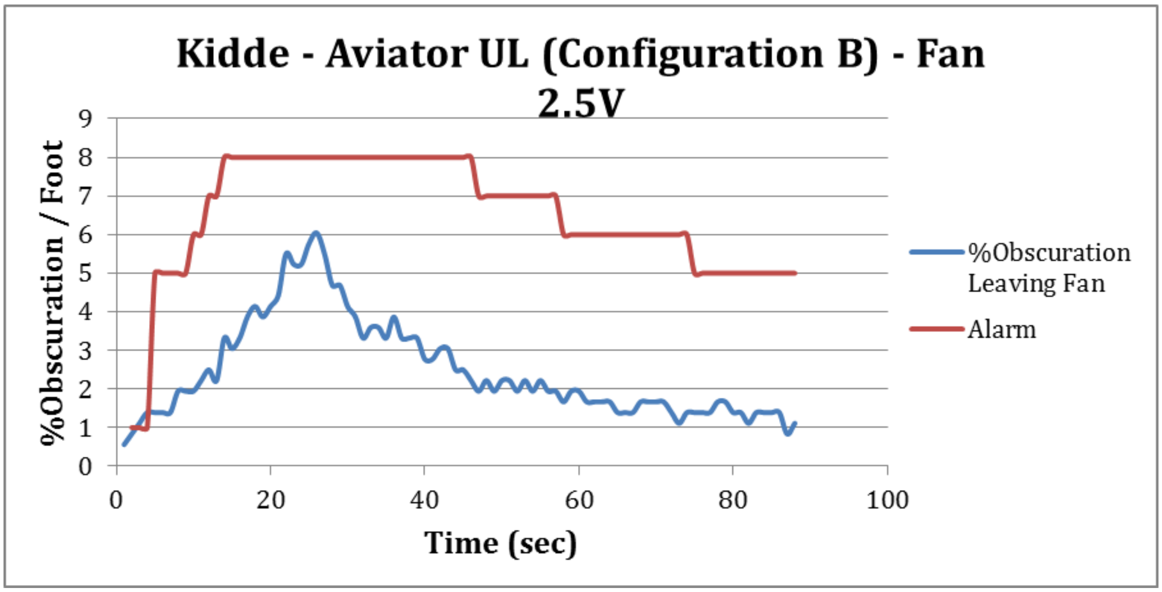

Figure 28 – Percent Obscuration Testing of Kidde Detector with Aviator UL Smoke machine with 2.5V Fan

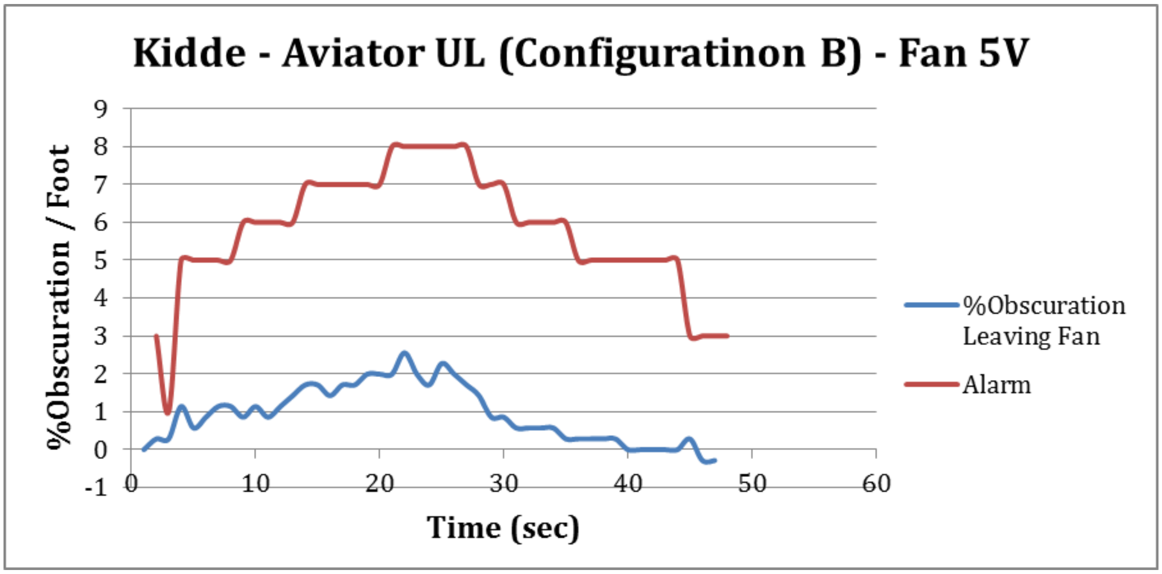

Figure 29 – Percent Obscuration Testing of Kidde Detector with Aviator UL Smoke Machine with 5V Fan

Aviator UL - Kidde - 2.5V	
No Filter – Configuration B	
	Fan Exit Meter
RUN	**%Obscuration/Foot Going Into Alarm**
March30 006	3.3
March30 007	3.1
March30 009	3.4
Average	3.3

Table 16 – Percent Obscuration Testing for Going into Alarm with the Aviator UL Smoke Machine and Kidde detector at a 2.5V Fan Speed

Aviator UL - Kidde - 5V	
No Filter – Configuration B	
	Fan Exit Meter
RUN	**%Obscuration/Foot Going Into Alarm**
March30 010	2.0
March30 011	2.6
March30 012	2.6
Average	2.4

Table 17 – Percent Obscuration Testing for Going into Alarm with the Aviator UL Smoke Machine and Kidde detector at a 5V Fan Speed

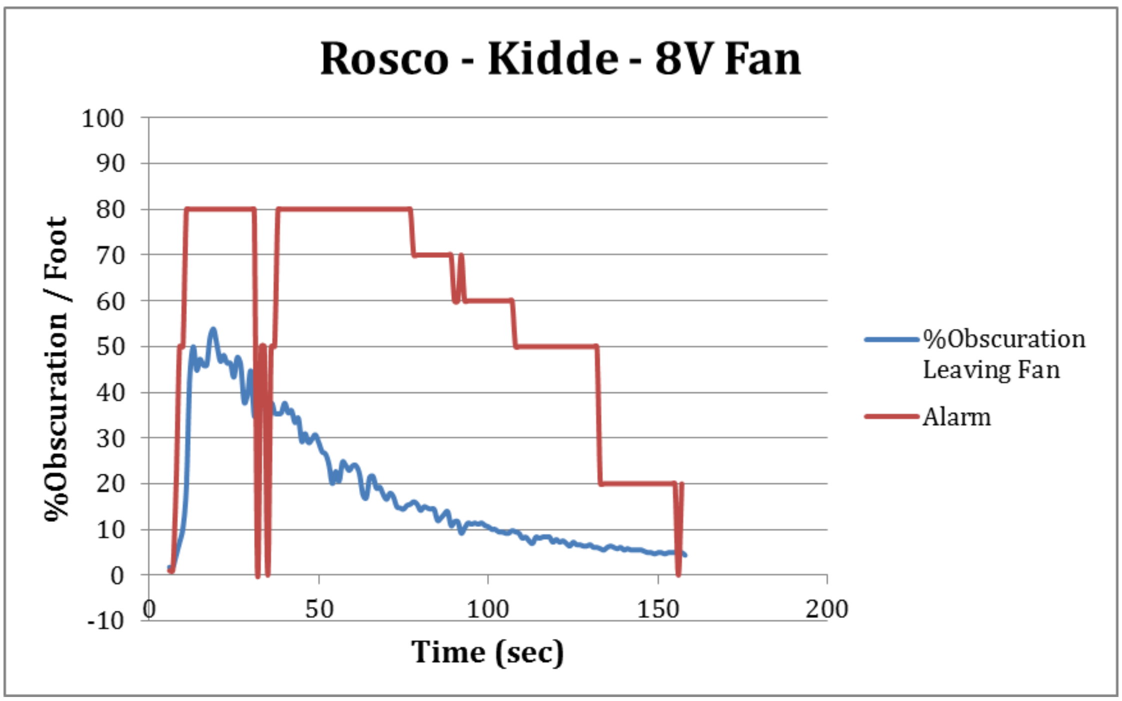

Figure 30 – Percent Obscuration Test Attempt for Going “into Alarm” with the Rosco Smoke Machine and Kidde detector at an 8V Fan Speed

5.3.3 Particle Size

5.3.3.a Choosing Fan Speed

All tests were taken with the fan speed set to 2.5V. This is chosen carefully with testing. The data from these tests are shown in Tables 18 and 19.

Rosco - Fan 2.5V							
RUN	**%Obscuration Before Test**	**D10**	**D20**	**D30**	**D32**	**# Particles Averaged**	**Time (sec)**
5	57.8	2.3	2.6	2.8	3.4	28880.0	306.4
6	45.0	2.4	2.7	2.9	3.4	12143.0	211.9
7	32.7	2.3	2.6	2.8	3.3	3581.0	112.7
8	21.7	2.2	2.5	2.7	3.2	1145.0	62.5
Average		2.3	2.6	2.8	3.3		
Standard Deviation		0.1	0.1	0.1	0.1		
%Standard Deviation		3.0%	2.8%	3.0%	3.4%		

Table 18 – Particle Size Data Taken for Rosco Smoke Machine with a 2.5V Fan

Rosco - Fan 5V							
RUN	**%Obscuration Before Test**	**D10**	**D20**	**D30**	**D32**	**# Particles Averaged**	**Time (sec)**
1	32.0	2.1	2.4	2.6	3.1	3943.0	86.5
2	15.7	2.0	2.3	2.5	3.0	1513.0	56.6
3	45.6	2.4	2.7	2.9	3.5	5609.0	24.4
4	61.7	2.3	2.6	2.9	3.5	19973.0	145.6
Average		2.2	2.5	2.7	3.3		
Standard Deviation		0.2	0.2	0.2	0.2		
%Standard Deviation		8.2%	7.8%	7.5%	6.8%		

Table 19 – Particle Size Data Taken for Rosco Smoke Machine with a 5V Fan

When observing the percent standard deviation of the average values for diameters, the Rosco with the 2.5V fan showed much more repeatable data than that with the 5V fan. When continuing taking data, the fan with the 2.5V data is more trusted even though the values only differed by 0.1 microns or less.

This also worked very well with the Aviator UL as shown in Table 20.

Aviator UL - 2.5V						
RUN	**D10**	**D20**	**D30**	**D32**	**# Particles Averaged**	**Time (sec)**
March20 012	1.50	1.73	1.98	2.57	203.00	46.34
March20 013	1.50	1.69	1.89	2.35	241.00	32.15
Average	1.50	1.71	1.93	2.46		
Standard Deviation	0.00	0.03	0.06	0.15		
%Standard Deviation	0.02%	1.69%	3.23%	6.30%		

Table 20 – Particle Size Data Taken for Aviator UL Smoke Machine with a 2.5V Fan

Because the maximum particle size limitations set by the program and our setup is 144 microns, the accuracy of D10 in this section is less than 1.45 microns.

5.3.3.b Smoke Detector Testing

The particle size of the Rosco was found while alarming the Whittaker detector and the Kidde detector as shown in Tables 21 and 22, respectively. The particle size of the Aviator UL while alarming the Whittaker and Kidde detectors are shown in Tables 23 and 24, respectively.

The maximum diameter size limitation here is 139.49 microns so the accuracy of D10 is less than 1.42 microns.

Rosco - 2.5V - Whittaker						
RUN	**D10**	**D20**	**D30**	**D32**	**# Particles Averaged**	**Time (sec)**
March20 005	3.5	4.0	4.4	5.5	2079.0	60.2
March20 006	3.5	4.0	4.6	6.2	502.0	29.7
March20 007	3.5	3.8	4.2	5.1	2147.0	56.3
March21 001	3.3	3.8	4.2	5.4	9457.0	97.0
Average	3.5	3.9	4.4	5.5		

Table 21 – Particle Size Data Taken for Rosco Smoke Machine with a 2.5V Fan Alarming Whittaker Detector

Rosco - 2.5V - Kidde						
RUN	**D10**	**D20**	**D30**	**D32**	**# Particles Averaged**	**Time (sec)**
March21 002	3.9	4.5	5.0	6.3	380.0	7.8
March20 009	3.3	3.9	4.5	6.0	1584.0	4.7
March20 010	3.4	3.9	4.5	5.8	3014.0	5.6
March21 003	3.8	4.4	4.9	6.2	699.0	13.0
Average	3.6	4.2	4.7	6.1		

Table 22 – Particle Size Data Taken for Rosco Smoke Machine with a 2.5V Fan Alarming Kidde Detector

Aviator UL – 2.5V - Whittaker						
RUN	**D10**	**D20**	**D30**	**D32**	**# Particles Averaged**	**Time (sec)**
March20 014	1.7	1.9	2.1	2.6	123.0	30.7
March20 015	1.6	1.9	2.1	2.7	189.0	39.7
Average	1.7	1.9	2.1	2.6		

Table 23 – Particle Size Data Taken for Aviator UL Smoke Machine with a 2.5V Fan Alarming Whittaker Detector

Aviator UL - 2.5V - Kidde						
RUN	**D10**	**D20**	**D30**	**D32**	**# Particles Averaged**	**Time (sec)**
March20 012	1.5	1.7	2.0	2.6	203.0	46.3
March20 013	1.5	1.7	1.9	2.3	241.0	32.2
Average	1.5	1.7	1.9	2.5		

Table 24 – Particle Size Data Taken for Aviator UL Smoke Machine with a 2.5V Fan Alarming Kidde Detector

In Figure 31, the distribution of the particles collected for the Rosco run is shown. The x-axis is the diameter size where the y-axis is the diameter count. There is an even bell curve in this chart shown by the PDPA's program called FlowSizer. In this run there were 2147 particles recorded and analyzed for the chart.

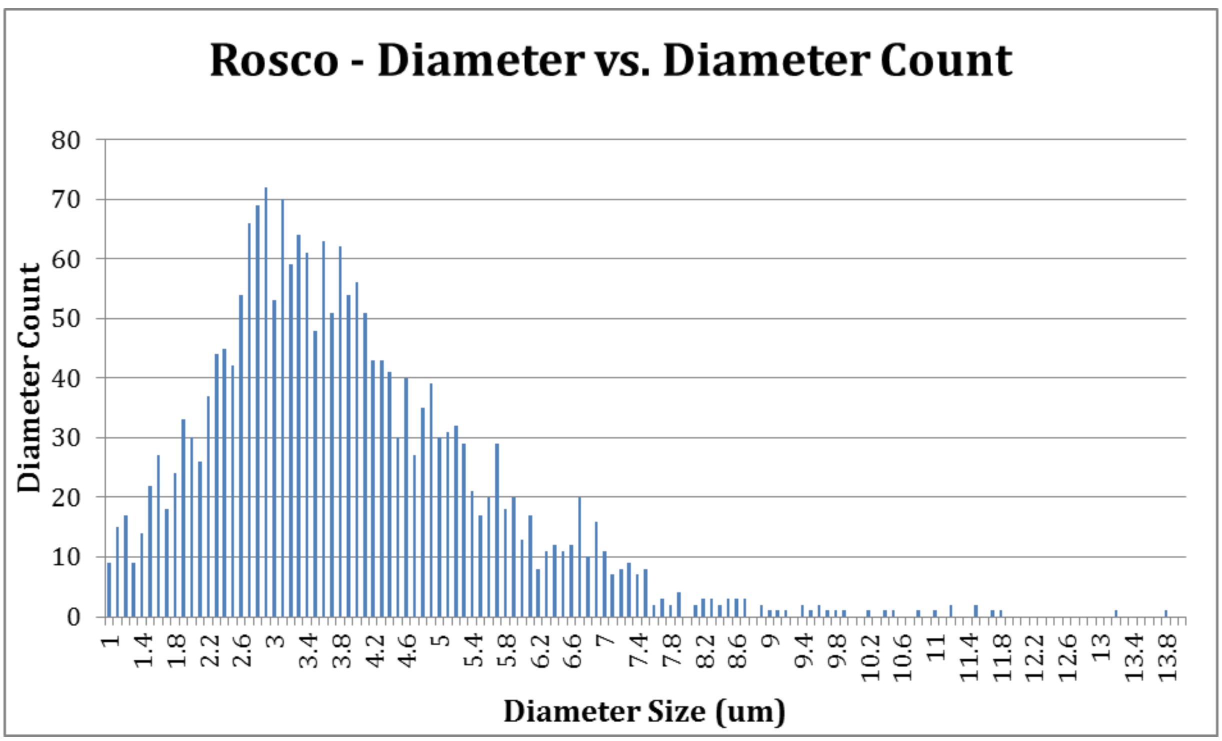

Figure 31 – Diameter versus Diameter Count for Rosco Smoke Machine

Figure 32 is the particle size distribution graph for the Aviator UL run. There are 203 particles averaged for this chart here, much less than before. Also, there is no clear bell curve as there was with the Rosco. The x-axis (diameter size) is extended to 14 microns to match that of the Rosco, making them more easily comparable.

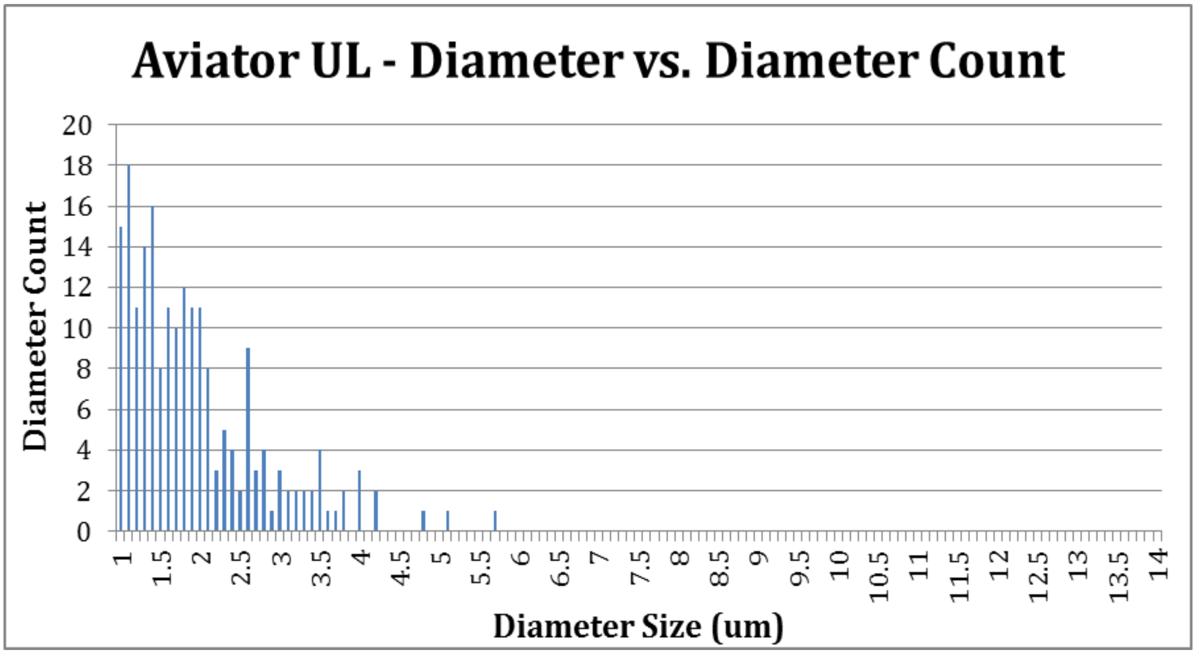

Figure 32 – Diameter versus Diameter Count for Aviator UL Smoke Machine

5.3.3.c Rosco Light Smoke Particle Size

The Rosco Light smoke fluid was unable to alarm the smoke detectors. The light smoke wasn't capable of reaching the high densities the other two fluids were able to do. The particle size of this smoke was recorded and shown in Table 25.

The accuracy of D10 in this set of data is less than 1.43 microns.

PDPA Rosco Light Data						
RUN	**D10**	**D20**	**D30**	**D32**	**# Particles Averaged**	**Time (sec)**
March21 004	3.6	4.0	4.4	5.5	5886.0	33.4
March21 005	3.6	4.0	4.4	5.3	6055.0	34.2
March21 006	4.0	4.4	4.9	6.0	4197.0	31.5
March21 007	4.0	4.4	4.7	5.6	10261.0	104.5
March21 008	4.5	5.0	5.5	5.5	6304.0	55.0
Average	4.0	4.4	4.8	5.6		

Table 25 – Particle Size Data Taken for Rosco Light Smoke Fluid

5.3.4 Water Steam

The particle size of water steam was measured as well. As seen in the graphs, the Whittaker detector is alarming on and off but the Kidde was barely able to reach an actual alarm. The highest alarm it reached was a Pre-Alarm for a second, seen as the tallest peak in Figure 34. The very high peaks of percent obscuration in this graph are the optical density meter's receiver fogging from the steam and being wiped off. So it was 100% covered by a cloth to clean it and continued with testing. The water steam alarmed both detectors on and off as shown in Figure 33 and Figure 34. There was no steady alarm.

The particle size was also recorded for the steam particles as large average D10 of 20 microns. As seen in Figure 33 the Whittaker detector using the current technology is alarming constantly with water droplets and the Kidde detector as seen in Figure 34 does not ever alarm. The highest peak for the Kidde detector tested with water droplets is at a Pre Alarm for one second during the test. This was an improvement for false alarm detection.

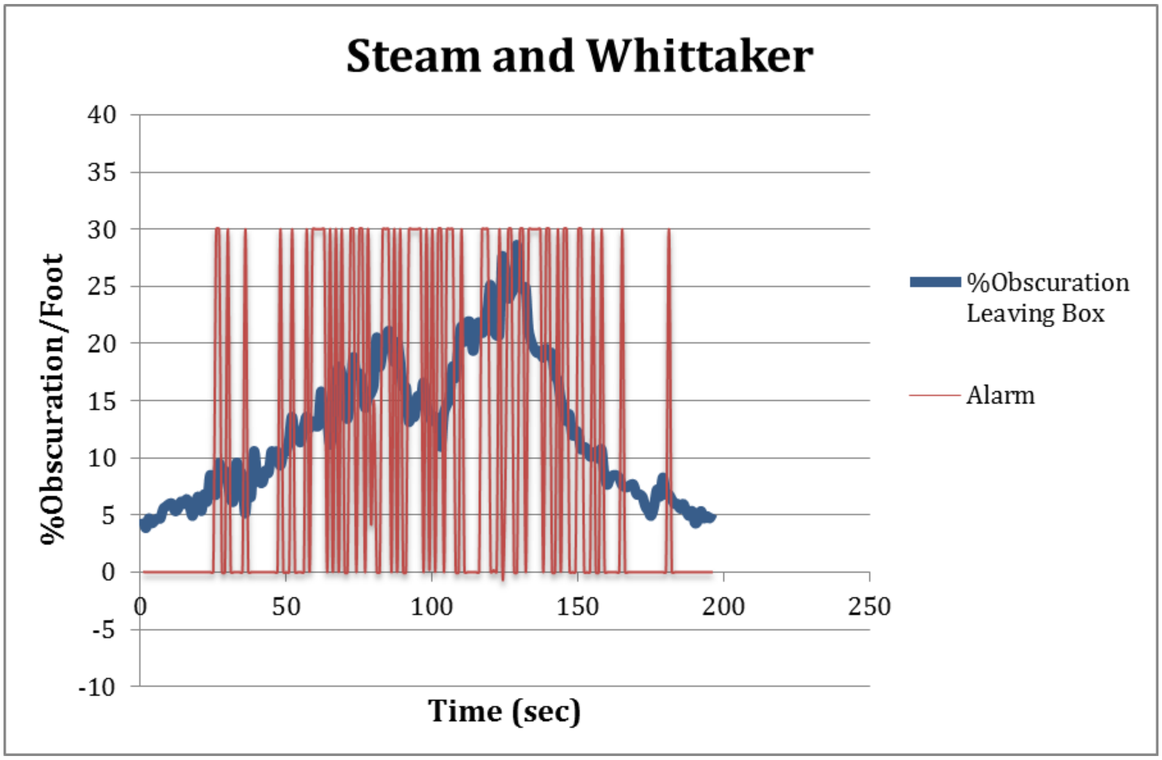

Figure 33 – Water Steam Alarming Whittaker Detector at Different Percent Obscurations

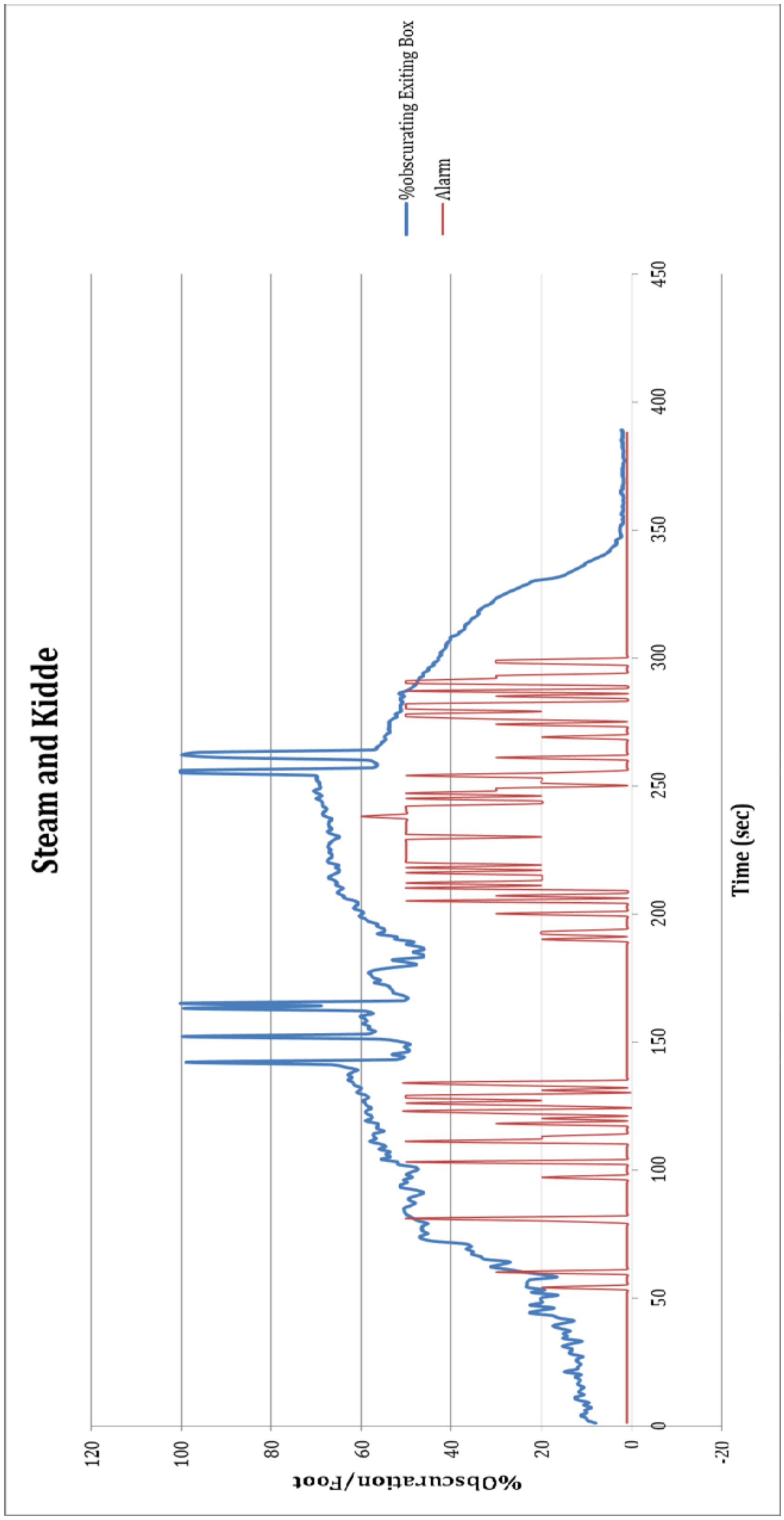

Figure 34 – Water Steam Alarming Kidde Detector at Different Percent Obscurations

Chapter 6: Analysis

6.1 Introduction

Now that the data is taken and shown in the tables in Chapter 5, it is analyzed and compared side by side in this chapter. The averages for the smoke detectors going “into alarm” and “out of alarm” are compared to understand the core differences between the two detectors. The particle sizes of all smoke droplets are compared next to each other as well to understand the effects of particle size in alarming the detectors.

6.2 Effects of Detector Positioning

Comparing Configuration 1 and 2 in Tables 2 and 3 in section 5.2, it can be seen that the average percent obscuration per foot increased when the detector was moved downwards, as the smoke is thicker when initially exiting the fan than a few inches above it when it spreads out in a cone shape. The smoke detectors are much closer to the optical density meters at this location so the readings are more accurate to the amount of smoke the detector is exposed to when alarming.

Now these values are compared to Configuration 3 as shown in Table 4. The optical density laser is now 6 inches away from its receiver and the average minimum percent obscuration when “leaving alarm” is higher than it was before. This is considered to be a more accurate reading because it is surrounding the detector more closely while testing. It is a more accurate measurement of the density of smoke the detector is exposed to compared to measuring all the smoke exiting the fan in general. The percentage doubled compared to Configuration 1. The difference between the three values recorded varies greatly, indicating that the distance between the optical density meter and the receiver and its proximity to the smoke detectors affects the optical density measurement.

6.3 Smoke Detectors Leaving Alarm

The percent obscuration per foot of when the detectors "left alarm" was found. In section 5.3.1a, the Aviator UL smoke machine alarming the Whittaker smoke detector was recorded with the exit fan connected to 2.5V, its lowest alarm was averaged in Table 5 and shown to be 2.9 percent obscuration per foot where with the Rosco it was 4.6 percent obscuration per foot shown in Table 6. With the exit fan connected to 5V still using the Whittaker smoke detector, the Aviator UL "left alarm" at an average of 2 percent obscuration per foot shown in Table 7 where the Rosco "left alarm" at an average of 2.7 percent obscuration per foot shown in Table 8.

The faster fan speeds recorded a lower percent obscuration per foot than the slower fan speeds. This could have to do with the faster fan speeds pushing the smoke so quickly out of the way that there is less smoke at the optical density lasers than there are at the detector. With the slower fan speeds, the smoke could be collecting near the detector and not being pushed away, leaving more smoke to linger around the optical density lasers, keeping the detectors alarming for a longer period of time.

The Aviator UL percent obscuration per foot only decreased slightly compared to the Rosco between the two fan speeds. This could have to do with the different types of smoke being composed of different chemicals leading them to act differently.

The Aviator UL "left alarm" at a lower percent obscuration per foot with the Whittaker detector than the Rosco did.

In section 5.3.1.b, it can be seen that the fan connected to 2.5V, the Aviator UL smoke leaving the Kidde alarm had a minimum average of 5.2 percent obscuration per foot shown in Table 10. The Rosco smoke machine had a very hard time alarming the Kidde detector. When it did alarm once, the Kidde detector measured a minimum of 48.5 percent obscuration per foot which is extremely dense smoke, as seen in Table 9. This is a very large difference in alarms. One observation is that the same Aviator UL smoke had to be denser to alarm the Kidde smoke detector than it did the Whittaker.

With the 5V fan, the Aviator UL saw an average minimum "leaving alarm" to be 3.3 percent obscuration per foot, seen in Table 12, where the Rosco saw an average "leaving alarm" to be 52.4 percent obscuration per foot for the Kidde detector, seen in Table 11. The Aviator UL percent obscuration decreased with the faster fan speed just as the previous testing did as well. The Rosco percent obscuration actually increased with the faster fan speeds. This could have to do with the fact that the Rosco just had to be extremely dense in general and these runs captured the thicker end of testing.

The results are compared in Table 26.

%Obscuration Per Foot Going Out Of Alarm				
	Aviator UL		**Rosco**	
	2.5V	*5V*	*2.5V*	*5V*
Kidde	5.2	3.3	48.5	52.4
Whittaker	2.9	2	4.6	2.7

Table 26 – Percent Obscuration per Foot Data Compared for "Going Out of Alarm"

When observing just the Aviator UL runs, it can be seen the Kidde detector stopped alarming sooner than the Whittaker. Also, both detectors alarmed at much lower smoke densities with the Aviator UL than with the Rosco. The results with the Aviator UL obtained with the Kidde are similar to those obtained with the Whittaker, but there seems to be no trend with the Rosco. The general idea taking from these findings is that the Rosco needed to be extremely dense to be able to alarm the Kidde detector but not the Whittaker.

6.4 Smoke Detectors Going Into Alarm

The Aviator UL produced smooth and even data for slowly introducing the detectors to alarm as seen in section 5.3.2. The Rosco had a much harder time with this. With the Whittaker smoke detector, the Aviator UL showed an average of 5.9 percent obscuration per foot, shown in Table 12, with the fan at 2.5V and an average of 4.8 percent obscuration per foot with the fan at 5V, shown in Table 13. Again, the faster the fan is moving, the lower average percent obscuration is observed.

The Rosco was much more difficult to find here. Using the same method as testing with the Whittaker did not work out so well with the Kidde detector. The Rosco smoke machine needs to be very dense to set off the Kidde alarm to begin with. Getting the machine to gradually increase to that density of alarm, which is about 40-50% obscuration per foot, is extremely difficult. The Rosco is either puffing out little amounts of smoke that are nowhere near alarming the detectors or releasing too much smoke.

To have the Rosco smoke exit the chamber as thin as possible, the fan was connected to an 8V power source and a tight knit scotch pad was inserted in the fan to dilute the smoke further. Data was taken multiple times to try to find an acceptable run. Although some runs appear to have shown better data than some others, it seems that is not the case. When observing the two runs in Figures 20 and 21 side by side, their slopes appear different. In Figure 22, the two peaks are placed on the same graph to observe them more thoroughly. Although one run has a lower peak, they both appear to have similar slopes, so it is still unclear when testing with the Rosco to find exactly when the Whittaker smoke detector goes “into alarm”. Further testing would need to be done with a setup that is built around the way the Rosco outputs smoke. Even though one peaked at a lower alarm, it is still unacceptable data. The results are also not too close in range but this is what comes with the unpredictability of the Rosco Smoke Machine. With future testing, a new test setup needs to be created around the Rosco smoke machine as well to account for the high density of the smoke it outputs quickly.

With the Kidde smoke detector, the high alarm was observed over its pre, medium, and low alarms as seen in section 5.3.2.b. With the fan at 2.5V, the Aviator UL brought the Kidde detector “into alarm” at an average of 3.3 percent obscuration per foot as shown in Table 16 and with the fan at 5V an average of 2.4 percent obscuration per foot as shown in Table 17. It is following the pattern of having a lower average percent obscuration per foot for faster fan speeds compared to the slower fan speeds. This method does not work with finding when the Rosco brings the Kidde detector “into alarm”. The results are compared in Table 28. None of the Rosco-Kidde tests were good enough to understand the true value of when this detector goes “into alarm” with this smoke machine.

	Aviator UL	
	2.5V	*5V*
Kidde	3.3	2.4
Whittaker	5.9	4.8

Table 27 – Percent Obscuration per Foot Data Compared for Going “into Alarm”

Here, the Kidde detector alarmed much sooner than the Whittaker detector did with the Aviator UL smoke machine. The Kidde detector continues to alarm more easily and sooner with the Aviator UL.

6.5 Comparing In and Out of Alarm

The percent obscuration of alarm should be the same number, but when testing practically, the values for in and out of alarm varied with each detector. Table 28 compares the values for in and out of alarm when testing with the Aviator UL.

Aviator UL	**2.5V Fan**		**5V Fan**	
	Into Alarm	Leaving Alarm	Into Alarm	Leaving Alarm
Whittaker	5.9	2.9	4.8	2
Kidde	3.3	5.2	2.4	3.3

Table 28 - Comparison of %Obscuration/Foot Values for Aviator UL in and out of Alarm

It can be seen that the Whittaker detector goes into alarm at a higher percent obscuration per foot and leaves alarm at a lower percent obscuration per foot when compared to the Kidde detector.

6.6 Particle Size

In section 5.3.3.b, the particle sizes were first measured for the Rosco alarming the Whittaker detector with an average of 3.5 microns as shown in Table 21. The Rosco alarmed the Kidde detector with an average of 3.6 microns as shown in Table 22. The 0.1 micron diameter difference is not significant here, so the particle size of the Rosco smoke is seen as 3.5 microns.

The Aviator UL alarming the Whittaker detector recorded an average particle size of 1.7 microns as shown in Table 23 where with the Kidde detector it averaged 1.5 microns shown in Table 24. The average recordable particle size of the Aviator UL smoke is 1.6 microns.

The Aviator UL must have particles that are smaller than the PDPA was able to record and this can be seen by noting that the left hand side of the bell curve is completely cut off in Figure 27. Further testing was done to understand this. The

PDPA's program, FlowSizer, allows the option to turn off the sizing feature, capturing data for other characteristics of the particles.

When sizing was turned off for the Aviator UL, the PDPA recorded 662 particles. When sizing was turned back on it was only able to record diameter size for 287 of those particles. Comparing this to Rosco data, the PDPA recorded 2592 particles and was able to size 2530 of those particles. The amount of Rosco smoke particles that was recorded did not change much, it stayed the same where the amount of Aviator UL smoke particles that was seen by the PDPA doubled when particle sizing was turned off.

The Rosco Light smoke particles were also measured for 90 seconds through because it wouldn't alarm the detectors as discussed in section 5.3.3.c. The particle size for the Rosco Light smoke fluid is an average of 4.0 microns, shown in Table 25, which is slightly larger than the particle size for the Rosco normal. It could be that this particle size is too large for the detector to alarm through particle size detection, and the smoke outputted is too light to alarm the detector through smoke density. This could be why the Rosco normal smoke needs to be at such a high density to alarm the Kidde detector, because the particle size is just as large as it is here. The Rosco light smoke just cannot reach that high of an optical density to alarm the Kidde detector.

Another large particle size was tested which was the water steam droplets. These had an average of 20 microns, as discussed in section 5.3.4, and barely alarmed the smoke detectors. The older detector kept alarming on and off but the new false alarm resistant detector only reached a pre alarm, it never fully went into alarm which improved this detection and did not alarm on a false reading.

Chapter 7: Conclusion

This research is based on characterizing the smoke from smoke machines to understand what alerts different smoke detectors, and what would best be used for safely testing them. Final observations can be concluded into three main points.

The first point is that when testing with the Aviator UL smoke machine, the Kidde detector goes into alarm at a lower percent obscuration per foot and leaves alarm at a higher percent obscuration per foot when compared with the Whittaker smoke detector.

The second point is that the water based smoke particles either needed to be extremely dense to alarm the new false alarm resistant detector, or were unable to alarm the detector in general. Testing with water steam proved to show an improvement with the false alarm resistant Kidde detector where it did not alarm with water particles but the Whittaker detector did.

The third point is that the Kidde detector is hypothesized to depend on particle size detection first and percent smoke obscuration second. This is shown through the Rosco smoke machine, with particles too large to alarm the Kidde, it only alarmed when the smoke was extremely dense. This level of density is significantly higher than that of the older detector. The Aviator UL smoke particle size of 1.5 microns was acceptable and the Rosco's particle size of 3.6 microns was not acceptable.

In conclusion, the Aviator UL smoke machine is a great non-toxic method of testing the new false alarm resistant Kidde smoke detector. The Aviator UL alarms the new false alarm resistant smoke detector easily based on its small particle sizes that it produces. The density of the Aviator UL smoke is also enough to alarm both old and new detectors much sooner and efficiently with less amounts of smoke.

Chapter 8: References

[1] *Air Accident Investigation Report Case Reference: 13/2010, Uncontained Cargo Fire Leading to Loss of Control Inflight and Uncontrolled Descent Into Terrain*. Rep. N.p. General Civil Aviation Authority of the United Arab Emirates, 2010. Web.

[2] *Aircraft Accident Report RP-C3336.* Rep. N.p.: Civil Aviation Authority of the Philippines, 2013. Web.

[3] Part 25 AIRWORTHINESS STANDARDS: TRANSPORT CATEGORY AIRPLANES - Subpart D - Design and Construction: Fire Protection, Rgl.faa.gov § 25.857 (2016). Web.

[4] Advisory Circular, AC 25-9A, "Smoke Detection, Penetration, and Evacuation Tests and Related Flight Manual Emergency Procedures," 1994.

[5] Suo-Anttila, Jill, Walt Gill, and Louis Gritzo. *Comparison of Actual and Simulated Smoke for the Certification of Smoke Detectors in Aircraft Cargo Compartments.* Tech. no. DOT/FAA/AR-03/34. N.p.: n.p., 2003. Web.

[6] "Rosco Model 1700 Operations Manuial." Rosco, n.d. Web.

[7] *Rosco Fog Fluid & Rosco Smoke Simulation Fluid Safety Data Sheet*. N.p.: Rosco, n.d. PDF.

[8]"Concept SDT - Smoke Detector Testing System." *Concept Smoke*. N.p., n.d. Web.

[9]Li, J., Wang, S., Dou, Z. et al. *Discrimination of smoke particles using infrared photoelectrical detection*. International Journal of Infrared and Millimeter Waves (2001) 22: 141. doi:10.1023/A:1010773906638

[10] M. Ahrens, "False Alarms and Unwanted Activations," From: U.S. Experience with smoke alarms and other fire detection/alarm equipment, Fire Analysis and Research Division, National Fire Protection Association, Quincy, MA, 2004.

[11] "Optical Beam Smoke Detectors." Fire Ray - Fire Fighting Enterprises, Apr. 2014. Web.

[12] "How Smoke Detectors Work." HowStuffWorks. N.p., 01 Apr. 2000. Web.

[13] *Cargo Compartment Fire Detection Instruments*. Rep. no. AS8036. N.p.: SAE International, 2013. Web.

[14] Cox, James F. (2001). Fundamentals of linear electronics: integrated and discrete. Cengage Learning. pp. 91–. ISBN 978-0-7668-3018-9.

[15] Single and Multiple Station Smoke Alarms – UL 217. N.p. 1997, pp 41-42. Print.

[16] Tamhane, T. V., J. B. Joshi, Kamachi Mudali, R. Natarajan, and R. N. Patil. *Measurement of Drop Size Characteristics in Annular Centrifugal Extractors Using Phase Doppler Particle Analyzer (PDPA).* Tech. 8th ed. Vol. 90. Mumbai: n.p., 2011. Web.

[17] Mahmoud Ahmed, and M.S. Youssef, *Influence of Spinning Cup and Disk Atomizer Configurations on Droplet Size and Velocity Characteristics*. Tech. Vol. 107. N.p. 2013. Web.

[18]A.C. Chapple and F.R. Hall. *A description of the droplet spectra produced by a flat-fan nozzle*. Atomization and Sprays. N.p. 1993. Web.

[19] Downer, R.A., Hall, F.R. Droplet analysis in agriculture. J.Florida Mosquito Control Association, 65, 1994, pp.54-58. Web.

[20] Nephtali Ntahimpera, J.K. Hacker, L.L. Wilson, F.R. Hall, and L.V. Madden. Characterization of splash droplets from different surfaces with a phase Doppler particle analyzer. Agriculture and Forest Meteorology, Volume 97, pp. 9-19. 1999. Web.

[21] Sun, Wenhai, and Ning Huang. *Influence of Slope Gradient on the Behavior of Saltating Sand Particles in a Wind Tunnel*. Tech. Vol. 148. N.p.: Lanzhou U, 2016. Ser. 2. Web.

[22]Van Den Moortela, T., Azarioa R. Santinia, and L. Tadrista. *Experimental Analysis of the Gas–particle Flow in a Circulating Fluidized Bed Using a Phase Doppler Particle Analyzer*. Tech. 10th ed. Vol. 53. N.p.: n.p., 1999. Web.

[23] Albrecht, Heinz-Eberhard, M. Borys, N. Damaschke, and C. Tropea. *Laser Doppler and Phase Doppler Measurement Techniques*. Berlin: Springer, 2011. Print.

[24] "PDPA Systems." *Phase Doppler Particle Analyzer; PDPA Systems; PDPA Instruments*. TSI, n.d. Web

[25] Durst, F., A. Melling, and J. Whitelaw. 1981. Principles and Practices of LaserDoppler Anemometry. Academic Press

[26] *PDPA Hardware Manual*. Shoreview, MN: TSI, n.d. PDF.

[27] *Rosco Model 1700 Spec Sheet*. N.p.: Rosco, n.d. PDF.

[28] *Rosco Clear Fog Fluid Safety Data Sheet*. N.p.: Rosco, n.d. PDF.

[29] "PubChem Compound." *National Center for Biotechnology Information. PubChem Compound Database*. U.S. National Library of Medicine, n.d. Web.

[30] Verkouteren, Jennifer. "Liquid Refractive Index - Mineral Oil." *NIST*. National Institute of Standards and Technology, n.d. Web.

[31] *Phase Doppler Particle Analyzer (PDPA)/Laser Doppler Velocimeter (LDV) Operations Manual*. N.p.: TSI, 2006. PDF.

[32]"Normal Response, 100.0mm2, Silicon Detector | Edmund Optics." Edmund Optics Worldwide, n.d. Web.

[33]Troolin, D., W. Lai, and J. Shakal. ACCURACY, RESOLUTION, AND REPEATABILITY OF POWERSIGHT PDPA AND LDV SYSTEMS. Shoreview: TSI, 2013. PDF.

[34] Microchip CAN BUS Analyzer User's Guide. N.p.: Microchip Technology Inc., n.d. PDF.