ABSTRACT

Title of Document: ANALYZING PHOTO-ELECTRIC SMOKE DETECTOR RESPONSE BASED ON ASPIRATED SMOKE DETECTOR OBSCURATION

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Accurate obscuration levels at the response time of photo-electric smoke detectors are needed for proper detection modeling and analysis. In recent works, obscuration meters were used to measure the obscuration level at photo-electric detector response. In this study, aspirated smoke detectors (VESDA) were used to measure this same obscuration level. These detailed measurements were used to reduce the ambient light and the technology difference error associated with the obscuration meters. The use of aspirated smoke detection (VESDA) instead of light obscuration meters displayed increased accuracy for a majority of the experiments conducted in the 2008 report titled "Validation of a Smoke Detection Performance Prediction Methodology" involving flaming and non-flaming incipient fire sources at 3 different ventilation conditions.

ANALYZING PHOTO-ELECTRIC SMOKE DETECTOR RESPONSE BASED ON ASPRIRATED SMOKE DETECTOR OBSCURATION

By

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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
Master of Science
2010

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Acknowledgements

I would like to thank my advisor Dr. James Milke for his tireless guidance during my completion of this thesis, and his valuable advice throughout my years at the Department of Fire Protection Engineering.

I would also like to express my gratitude to the other committee members, Dr. Frederick Mowrer and Dr. Peter Sunderland, for their generous support and involvement in this project.

I would also like to extend my appreciation to Mr. John Vythoulkas and Mr. Yun Jiang from Xtralis, Inc. for their advice and support throughout this project.

I would like to thank my wife, Kelly, and my two lovely children, Jack and Dania, for enduring my extended absence in body and mind during the completion of this thesis.

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Chapter 1: Introduction

This thesis will analyze the response of conventional spot type photo-electric smoke detectors to flaming and non-flaming incipient fire sources in a ventilated room environment. The response of these detectors will be determined for three different ventilation conditions by using the obscuration readings of highly sensitive aspirated smoke detectors sampling in the same conditions. The expected result of this thesis is to improve the obscuration level response accuracy of spot type photo-electric smoke detectors when exposed to incipient fire sources. In previous studies, obscuration meters have been used to analyze the response of these detectors. The improved result in this thesis is suggested due to the fact that aspirated smoke detectors use the same light scattering technology as spot photo-electric detectors. Also, the aspirated smoke detectors remove the smoke sample from the room environment before reporting an obscuration which limits the effect of ambient light, room temperature, and smoke velocity on these readings. This thesis is an extension of a 2008 project completed jointly by the University of Maryland (UM) and Underwriters Laboratories, Inc. (UL) under the auspices of the Fire Protection Research Foundation (FPRF) titled “Validation of a Smoke Detection Performance Prediction Methodology”. This 2008 project, which will be referred to as the “2008 report” throughout this document, utilized obscuration meters inside the test room to determine the obscuration level at the response time of the spot type photo-electric detectors. This thesis will focus on improving the accuracy or validity of the data reported in this project by analyzing the response of these detectors in a different way.

Chapter 2: Overview of 2008 Report

The October 2008 report is divided into four volumes, and describes the test methods, test results, computer simulations and analysis used for this project, which addresses the validation of a smoke detection performance prediction methodology. The four volumes of this report include the following:

- Volume 1 addresses the characterization of the heat and smoke release rates of eight incipient fire sources;
- Volume 2 addresses the large-scale room fire tests conducted as part of this project;
- Volume 3 addresses evaluation of smoke detector performance in the large-scale room fire tests conducted as part of the project;
- Volume 4 addresses comparisons of FDS smoke detection prediction methodologies and actual smoke detector performance in the large scale room fire tests.

The overall objective of this project was to evaluate the capabilities of the Fire Dynamics Simulator (FDS) to predict smoke detector activation in response to relatively low energy incipient fire sources. The project was subdivided into four tasks, consistent with the four volumes included in the 2008 report.

The 88 room fire tests conducted as part of this project provide a large amount of data on the conditions resulting from the 8 incipient fire sources and the response of spot, beam and aspirated detection systems to these conditions in both unventilated and mechanically ventilated enclosures [1]. The basis for this thesis is that only a fraction of this data has been analyzed in detail as part of this 2008 report. This thesis will focus on providing improved results to Volume 3 (evaluation of smoke detector performance in the large-scale room fire tests) of this 2008 report. These results will be compared to the results obtained in this 2008 report where the obscuration meters were used to characterize the photo-electric detector response. These results will then be compared to methodologies available in the fire protection engineering literature for predicting the activation of photo-electric smoke detectors [1].

Chapter 3: Spot Photo-Electric Smoke Detector Principles

The response of traditional spot type smoke detectors is dependent on the characteristics of the smoke in the vicinity of the detector and the characteristics of the detector. Most of the current smoke detectors operate based on one of two types of detection technologies: photo-electric or ionization. Contemporary photo-electric smoke detectors respond based on the scattering of light caused by smoke particles, and this type of detector will be the main focus of this discussion. The alarms on these smoke detectors activate when a set threshold is reached [1].

The suspended smoke particles generated during the combustion process affect the propagation of a light beam passing through the air. This effect can be employed to detect the presence of a fire in two ways: obscuration of light intensity over the beam path and scattering of the light beam from its path of travel (photo-electric). Light scattering involves light being reflected or refracted by smoke particles. Light scattering smoke detectors are usually of the spot type and contain a light source and a photo-sensitive device arranged so the light normally does not fall onto the photo-sensitive device. When suspended smoke particles enter the light path, the light strikes the particles and is scattered onto the photo-sensitive device, causing the detector to respond (see Figure 3-1). A photo-diode or photo-transistor is usually the receiving device used in light scattering detectors [2].

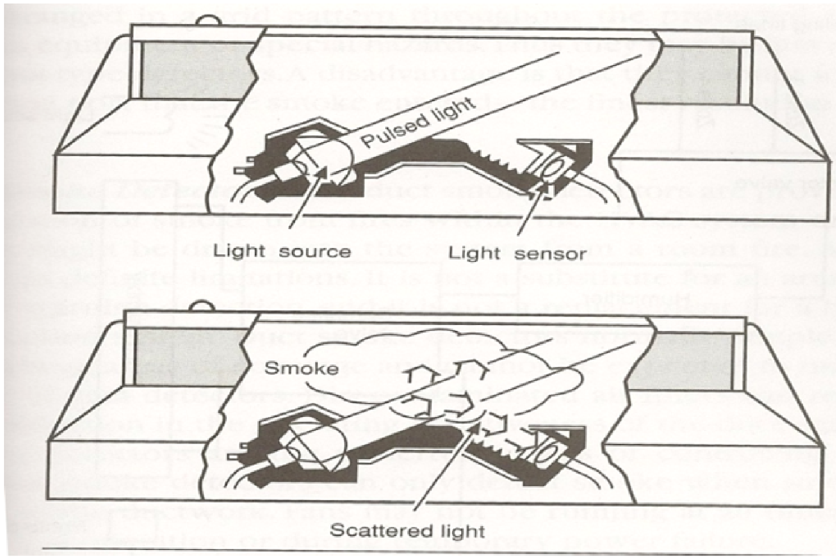

Figure 3-1: Typical Conditions Associated with Photo-Electric Detector Response [2].

In order to determine when a photo-electric detector will respond to a given obscuration level, a number of factors need to be assessed including smoke characteristics, smoke transport, and detector characteristics. Smoke characteristics are a function of the incipient fuel source composition, the mode of combustion (smoldering or flaming), and the amount of mixing with the ambient air. These factors are important for determining the characteristics of the products of combustion, such as particle size, distribution, composition, concentration, and refractive index. Whether smoke detectors detect by sensing scattered light, loss of light transmission, or reduction of ion current, they are really particle detectors. Thus, particle size, concentration, color, and size distribution affect each sensing technology differently. It is generally acknowledged that a flaming, well-ventilated fire produces smoke having a larger proportion of the sub-micron diameter particulates as opposed to a smoldering fire that produces smoke with a majority of large, super-micron particulates. It is also acknowledged that as the smoke cools, the smaller particles agglomerate to form larger particles as they age, and are carried away from the fire source [3].

All smoke detection depends on the plume and ceiling jet flows to move the smoke from the area of the fire to the detector. Many concerns must be addressed during this transport time, including changes to the characteristics of the smoke that occur with time and the distance from the source, and transport time of smoke from the source to the detector. The smoke characteristic changes that occur during transport relate mainly to the particle size distribution. Particle size changes during transport occur mainly as a result of sedimentation and agglomeration. Transport time is a function of the characteristics of the path of travel from the source to the detector. Other important characteristics that should be considered include ceiling height and configuration, intervening barriers such as doors and beams, as well as dilution and buoyancy effects such as stratification that might delay or prevent smoke in being transported to the detector. In smoldering fires, thermal energy provides a force for transporting smoke particles to the smoke detector sensor. However, usually in the context of smoke detection, the rate of energy release is small and the rate of growth of the fire is slow. In the early stages of development of a growing fire, interior environmental effects including ambient airflow from ventilation systems can have a dominant influence on the transport of smoke. This is particularly important in spaces having high ceilings. Greater thermal energy release from the fire is necessary to overcome these interior environmental effects [3].

Once smoke is transported to the detector, other factors become important in determining whether response will occur. These include the aerodynamic characteristics of the detector and the type of sensor within the detector. The aerodynamics of the detector relates to how easily smoke can pass through the detector housing and enter the sensor portion of the detector unit. Also, the location of the entry portion to the sensor with respect to the velocity profile of the ceiling jet is also an important factor. Finally, different sensing methods (e.g., ionization or photoelectric) will respond differently, depending on the smoke characteristics (i.e. smoke color, particle size, optical density). There will be variations depending on the wavelengths of light and the scattering angles employed by each individual detector type. All spot-type smoke detectors require smoke to enter the detection chamber in order to be sensed. This requires additional factors to be taken into consideration when attempting to estimate smoke detector response, as smoke entry into the detection chamber can be affected in several ways including insect screens, sensing chamber configuration, and location of the detector with respect to the ceiling [3].

The evaluation of these three major factors affecting photo-electric detector response (smoke characteristics, smoke transport, and detector characteristics) will be expanded upon further in the "Conditions Affecting Photo-Electric Detector Response" section of this thesis.

Chapter 4: Aspirated Smoke Detector Principles

Aspirated smoke detection (sometimes referred to as optical air sampling) equipment has been configured to provide another technique for early warning fire detection. These particle detectors sample the air from a protected area and are capable of protecting large spaces because of their inherent sensitivity. In addition, the detectors can be used in areas having high air change rates where dilute smoke concentrations or laminar airflows interfere with proper operation of other types of smoke detectors. These air-sampling detectors can draw air through a piping network to the detector unit by an air-aspirating fan in the detector assembly. Air samples are illuminated with a high intensity light, which causes smoke particles to reflect light to a solid-state photo-receiver. An analog signal is generated from the detector to the control unit, which displays the smoke obscuration sensitivity. The detector system provides independent programmable levels of alarms to indicate different levels of fire conditions. The two main advantages of this type of detection are the use of sensitivity settings for incipient fire detection and the fact that one detector apparatus can cover relatively large areas by using perforated piping for air sampling in the protected area. Aspirated smoke detectors can be set at much higher sensitivities than other smoke detectors because they are unaffected by air velocity, temperature, and humidity in the protected area. Although they are expensive, they sample from multiple points arranged in a grid pattern throughout the protected areas or even from within equipment or special hazards. A disadvantage is that they cannot identify the specific sampling port that the smoke entered-the finest resolution is normally by sampling zone [2].

The air sampling smoke detection system used in this experiment was the Xtralis VESDA (Very Early Smoke Detection Apparatus) VLC (LaserCOMPACT). This system works by continually drawing air into the pipe network via a high efficiency aspirator. A sample of this air is then passed through a dual stage filter. The first stage removes dust and dirt from the air sample before it allows the sample to enter the laser detection chamber for smoke detection. The second (ultra-fine) stage provides an additional clean air supply to keep the detector's optical surfaces free from contamination, ensuring stable calibration and longer detector life. From the filter, the air sample is passed through to the calibrated detection chamber where it is exposed to a highly stable laser light source with a 3.5mm diameter laser beam. When smoke is present, light is scattered within the detection chamber and is identified by the highly sensitive receiver system [4].

Chapter 5: Conditions Affecting Photo-Electric Detector Response

The response characteristics of photo-electric smoke detectors are not as well understood as those of sprinklers and thermal detectors. There are many conditions that affect the response of a spot photo-electric smoke detector when it is subjected to an incipient fire source. Photo-electric smoke detector alarm conditions depend on more than smoke concentration. Smoke particle sizes and optical or particle scattering properties can affect the smoke concentration value necessary to reach the alarm condition [5]. The quantity of light scattered by the smoke of an incipient fire source is very complex and is related to many factors such as particle number density and size distribution, refractive index, the wavelength of the light source, and the angle between the light source and the receiving unit [1].

Even though some of these variables can be described by the detector manufacturer, many require information about the smoke produced by the incipient fire source and its transport to the detector location. Experimental results regarding smoke properties related to light scattering is presently limited to a few types of incipient fire sources and is not readily available to practicing fire protection engineers. At the present time, there are no practical methods available to accurately predict the response of photo-electric smoke detectors.

A photo-electric smoke detector responds at different obscuration levels for different types of smoke. For example, a photo-electric smoke detector that responds to a 2 %/ft obscuration level to smoke produced by a smoldering cotton lamp wick may not respond until an obscuration level of 10 %/ft is reached for smoke from a kerosene fire. At the response set point, both types of smoke are scattering the same amount of light to the photo-diode of the photo-electric smoke detector. There are many factors in this effect, and one is that the darker smoke from the kerosene fire source does not reflect as much light as the lighter colored smoke from the smoldering cotton lamp wick fire source. The amount of light being scattered when two smoke samples have the same optical density is another way to understand the differing responses of a photo-electric smoke detector. Both samples of smoke equally distort our vision of the light reflected by an object. One type of smoke may be composed of large and highly reflective particles that cause the light to scatter in many directions reducing the light in the forward direction. The other type of smoke may consist of a smaller number of larger particles that absorb light more easily than they reflect it. Even though they have equal optical densities, one is more likely to scatter the light and set off a photo-electric smoke detector [4].

In order to predict the response of a photo-electric detector using obscuration, it is imperative to know the obscuration required for a particular type of smoke to alarm a particular model detector. Many manufacturers label their smoke detectors with a unit obscuration (O_u) based on a calibration test that is part of UL standard number 217/268. That O_u indicates the unit obscuration required for that detector to respond to smoke having very specific characteristics. The obscuration required to alarm a particular detector as quoted by the manufacturer is just one value for a given particle size distribution, concentration, color, etc. used in the laboratory calibration test of that model detector. If the smoke and conditions around the detector are similar to that used in the test of the detector, the specified obscuration alarm threshold can be expected to react appropriately. Even with the completion of this calibration test, it is not adequate to have data for a particular fuel and detector combination. It is known that smoke changes as it travels away from an incipient fire source. There may be changes in the quantity, size, shape, and velocity of the particles. The obscuration at response to any smoke signature other than the laboratory calibration test will be different and will fluctuate with different incipient fire sources and burning modes (i.e. flaming or smoldering) [4].

There are 3 regions of light scattering behavior available in the literature for single, spherical particles (Rayleigh, Mie, and Bricard) and they are dependent on the particle diameter (d) and the wavelength of light (λ) [7]. Mie theory ($0.1 < d/\lambda < 0.4$) can be examined to study the effect of smoke particle properties on photo-electric detector response considering the wavelength of light used in these detectors and the range of particle sizes produced in fires [1]. Mie theory states that light scattering (LS) is linearly proportional to the number of smoke particles (n_i) and the square of the diameter of the particles (d_i):

$$LS \ \alpha \sum n_i * d_i^2 \qquad (1)$$

The conditions in a ceiling jet or smoke layer of an incipient fire source determined with fire protection engineering methods include estimates of light obscuration, temperature, and velocity. These methods do not include smoke particle size and concentration which provides an inherent difficulty in estimating the response of photo-electric detectors [4]. In order to analyze smoke particle data, a correlation based on Beer’s Law was developed for smoke obscuration and particle size and number. Beer’s Law as applied to smoke relates optical density (OD) per unit path length (L) to smoke concentration at a given time (C_s) [8]:

$$OD/L \ \alpha \ C_s \qquad (2)$$

The smoke concentration is related to the smoke number density as [8]:

$$C_s \ \alpha \ \sum n_i * d_i^3 \tag{3}$$

Where n_i and d_i are the number count and particle diameter for a range of particle size "i". Combining equation (2) and (3) above yields a relationship between optical density per unit path length and the number count and particle diameter at a given time [8]:

$$OD/L \ \alpha \ \sum n_i * d_i^3 \tag{4}$$

The optical density (OD) and obscuration per meter (OBS) can be related by [1]:

$$OBS = 100[1\text{-}10^{-OD}] \tag{5}$$

A particular level of obscuration does not uniquely describe the characteristics of a particular type of smoke from an incipient fire source. This issue was addressed in the recent Smoke Characterization Project conducted by UL [1]. This study collected detailed information of the smoke particle size, concentration, light obscuration, and other parameters relative to smokes produced by several different fuels [8]. The research found that the mean particle diameter producing the same level of light obscuration ranged from 0.08 to 0.22 microns. With this information, even though the level of light obscuration is the same for these smokes, their detect ability by a light scattering detector would vary given that the detection technology is dependent on the square of the particle diameter [1].

NFPA 72 includes an engineering approach in Annex B for estimating the response of photo-electric detectors to flaming fires. There are three parameters identified in this literature including obscuration, velocity, and temperature rise that can be used as "surrogate' conditions in determining detector response. In previous work, Heskestad and Delichatsios suggested values of the optical density (i.e. obscuration) that coincided with smoke detector response based on their measurements [12]. Their suggestions were incorporated into the optical densities noted in NFPA 72, Annex B. The obscuration level corresponding with detector responses varied by the detection technology and fuel, this issue has been discussed previously in this report. The range in obscuration levels for smokes from various fuels varied by a factor of 11 for photo-electric detectors [1]. A secondary means of determining time to detector activation is the critical velocity of the ceiling jet. Research has shown that a minimum critical velocity is necessary before smoke can enter the sensing chamber of a smoke detector. This “surrogate’ method assumes that if this critical velocity has been attained, sufficient smoke concentration is in the ceiling jet gas flow to produce an alarm signal [3]. The critical velocity associated with the response of photo-electric smoke detectors ranges from 0.13-0.15 m/s for flaming fires [11]. Schifiliti and Pucci estimated the temperature rise necessary for detection to fires involving fuels based on ratios of the optical density and temperature at detector response determined by Heskestad and Delichatsios [7]. The temperature rises resulting from their work were used to estimate smoke detector response and are included in NFPA 72. A temperature rise of 13 K for photo-electric detectors exposed to any type of fuel is suggested. However, evidence has shown that fires involving wood cribs and cotton fabrics produce much higher temperature increases [1]. Considering that light scattering technology in a photo-electric detector does not respond to conditions represented by any of these three parameters, intrinsic errors are to be expected when applying any of these parameters for estimating the response of photo-electric smoke detectors [7].

Chapter 6: Experimental Program

Part 1: Experimental Procedure

A set of 88 large-scale room fire tests were conducted to develop data for use in the 2008 report and potential future studies. Out of this set, a series of 24 tests were conducted under unventilated conditions in the standard room used to test smoke detectors for the UL 217/268 standards. This unventilated test room measured 10.8 m long by 6.6 m wide by 3.0 m tall. These 24 tests were not used in this thesis for analysis because the aspirated smoke detection system (VESDA) was not installed in this space. The second set of 64 large-scale tests, which will be the focus of this analysis, were conducted in a room constructed particularly for this project to represent a mechanically ventilated space in a commercial facility. This test room was provided with mechanically injected ventilation and a ceiling return air plenum to represent a typical commercial installation. Replicate tests (3) were conducted with each of the 8 incipient fire sources at nominal mechanical ventilation rates of 6 and 12 air changes per hour; replicate tests (2) were also conducted with each of the 8 incipient fire sources under unventilated conditions in this room. Matrices showing the test designations of the 88 large-scale tests and the 8 incipient fire sources used in these experiments are provided in Tables 6-1 and 6-2.

Table 6-1: Incipient fire sources [1]

Fuel source	**Ignition source**	**Fire type**
Shredded office paper	Small flame (50 W)	Flaming
Flexible PU foam / microfiber fabric	Small flame (50 W)	Flaming
Flexible PU foam / microfiber fabric	Hotplate	Smoldering/pyrolysis
Ponderosa pine	Hotplate	Smoldering/pyrolysis
Cotton linen fabric	Hotplate	Smoldering/pyrolysis
PVC wire	Electric overcurrent	Smoldering/pyrolysis
Computer case	Small flame (UL 94)	Flaming
Printed circuit board	Small flame (ATIS T1.319)	Flaming

Table 6-2: Matrix of large-scale room fire test designations [1]

Incipient fire source	**Unventilated room**	**Ventilated room**		
		6 ach	**12 ach**	**0 ach**
Shredded office paper	1, 2, 3	25, 26, 27	49, 50, 51	73, 74
Flaming PU foam / microfiber fabric	4, 5, 6	28, 29, 30	52, 53, 54	75, 76
Smoldering PU foam / microfiber fabric	7, 8, 9	31, 32, 33	55, 56, 57	77, 78
Ponderosa pine	10, 11, 12	34, 35, 36	58, 59, 60	79, 80
Cotton linen fabric	13, 14, 15	37, 38, 39	61, 62, 63	81, 82
PVC wire	16, 17, 18	40, 41, 42	64, 65, 66	83, 84
Computer case	19, 20, 21	43, 44, 45	67, 68, 69	85, 86
Printed circuit board	22, 23, 24	46, 47, 48	70, 71, 72	87, 88

ach = nominal mechanical injection ventilation rate in air changes per hour

The ventilated test enclosure used for the 64 large-scale room fire tests is illustrated in Figure 6-1. The origin of the coordinate system for this figure is located in the lower left-hand corner (all locations were measured from that point).

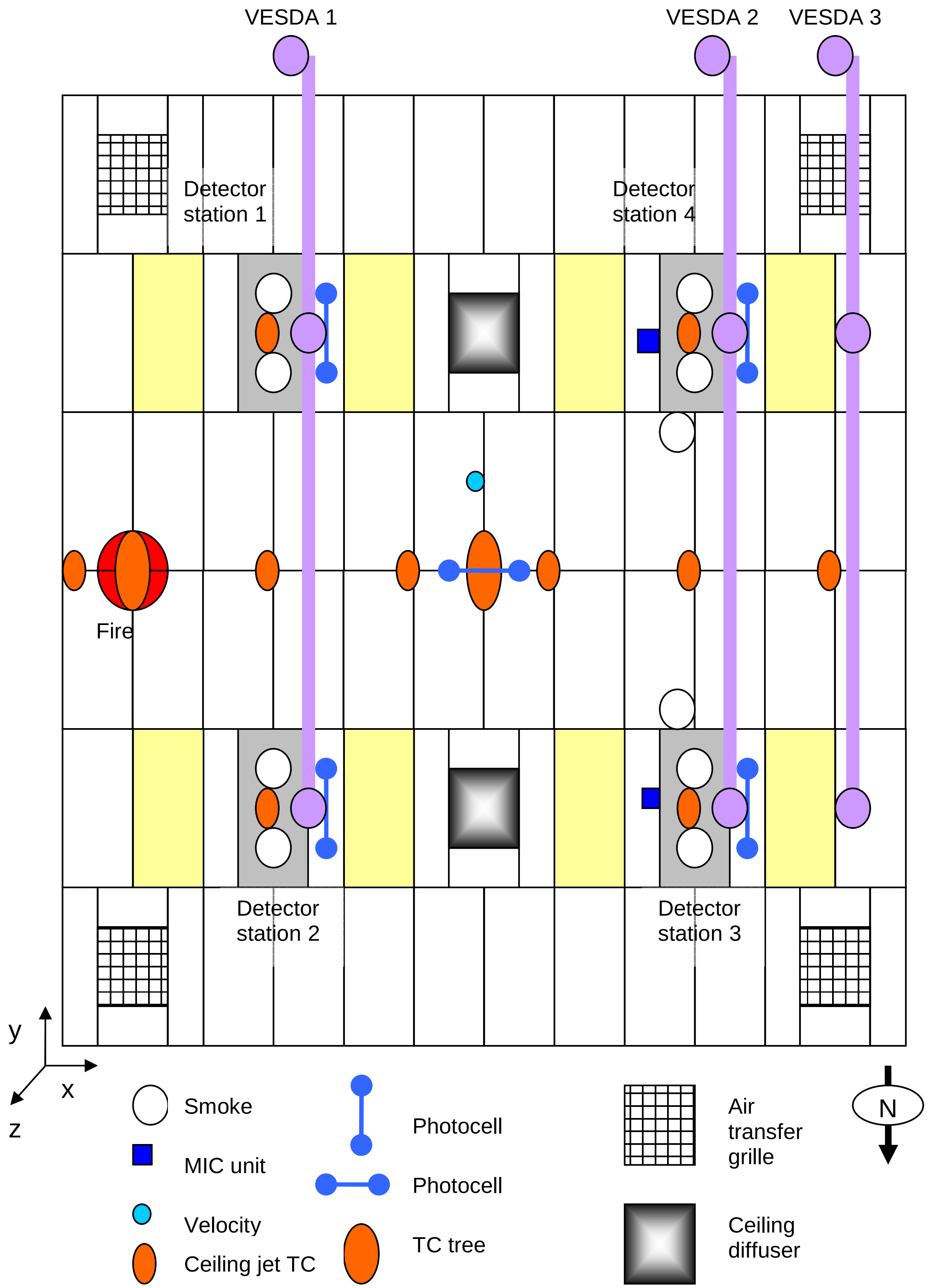

Figure 6-1: Approximate Instrumentation Locations in Ventilated Test Room [3]

The 8 flaming or smoldering incipient fire sources used in this experiment were selected due to their association with commercial operations. Each of the eight fuel sources chosen for this project was characterized in UL's IMO intermediate-scale calorimeter (based on the principle of oxygen consumption calorimetry). Three tests were performed for each fuel source to obtain replicate data sets. The information collected included mass loss (for flaming sources), heat release rate (for flaming sources), smoke release rate, smoke particle size and number, and gas effluents. The incipient fuel source packages were designed to share similar physical characteristics to how they would be used in manufactured products [1].

The following paragraphs are a brief description of each of the eight incipient fire sources and how ignition or smoldering of each was achieved. A summary of the results of these characterization tests is also included with each incipient fire source description. A more detailed description of these fire sources and the results of these characterization experiments can be found in Volume 1 of the 2008 report mentioned previously in this document.

The shredded office paper test arrangement included a solid metal wastebasket measuring 35.5 cm tall x 28 cm in diameter at the top and by 22 cm in diameter at the bottom, standard office paper cut into strips measuring 6.35 mm wide x 25.4 mm to 101.6 mm long (UL 217), and a fabricated disk to tamp the paper to a depth of 10 cm from the base of the wastebasket. This test was initiated by inserting a burner 25 mm into a hole at the bottom of the wastebasket for 5 seconds [1]. The shredded office paper tests showed similarities between the tests, but there was some inconsistency. Overall, this test is repeatable within a range of outcomes. The primary cause of the inconsistency was the flame-through time. The flame-through time is the time at which the test transitioned from smoldering to flaming. This occurs when the smoldering material at the base creates enough heat to ignite the material above it and produce flames above the paper. The flame-through time is significantly affected by the packing density of the paper. The mass loss from the shredded office paper tests were similar in rate, but differed in time again due to the inconsistent packing density. The smoke release rate data was consistent in nature with the heat release rate and the mass loss data. The mean particle diameters ranged from 0.10 microns to 0.45 microns over the course of the tests. These larger particles can be attributed to the smoldering phase of these tests [1].

PU foam with micro-fiber fabric was used to simulate a typical commercial upholstery assembly. The ignition source used for this experiment was the same burner assembly used for the shredded office paper test (similar to a butane cigarette lighter flame). Two blocks of PU foam measuring 20 x 8 x 10 cm were wrapped in a 50 x 60 cm sheet of micro-fiber fabric to create a block of material that measures 20 x 16 x 10 cm. A foil tray was positioned beneath the source during testing to contain the liquefied PU foam. The specimen was placed on the foil tray with the 20 x 16 cm side down, which incorporated the pinned fabric. Initiation of the test began with igniting the burner and establishing a 35 mm tall flame with the burner held horizontally. The burner flame was then placed against the base of the front side of the PU foam assembly near the center for 20 seconds. As the foam liquefied and the micro-fiber fabric burned away, the flame was kept in contact with the material, adjusting for the deformation during the 20 second ignition period [1]. The flaming PU foam with micro-fiber fabric test produced results which were appreciably different than those from other materials due to the thermal response of the polyurethane foam. In general, the data from the tests with this sample were consistent and the tests were repeatable. The heat release rate curves produced from these tests displayed similar traits and the smoke release rate followed a similar profile. The particle count density is similar between the tests with the peak diameter of 0.30 microns being reached at approximately 320 seconds [1].

The printed circuit (PC) board tests were used to assess the fire spread risk of telecommunications equipment assemblies. A different type of burner was used to initiate these tests (ATIS T1.319 line burner). Two 7.5 x 7.5 x 1.57 mm printed circuit boards conditioned to 23 ± 0.5 ˚C and 50 ± 5 % relative humidity for a minimum of 24 hours were placed 2 cm apart in a vertical arrangement. The line burner was centered 1.5 cm below the PC board assembly, perpendicular to the PC boards. The specimen assembly was elevated 2.5 cm off of the platform of the load cell to accommodate the location of the line burner. The line burner valley was 3 cm wide and the valley running parallel to the PC boards was 2.5 cm wide. The specimen assembly was placed such that the PC boards were over the 2.5 cm valley. To begin this test, the line burner was ignited, and the methane flow was brought up to provide a 65 mm flame height. The flame of the line burner was allowed to burn for 1 minute to stabilize before the printed circuit boards were placed on top. The PC boards were placed above the center of the line burner, oriented perpendicular to the line burner. The line burner remained on for the duration of the test because the PC boards would not sustain a flame without an external heat source [1]. The printed circuit board tests showed consistent values between the tests. This material showed significant reactions during the beginning of the tests and only minor changes near the end. The heat release rate curves produced from these tests included the contributions of the line burner and showed that the PC boards created a peak in the heat release rate just before 60 seconds, and then provided a minor contribution for the remainder of the test. The mass loss was consistent between the tests and shows that the fuel consumption rate was highest from approximately 20 seconds to 90 seconds. The smoke release rates were consistent and peak just prior to 60 seconds with a majority of the smoke production during the first two minutes of the test. Particle count density was not consistent, but the mean particle diameter showed similar trends between the tests [1].

The computer case material selected for these tests were representative of the materials used as external casing for electronics equipment. A 50 W Bunsen burner was used as the ignition source for these tests (specified in UL 94). The specimen was 125 mm tall x 13 mm wide x 3.5 mm thick and was conditioned for a minimum of 24 hours at 23 ± 0.5 ˚C and 50 ± 5 % relative humidity. The specimen was wrapped in a 6 x 15 cm piece of hexagonal wire mesh to prevent dripping, which caused significant inconsistencies with smoke output and mass loss readings. The top of the burner was positioned 1 cm from the bottom of the specimen. The ignition of the specimen was achieved by placing a 20 mm flame 1 cm from the bottom of the specimen and remained ignited for the duration of the test. If any material began to sag down from the wire, the burner was pulled down slightly to maintain the 1 cm distance to prevent the material from getting into the burner tube [1]. The results of the computer case tests were difficult to analyze because some of the data was below the accuracy of the instruments. However, there were some consistencies between the test regarding mass loss, heat release rate, particle size and concentration.

The smoldering tests for the polyurethane foam with micro-fiber fabric used the UL 217 smoldering smoke test temperature profile and the Wenesco HP1212YX hotplate. The material was placed in a 22.8 x 22.8 cm steel pan lined with foil and then placed on the heated surface of the hotplate. Two blocks of PU foam measuring 20 x 8 x 10 cm were wrapped in a 50 x 60 cm sheet of micro-fiber fabric in the manner to create a block of material that measured 20 x 16 x 10 cm. The assembled specimen was then placed in a 22.8 x 22.8 in. steel pan lined with foil to protect the hotplate. The hotplate surface was approximately level with the bottom of the hood curtain to ensure that the low buoyancy smoke produced from this smoldering source was completely collected by the exhaust duct. The smoldering test began by placing the 22.8 x 22.8 cm tray on the center of the hotplate [1]. The smoldering tests for the PU foam with micro-fiber fabric produced consistent data. The smoke release rate from these tests did not become significant until approximately 2300 seconds. At this point, the smoke release rate continued to rise and peak at approximately 3700 to 3800 seconds. The smoke release rate was low compared to the flaming tests, but total smoke generation was significantly higher. The particle count density data displayed a peak near the beginning of the smoke release rate curve and the mean particle diameter followed a similar profile as the smoke release rate [1].

Ponderosa Pine was used in the smoldering smoke test detailed in UL 217 that evaluates spot type smoke detectors. The UL 217 hotplate and temperature profile were used for this test. Ten ponderosa pine sticks, free from knots and pitches, were placed in a spoke pattern on the hotplate so that the sticks were 36° apart. The sticks were 7.6 x 2.5 x 1.9 cm with the 1.9 x 7.6 cm side in contact with the hotplate. The hotplate surface was approximately level with the bottom of the hood curtain to ensure that the low buoyancy smoke produced from this smoldering source was completely collected by the exhaust duct. The test was initiated by placing the ponderosa pine sticks on the hotplate. The sticks lost most of their original mass and much of what was left was only char [1]. The ponderosa pine tests were consistent and showed similar trends between tests. The smoke release rate of smoldering ponderosa pine began much earlier than the PU foam package. The particle count density data showed that particle production lags significantly behind smoke release. The mean particle diameters produced during the smoldering ponderosa pine tests showed the same pattern between tests with only minor variations [1].

The cotton linen fabric tests were intended to represent cloth material such as a napkin or tablecloth that smolders after a heat source incident. The hotplate described previously was used for this test, with the temperature profile specified in UL 217. Two 30 x 30 cm sheets of cotton linen fabric were placed on the hotplate and smoothed out over the surface. The sheets nearly covered the entire heated surface. The proportioning temperature controller maintained the UL 217 temperature profile. The hotplate surface was approximately level with the bottom of the hood curtain to ensure that the low buoyancy smoke produced from this smoldering source was completely collected by the exhaust duct. To begin this test, the two sheets of fabric were stacked and adjusted so that the edges and corners matched up. They were then placed on the hotplate, pressed flat and smoothed out across the heated surface [1]. The cotton linen fabric tests showed two peaks similar to the flaming PU foam package. The dual peaks could be seen in the smoke release rate and the particle count density. The mean particle diameter data did not change significantly between tests [1].

The PVC insulated wire tests were representative of smoke produced from an electrical overload. The smoke produced from these tests simulated the smoke that might be produced during the early stages of a telecommunications fire. The North American Wire Test was used as the procedure for these tests. A 1 m long PVC insulated solid 22 AWG copper wire with a radial insulation thickness of 1.1 mm was subjected to a constant current of 28 amps and a varying voltage from 0 to 18 V to compensate for the changing resistance in the wire. The wire was placed on a foil covered surface in a manner that prevented kinks or crossovers that could interfere with the current application. The ends were connected to a reef bar that was connected to the Sorensen DCS 60-50 power supply through 10 AWG stranded wire. The foil surface for this test was level with the base of the hood curtain to limit the possibility of smoke loss from the hood. To begin this test, the wire was connected to the reef bar. The power supply was then switched on and set to a constant current of 28 amps. The current was applied for 1 minute as the voltage increased to maintain 28 amps [1]. The PVC insulated wire tests were unique to the smoldering tests in that they were of short duration and had no significant heat source. Smoke generation did not begin until after 60 seconds. At this point it rapidly increased, creating a peak in the smoke release rate data that was consistent in time and duration for the tests. The particle count density and the mean particle diameter showed some consistency between the data sets [1].

This ventilated enclosure measures 7.2 meters long x 7.2 meters wide x 3.0 meters tall and was equipped with a number of spot-type commercial smoke detectors from two different manufacturers, designated as SS and SG (SG photo-electric detectors will be the focus of this analysis). The ventilated test room was also equipped with three aspirated smoke detection systems from one manufacturer (Xtralis) [1]. The enclosure was equipped with a mechanically injected ventilation system, with two ceiling air diffusers provided for air injection and four transfer grilles provided in the ceiling for air exhaust to a 1.5 m deep plenum located above the ventilated test room. The ceiling plenum was vented to the general laboratory space through a large opening in the east wall. The air diffuser and transfer grille locations are shown in Figure 6-1 [1].

For test purposes, the fire source was located on a stand located 0.6 m from the north wall along the longitudinal centerline of the room as illustrated in Figure 6-1. The top of the stand was located 0.75 m above floor level. In the coordinate system adopted for this project, with the northeast corner of the room serving as the origin, the coordinates of the fire source base would be $x = 0.6$ m, $y = 3.6$ m and $z = 0.75$ m, as illustrated in Figure 6-1. This fire source location was used for all tests in this series [1].

The ventilated test enclosure was equipped with four detector stations located at ceiling level at the quarter-points of the room, as shown in Figure 6-1. Each detector station was equipped with two spot-type smoke detectors, including one of each brand (SS and SG), a photocell/lamp assembly and a thermocouple. The photocell and lamp units of each assembly were spaced 0.3 m from each other; the purpose of these assemblies was to measure light obscuration in the vicinity of the west, center and east detector stations, respectively. The photocell used in these assemblies was a Weston Photronic Cell Model 856-9901013-BB unit, while the lamp was a General Electric Edison Spot Halogen 20 #99372 (Q20MR16NSPICG) 12 volt/20 watt unit [1].

The ventilated test enclosure was also equipped with three aspiration type (VESDA) smoke detection systems. Each aspirated system had two sampling ports within the test enclosure, as illustrated in Figure 6-1, as well as one sampling port located outside the test enclosure. The VESDA 1, VESDA 2, and VESDA 3 systems had sampling ports located near detector stations 1 and 2, detector stations 3 and 4, and near the west wall of the enclosure, respectively. Below is a list of the sampling port locations for each branch [1]:

-VESDA 1 (2 port locations) - x = 1.95 m, y = 1.8 m, z = 2.98 m

- x = 1.95 m, y = 5.4 m, z = 2.98 m

-VESDA 2 (2 port locations) - x = 5.55 m, y = 1.8 m, z = 2.98 m

- x = 5.55 m, y = 5.4 m, z = 2.98 m

-VESDA 3 (2 port locations) - x = 6.98 m, y = 1.8 m, z = 2.98 m

- x = 6.98 m, y = 5.4 m, z = 2.98 m

The ventilated enclosure was also equipped with additional instrumentation for these test sets, including the following:

- A photocell tree with 3 photocell/lamp assemblies and associated thermocouples mounted at three different heights located at the center of the room. This apparatus was located at coordinates of x = 3.6 m and y = 3.6 m relative to the northeast corner of the test room. The elevations of the three photocell assemblies and associated thermocouples were 1.5 m, 2.4 m and 2.7 m above the floor, respectively. The photocell used in these assemblies was a Weston Photronic Cell Model 856-9901013-BB unit, while the lamp was a General Electric Edison Spot Halogen 20 #99372 (Q20MR16NSPICG) 12 volt/20 watt unit. A thermocouple was located adjacent to each photocell assembly (all thermocouples used for this project were Type K thermocouples with exposed beads) [1].

- A thermocouple tree with 8 thermocouples mounted at eight different heights located in the center of the room. This apparatus was located at coordinates of x = 3.6 m and y = 3.6 m relative to the northeast corner of the room. The eight thermocouples were located at elevations of 2.1 m, 2.5 m, 2.7 m, 2.85 m, 2.9 m, 2.925 m, 2.95 m and 2.975 m above the floor, respectively [1].

- Three thermocouples located at three elevations within the fire plume and one thermocouple to measure the hotplate temperature during tests that used the hotplate. These apparatus were centered on the fire source at coordinates of x = 0.6 m and y = 3.6 m. The lowest of the three plume thermocouples was located at an elevation of 0.1 m above the surface of the fuel, so the elevation of this thermocouple depended on the fuel source geometry. The middle of the three plume thermocouples was located at an elevation of 2.1 m above the floor and the upper plume thermocouple was located at an elevation of 2.85 m above the floor [1].

- Six thermocouples mounted in the ceiling jet along the longitudinal centerline. These apparatus were all located along the longitudinal centerline of the room (y = 3.6 m) at an elevation of 2.925 m above the floor. The x-coordinates for these ceiling jet thermocouples were approximately 0.1 m, 1.8 m, 3.0 m, 4.2 m, 5.4 m and 6.6 m, respectively [1].

- Probe to measure velocities in the x- and y-directions at one location in the ceiling jet, along with the gas temperature at this location. This apparatus was located at coordinates of x = 3.6 m, y = 4.2 m and z = 2.975 m relative to the southeast corner of the room. The velocity probe was also equipped with a thermocouple to measure gas temperature at the location of the velocity probe [1].

Part 2: Experimental Results

The purpose of this project was to identify relationships between photo-electric smoke detectors and smoke parameters which are included within current numerical models. Considering that optical density is computed by several numerical models, the relationship of photo-electric smoke detector response to light obscuration is sought in this analysis [1]. The characteristics of the environment in the vicinity of the spot type photo-electric detectors at the time of response are described in terms of the obscuration recorded by the aspirated smoke detectors in the same vicinity. Spot photo-electric smoke detectors from two manufacturers (SS and SG) were included in the ventilated test room. The SS photo-electric detector was not used in this analysis because the proprietary algorithm to obtain results was not available. The SG photo-electric detector data was available and used for this analysis. Aspirated smoke detectors (VESDA) from one manufacturer (Xtralis) were included in the ventilated test room and used for this analysis.

The response of the detectors was collected on proprietary systems provided by each of the detection system manufacturers (SG and Xtralis). The SG photo-electric detectors were judged to operate when they reported an obscuration level of 2.5 %/ft based on the UL 217 Sensitivity Test Smoke Box. The Xtralis aspirated smoke detectors

(VESDA) were judged to record very low obscuration levels and operate when they reported an obscuration level of 0.062 %/ft [9].

The results of this analysis were obtained by a multi-step process. First, the activation times (seconds) of the SG spot photo-electric detectors in the 64 ventilated room tests were recorded (from excel files for each test). Second, these spot photo-electric detector activation times were used to find the corresponding obscuration level (% obs/ft) recorded by the VESDA aspirated detection system (from excel files for each test).

The activation times of the spot photo-electric detectors were recorded for all four locations inside the ventilated test room. These locations are labeled as detector stations 1-4 as denoted in Figure 6-1. Each of the spot photo-electric detectors at these stations was described based on the manufacturer and location and are denoted as follows:

Detector Station 1 – SG Station 1

Detector Station 2 – SG Station 2

Detector Station 3 – SG Station 3

Detector Station 4 – SG Station 4

The activation time data obtained for these four detectors from the excel files was then averaged along the corresponding aspirated smoke detector (VESDA) branch line. For example, the detector activation times SG Station 1 and SG Station 2 were averaged to create an SG Station 1/2 Avg activation time which corresponds to the VESDA 1 branch (see Figure 6-1).

The average spot photo-electric activation times (i.e. SG Station 1/2 Avg) were then used to find the corresponding obscuration level recorded by the aspirated smoke detector (VESDA). The use of these average values was necessary as the VESDA system only provided obscuration levels for each branch of the system (i.e. one data point for both VESDA detectors in branch). For example, the VESDA 1 branch line provided one obscuration level corresponding to the spot photo-electric detector SG Station 1/2 Avg activation time. These average activation times along with the corresponding VESDA obscuration levels are listed for each test in Tables A1 – A3 of the Appendix.

The obscuration levels recorded by the VESDA system were corrected in order to account for the dilution of the smoke sample with the aspirated air introduced by the VESDA 3 branch line (see Figure 6-1). Each obscuration value obtained by the VESDA system was divided by a factor of 0.68 in order to account for this dilution of the sample and give the correct obscuration level inside the test room at SG photo-electric detector response.

There are also many factors contributing to the uncertainty of the obscuration level data obtained from the VESDA system. These uncertainties are a factor of many things including the offset time, the filters employed in the VESDA system, and the smoke transport lag. The first factor contributing to the uncertainty of these obscuration measurements was the VESDA offset time. There was no reset time to indicate the start of each test from the event logs of these experiments. In order to mitigate this, time offsets were provided by Xtralis, Inc. for the VESDA system for each individual test. These synchronization offsets were determined when the background level for both the obscuration meter and the VESDA system increased considerably to indicate ignition had occurred. The time offsets were necessary in order to align the obscuration meter with the aspirated smoke detection system (VESDA) [10]. The potential inaccuracy of these time offsets could have contributed to the uncertainty of the data obtained in this analysis. The second factor affecting the uncertainty of these measurements was the use of the dual stage filter in the VESDA aspirated detection system. The dual stage filters employed by the VESDA system may have removed some of the smoke particles present in the smoke sample as it was transported to the detection chamber. This filtering of smoke particles may have had an impact on the results of the obscuration measurements considering that particle size and number in the test chamber affect the smoke sample's ability to scatter light to the receiving photo-sensitive device. The third factor contributing to the uncertainty of these obscuration measurements was the smoke transport lag from the test room to the light scattering chamber of the VESDA system. This transport time was not taken into account when the data points of this analysis were obtained. This transport time difference could have had an impact on the accuracy of these results, considering that many of the data points obtained in this analysis are from rapidly increasing portions of the VESDA obscuration curves as shown in Figures 6-2 through 6-41. Figures 6-2 through 6-41 on the following pages of this chapter are displaying the SG photo-electric detector activation times on the VESDA obscuration curves for each test at 0, 6, and 12 ACH where this data was available. The text boxes on each plot provide the following information:

- SG Activation Total Time: This is the total time used to pinpoint the detector response on the VESDA obscuration curve.

-VESDA Offset: This is the time provided to align the VESDA system with the obscuration meters which was discussed earlier (can be added or subtracted from activation time).

-Activation Time: This is the actual activation time recorded for the SG photo-electric smoke detectors (it is the average time between station 1 and 2 or 3 and 4).

-Room Obs: This value is the obscuration level in the room recorded by VESDA at the time of detector activation.

-VESDA Obs: This value is the obscuration level recorded in the VESDA light scattering test chamber. This value is different than the room obscuration value due to the dilution of the test sample by the aspirated air used in this system.

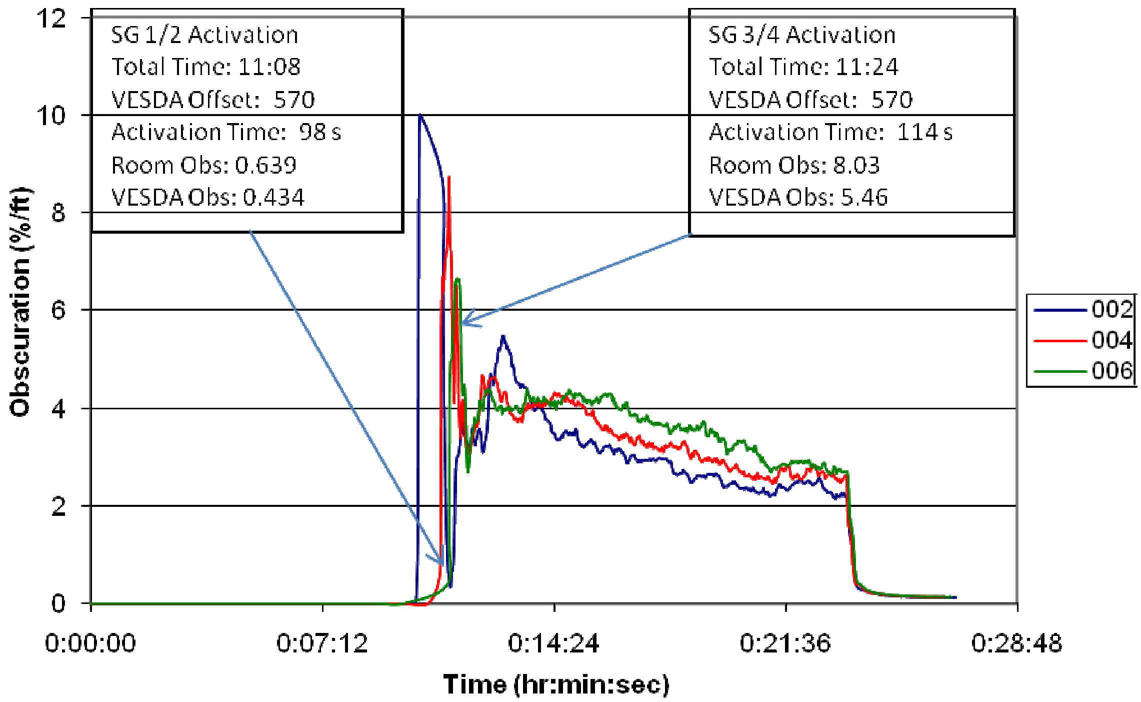

Figure 6-2: VESDA Obscuration vs. Time for Test #73. Shredded Office Paper at 0 ACH

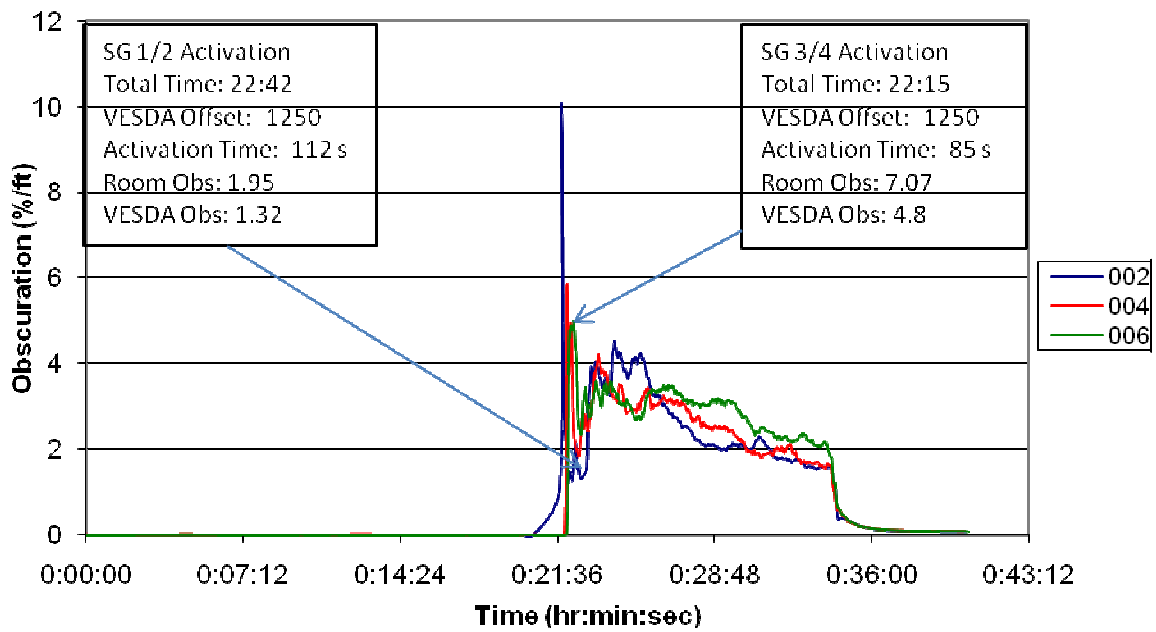

Figure 6-3: VESDA Obscuration vs. Time for Test #74. Shredded Office Paper at 0 ACH

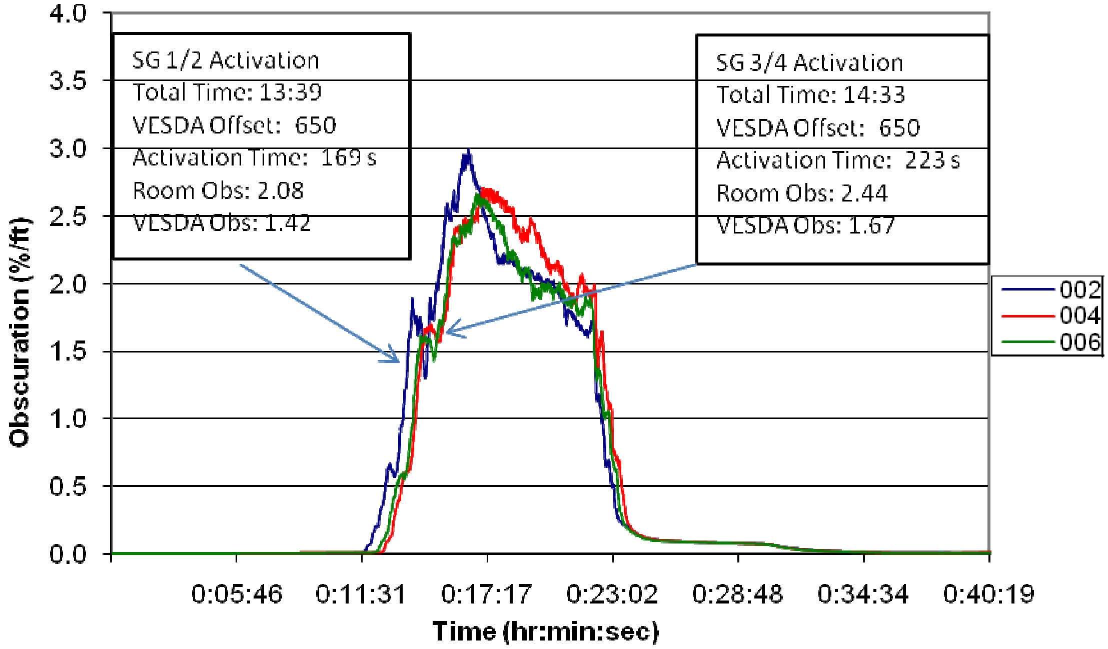

Figure 6-4: VESDA Obscuration vs. Time for Test #75. Flaming PU Foam/Microfiber Fabric at 0 ACH

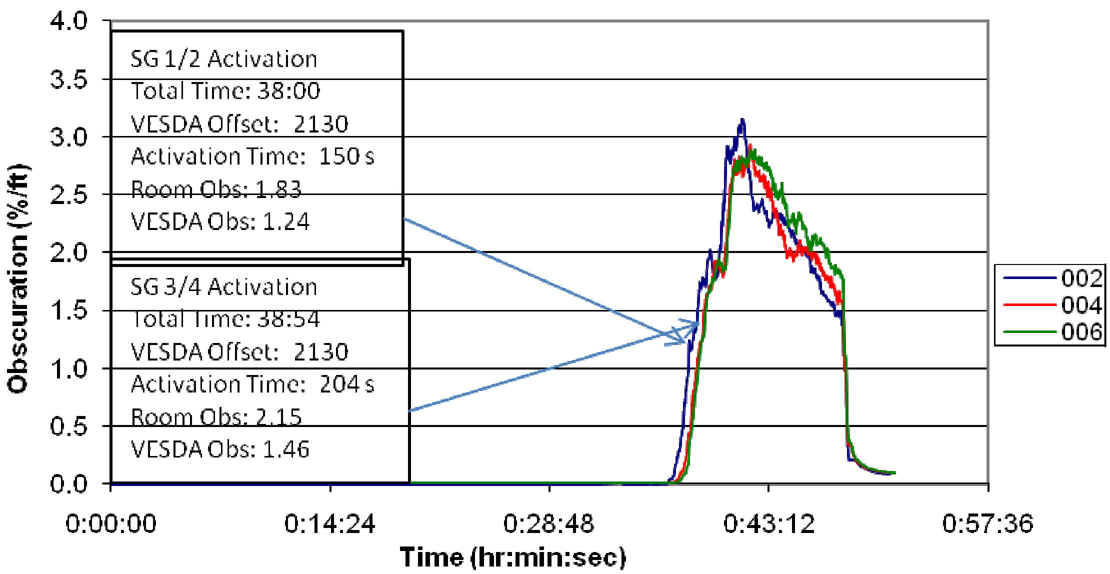

Figure 6-5: VESDA Obscuration vs. Time for Test #76. Flaming PU Foam/Microfiber Fabric at 0 ACH

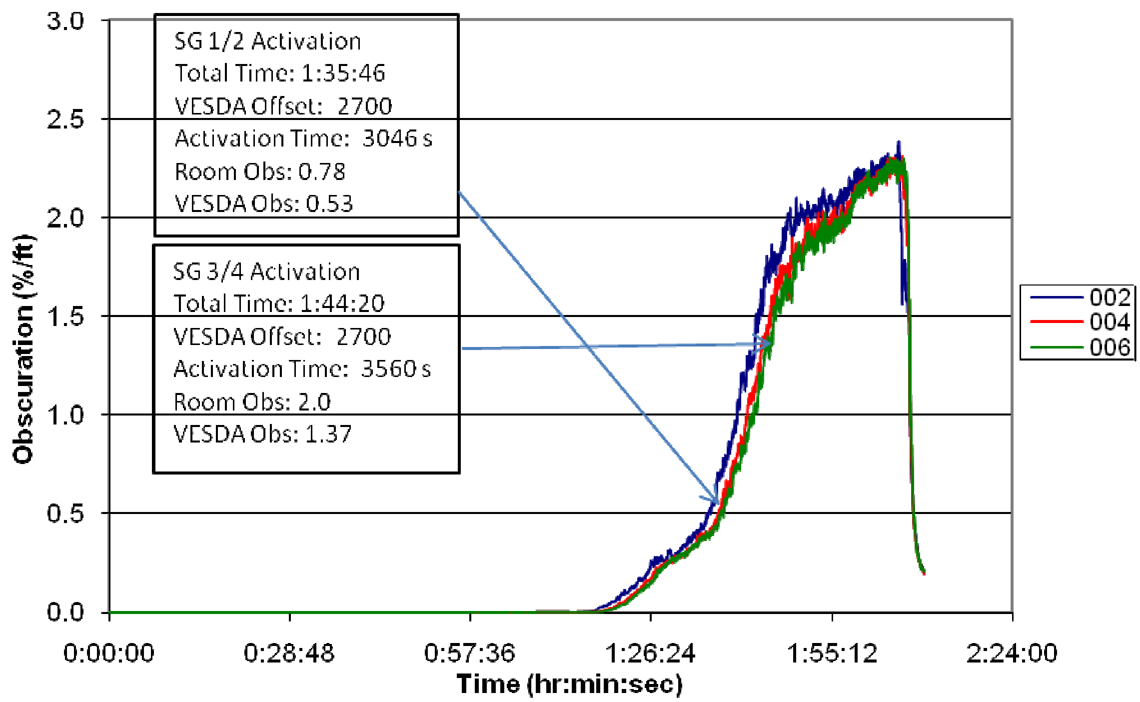

Figure 6-6: VESDA Obscuration vs. Time for Test #77. Smoldering PU Foam/Microfiber Fabric at 0 ACH

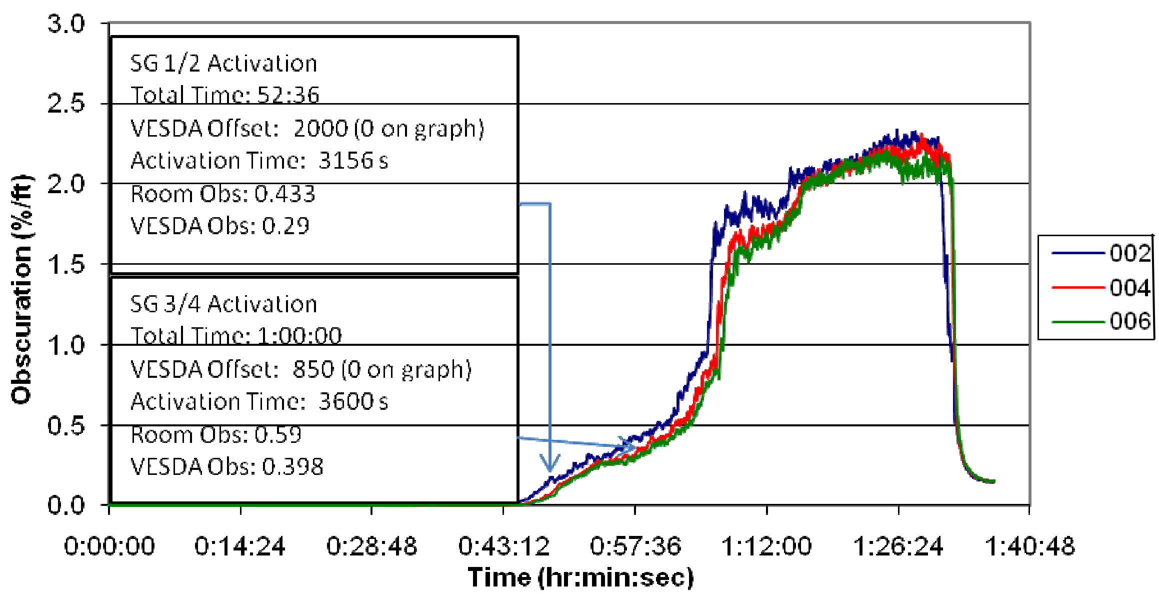

Figure 6-7: VESDA Obscuration vs. Time for Test #78. Smoldering PU Foam/Microfiber Fabric at 0 ACH

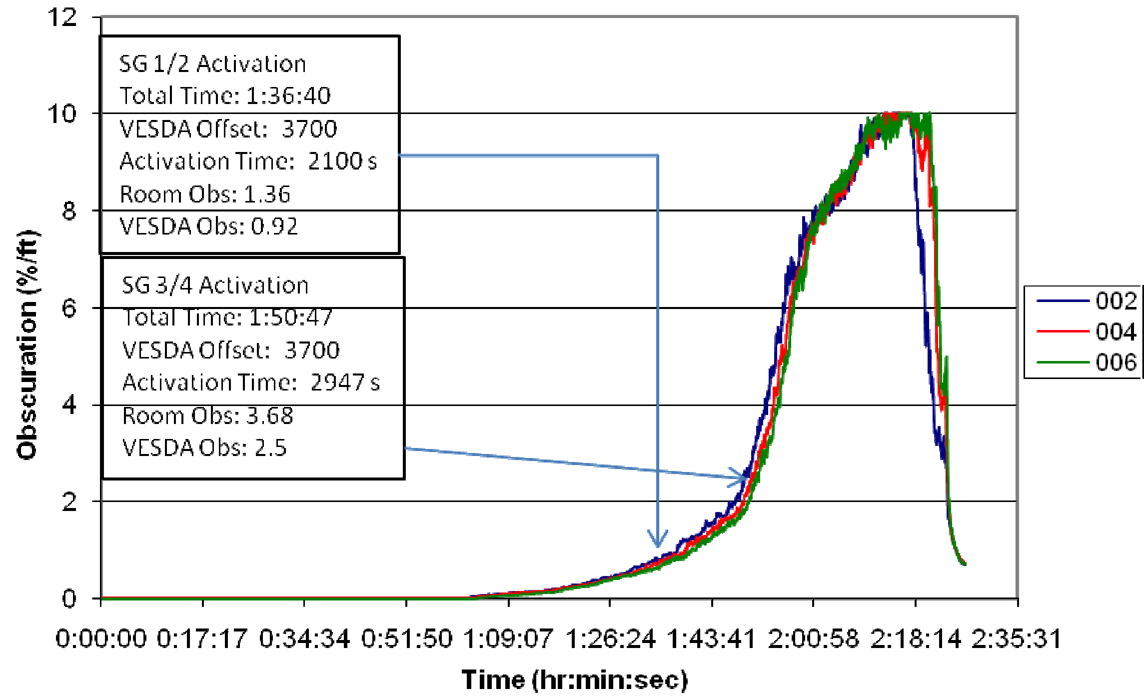

Figure 6-8: VESDA Obscuration vs. Time for Test #79. Ponderosa Pine at 0 ACH

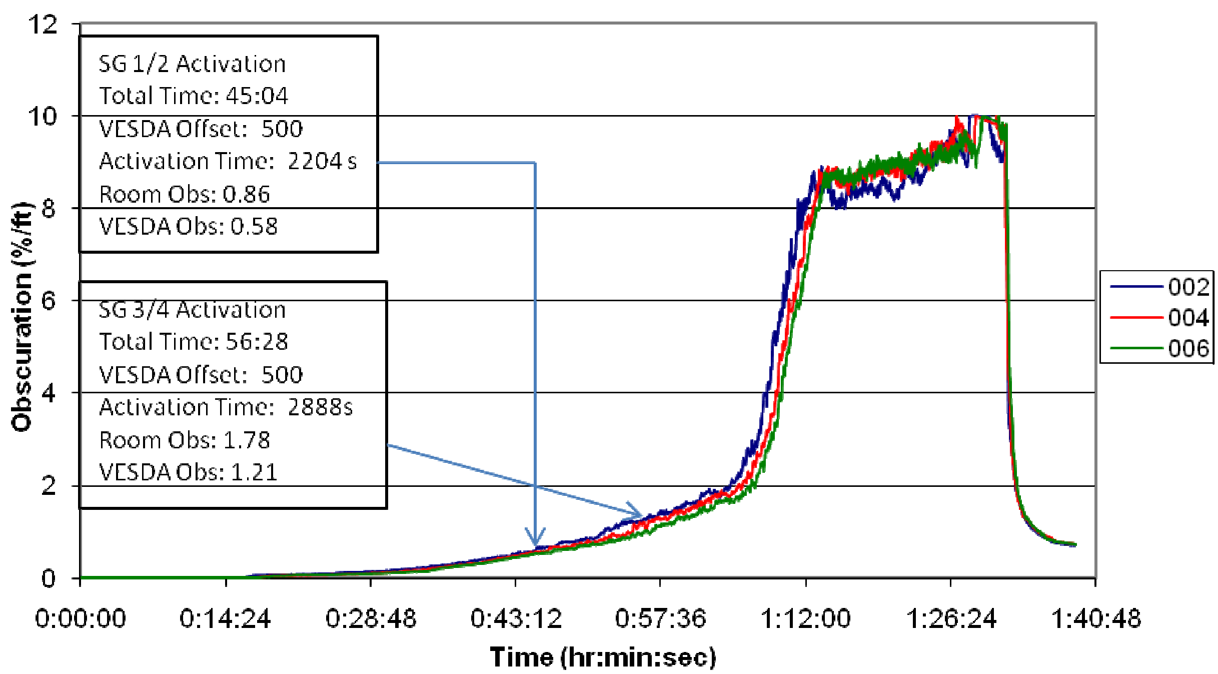

Figure 6-9: VESDA Obscuration vs. Time for Test #80. Ponderosa Pine at 0 ACH

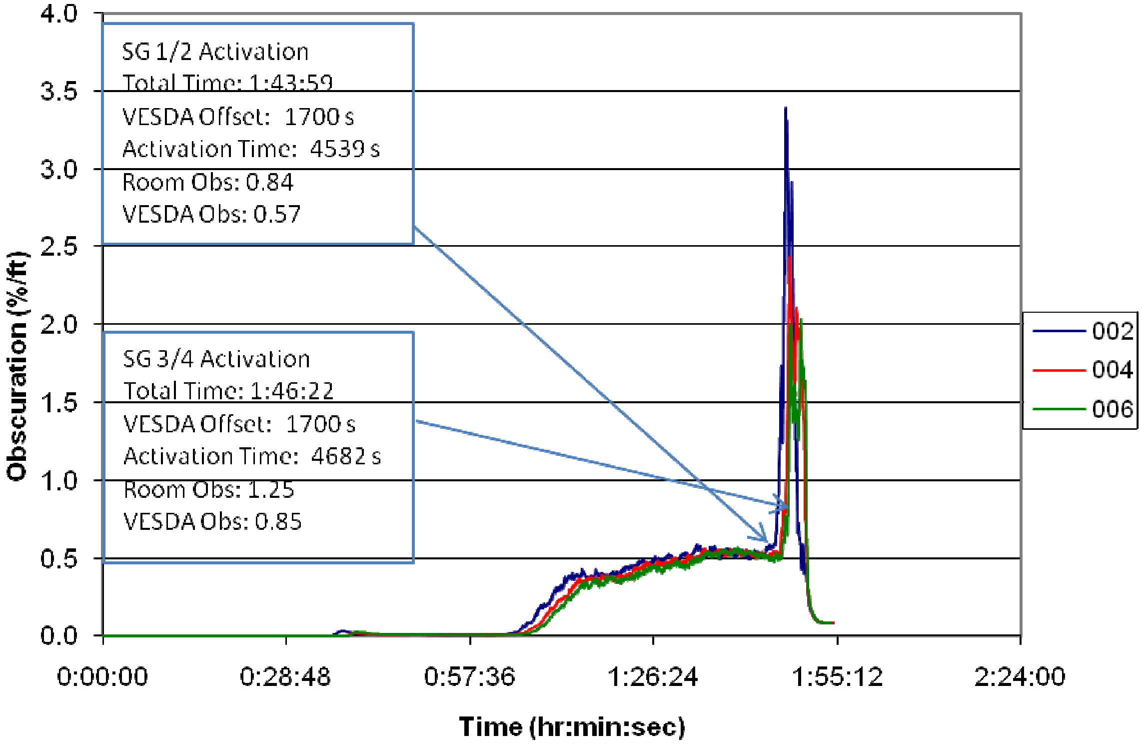

Figure 6-10: VESDA Obscuration vs. Time for Test #82. Cotton Linen Fabric at 0 ACH

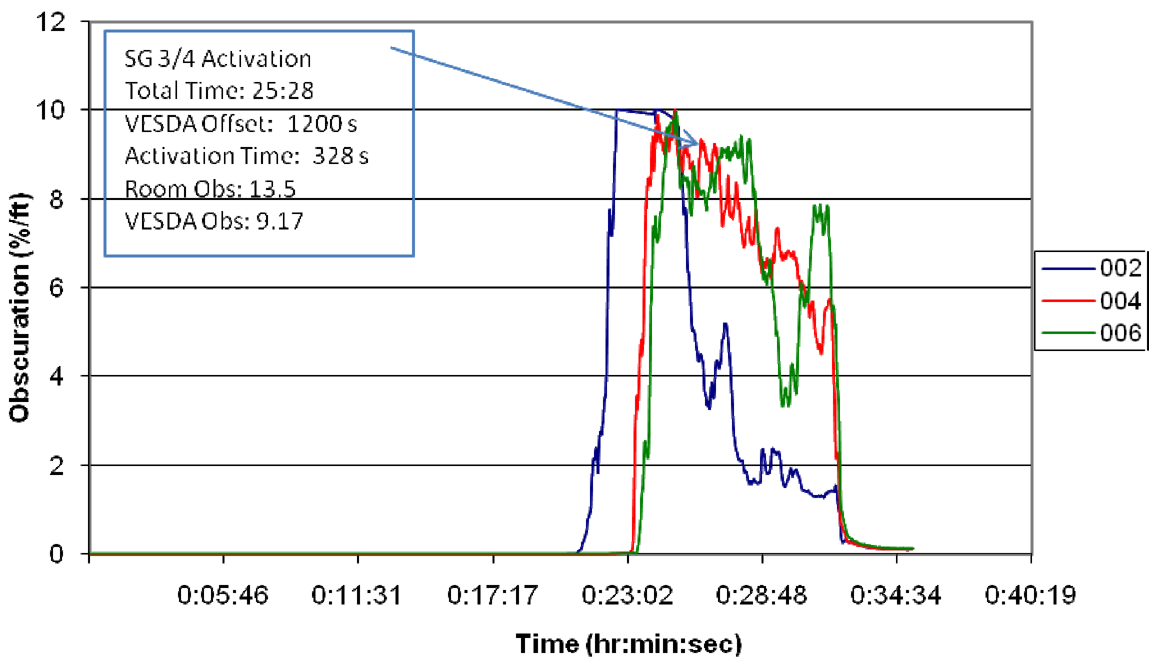

Figure 6-11: VESDA Obscuration vs. Time for Test #85. Computer Case at 0 ACH

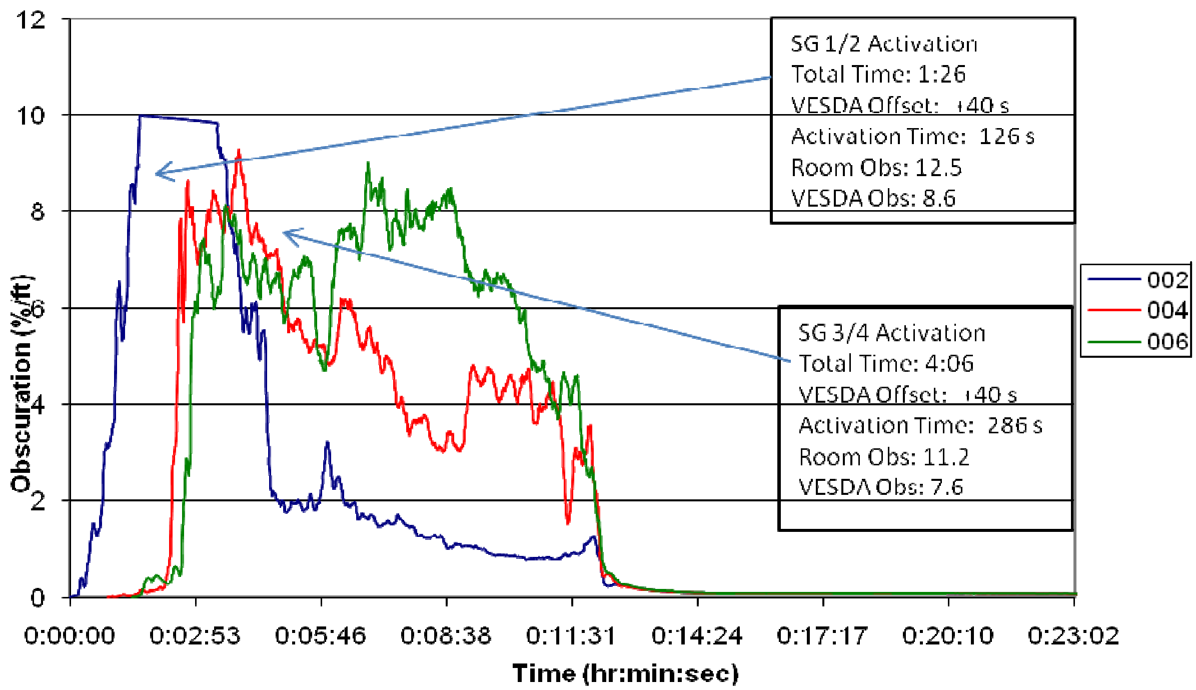

Figure 6-12: VESDA Obscuration vs. Time for Test #86. Computer Case at 0 ACH

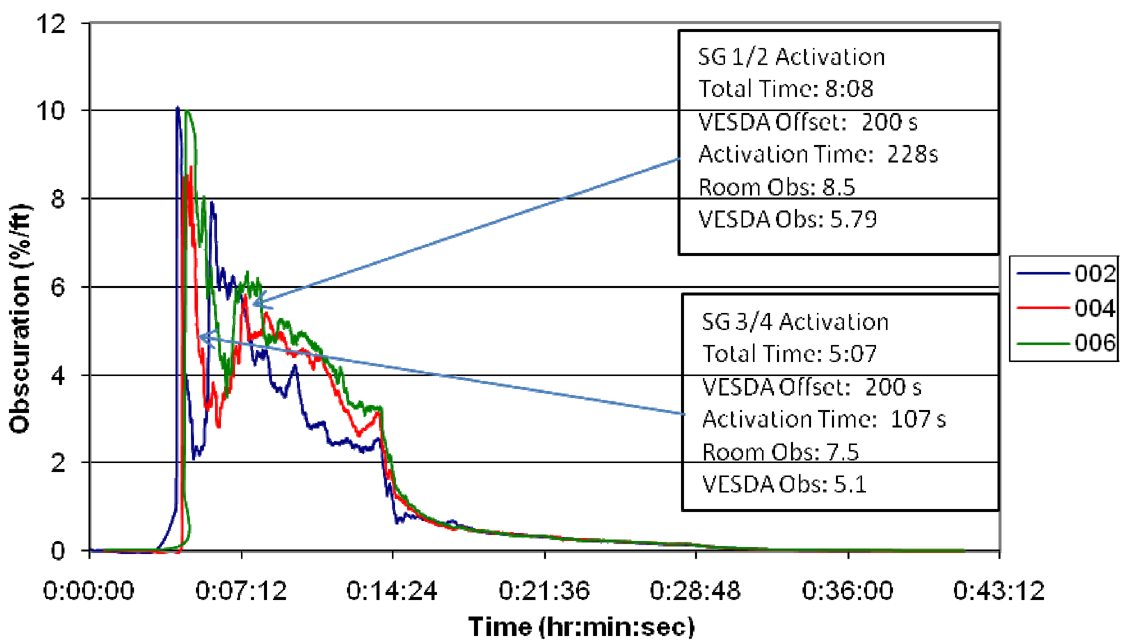

Figure 6-13: VESDA Obscuration vs. Time for Test #87. Printed Circuit Board at 0 ACH

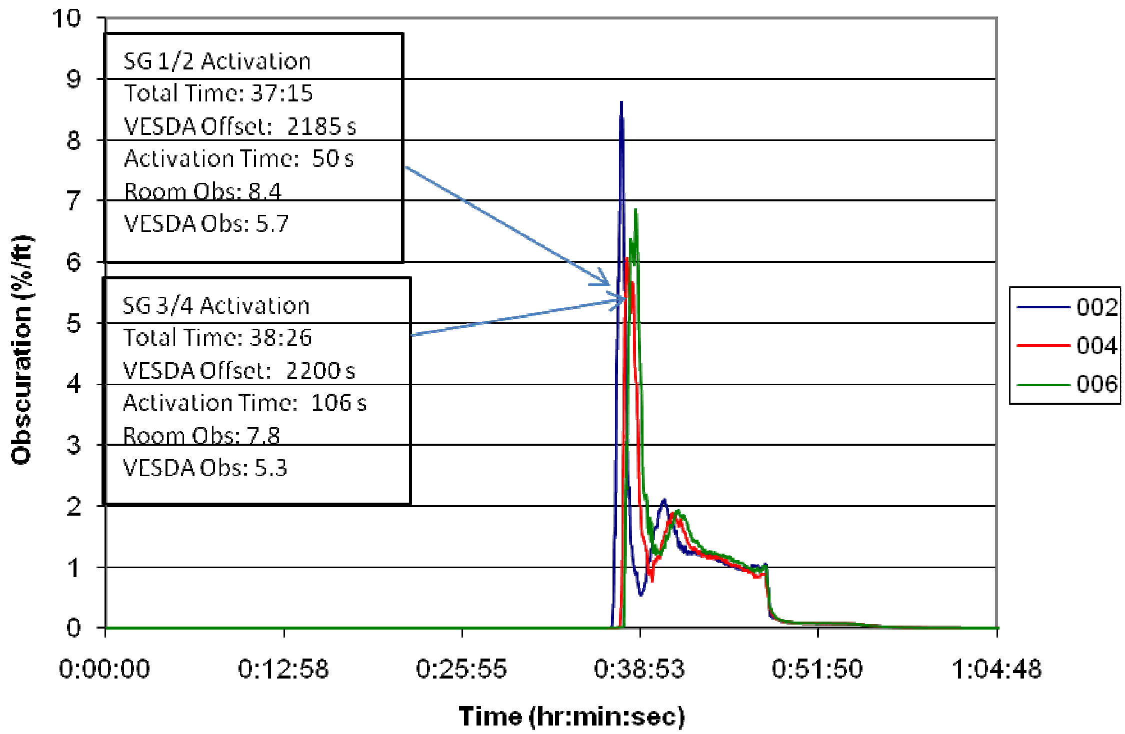

Figure 6-14: VESDA Obscuration vs. Time for Test #88. Printed Circuit Board at 0 ACH

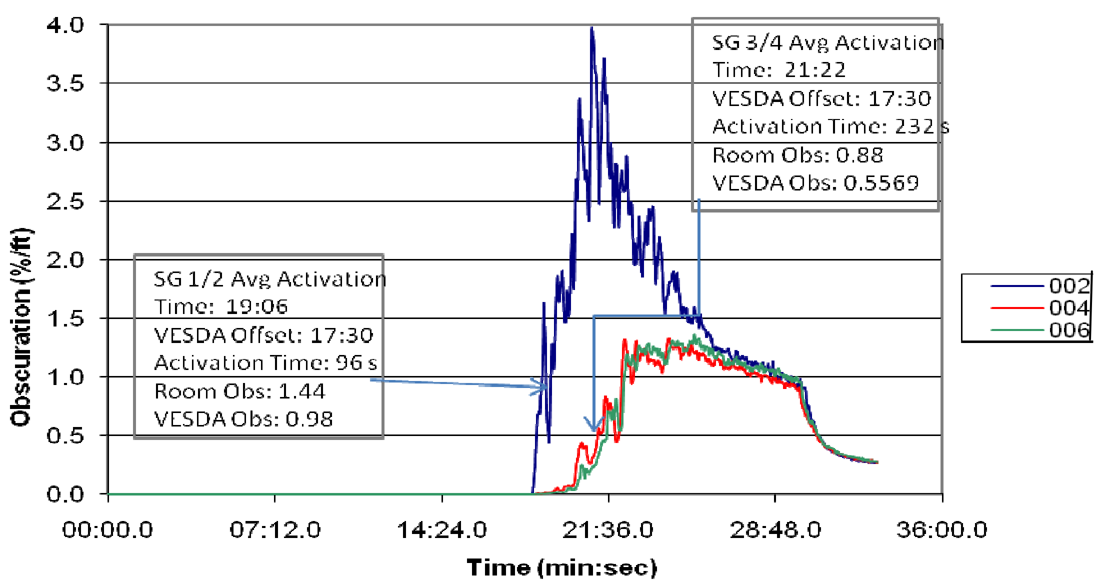

Figure 6-15: VESDA Obscuration vs. Time for Test #25. Shredded Office Paper at 6 ACH

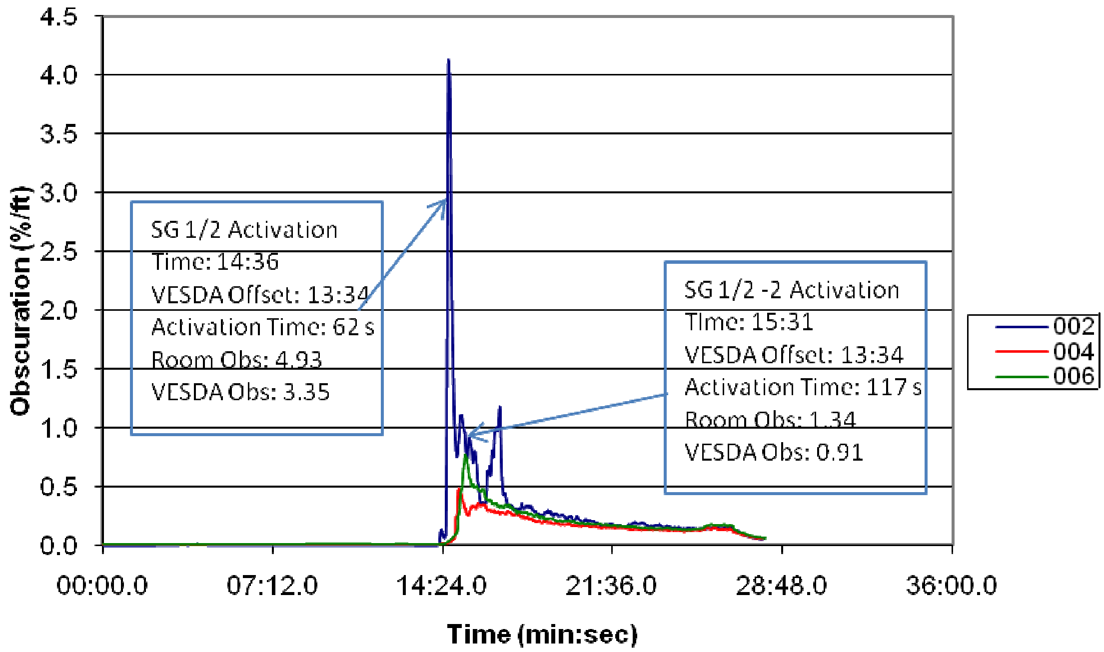

Figure 6-16: VESDA Obscuration vs. Time for Test #26. Shredded Office Paper at 6 ACH

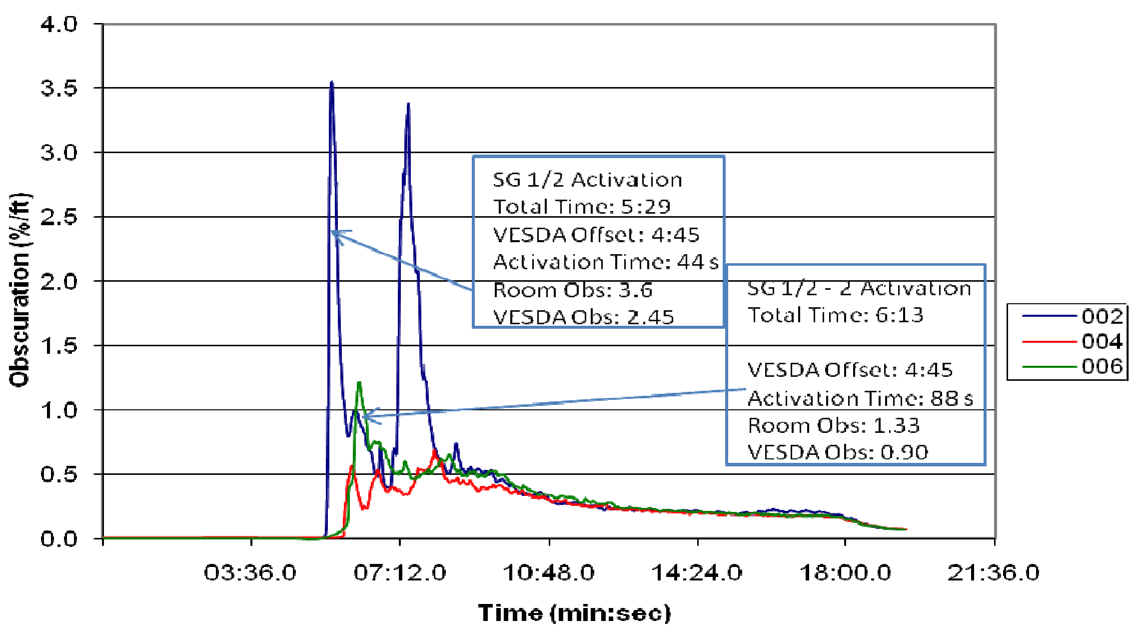

Figure 6-17: VESDA Obscuration vs. Time for Test #27. Shredded Office Paper at 6 ACH

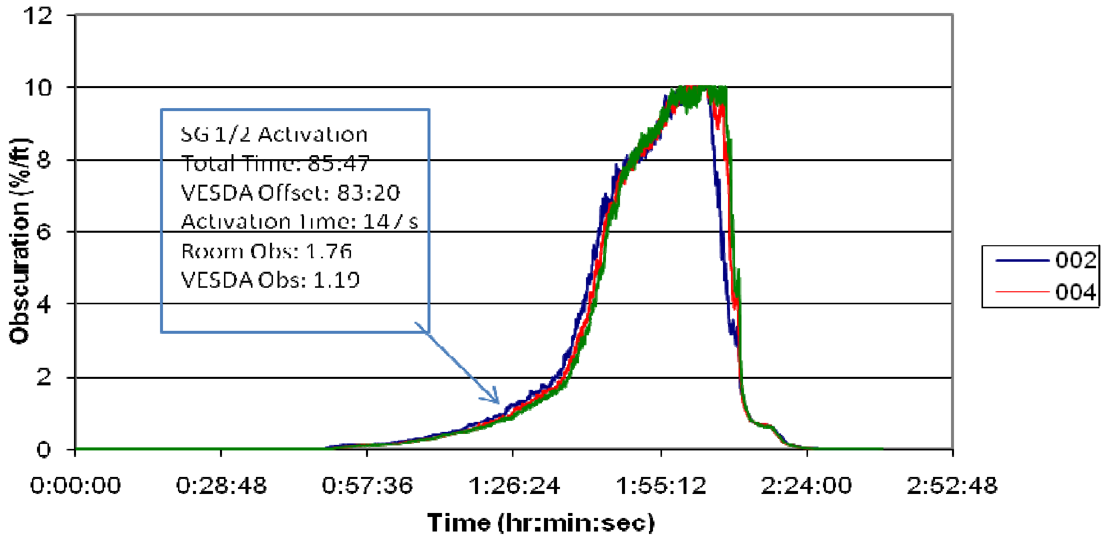

Figure 6-18: VESDA Obscuration vs. Time for Test #28. Flaming PU Foam/Microfiber Fabric at 6 ACH

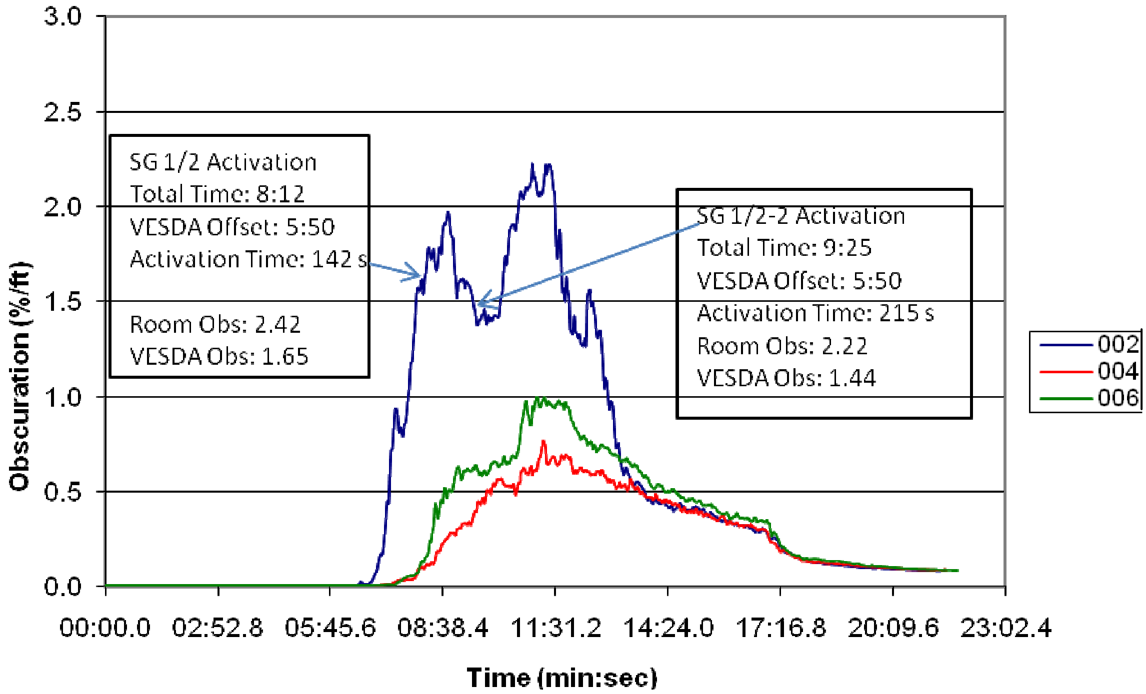

Figure 6-19: VESDA Obscuration vs. Time for Test #29. Flaming PU Foam/Microfiber Fabric at 6 ACH

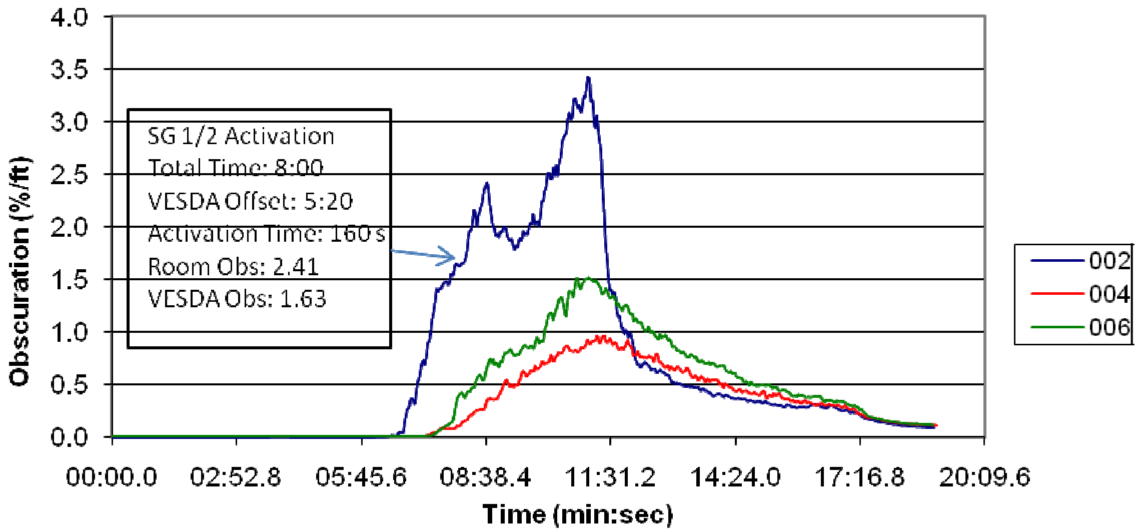

Figure 6-20: VESDA Obscuration vs. Time for Test #30. Flaming PU Foam/Microfiber Fabric at 6 ACH

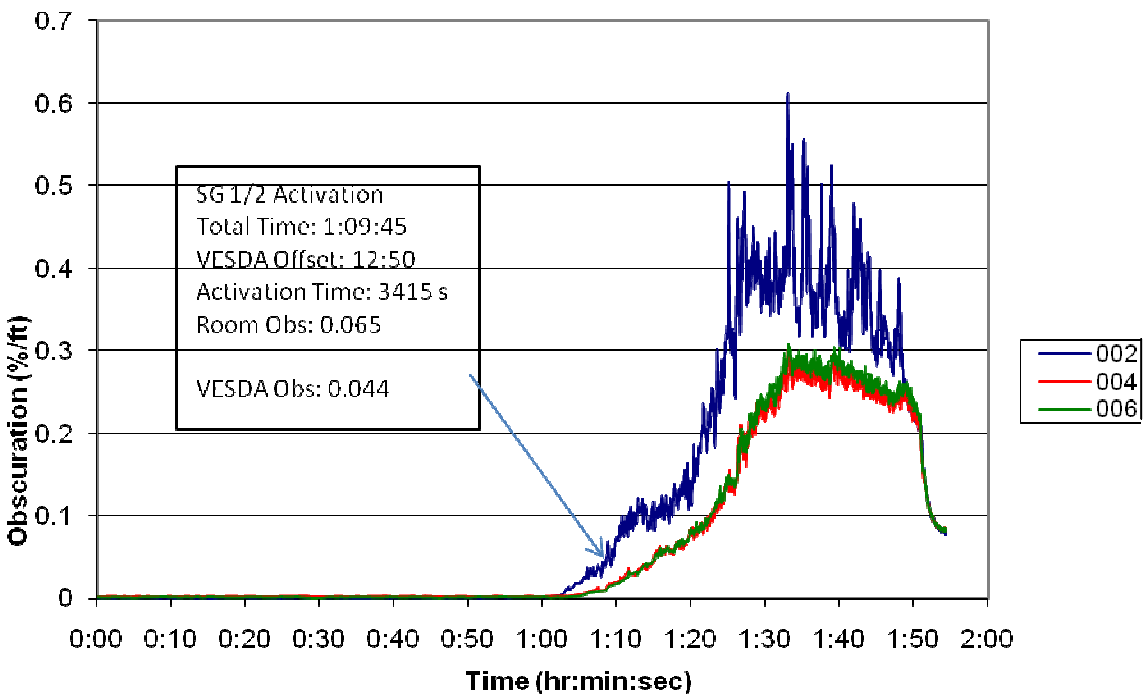

Figure 6-21: VESDA Obscuration vs. Time for Test #31. Smoldering PU Foam/Microfiber Fabric at 6 ACH

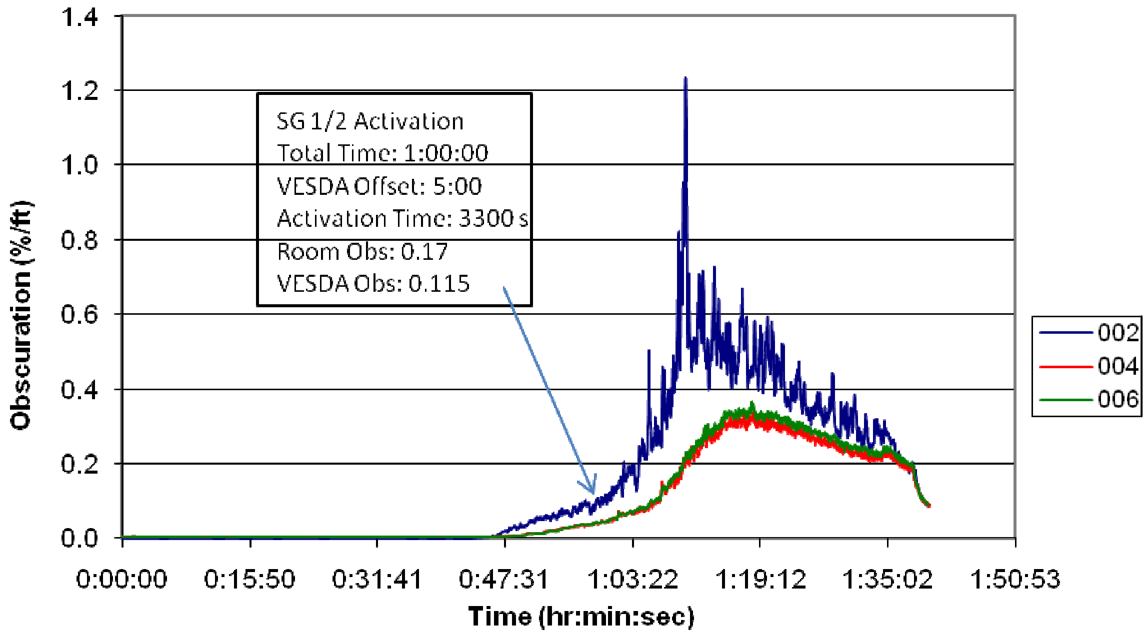

Figure 6-22: VESDA Obscuration vs. Time for Test #32. Smoldering PU Foam/Microfiber Fabric at 6 ACH

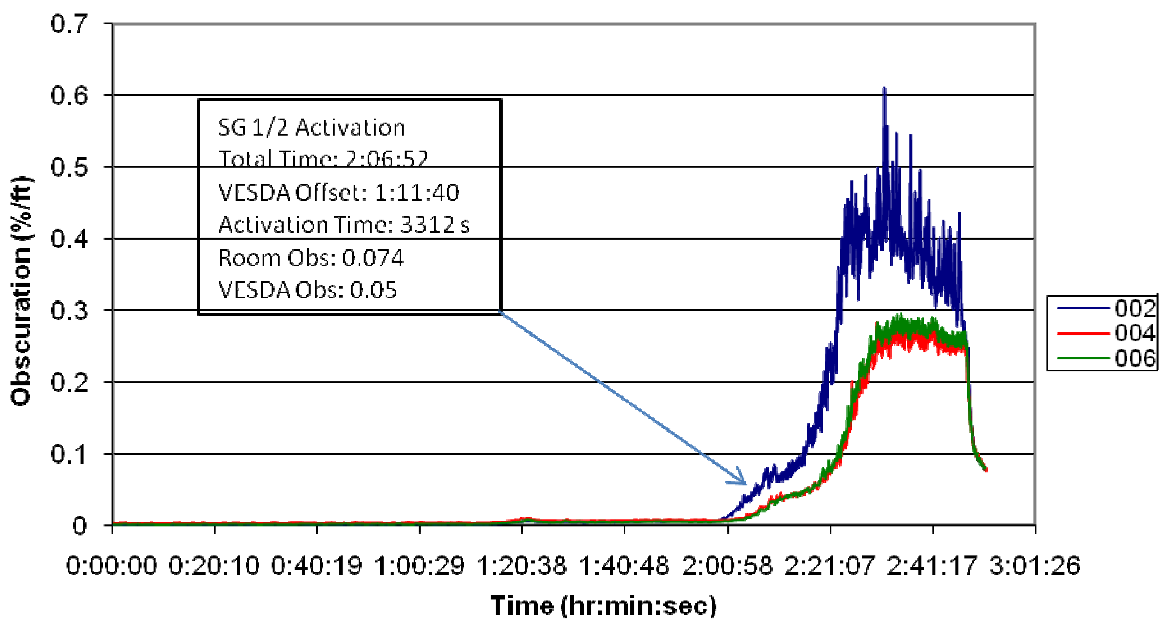

Figure 6-23: VESDA Obscuration vs. Time for Test #33. Smoldering PU Foam/Microfiber Fabric at 6 ACH

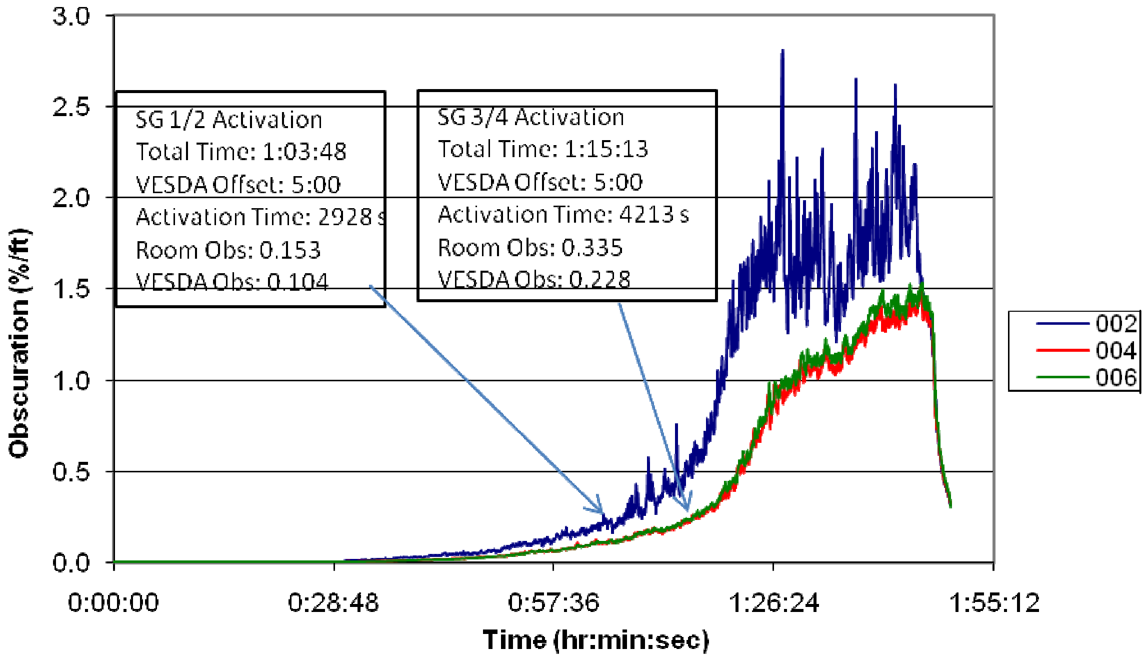

Figure 6-24: VESDA Obscuration vs. Time for Test #34. Ponderosa Pine at 6 ACH

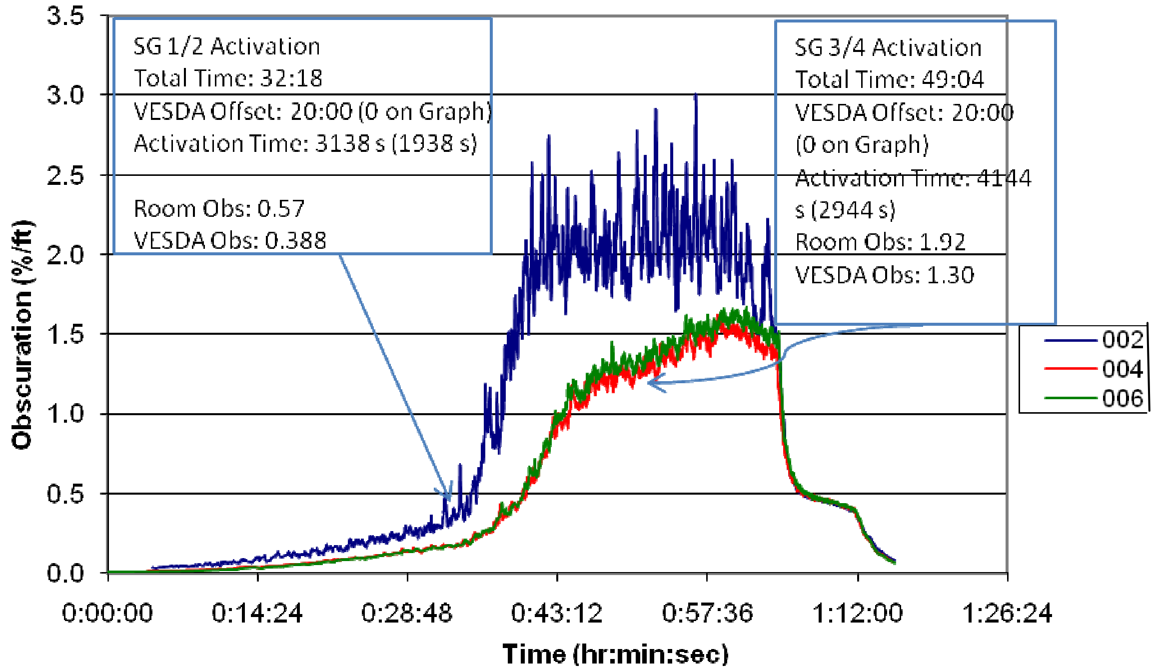

Figure 6-25: VESDA Obscuration vs. Time for Test #35. Ponderosa Pine at 6 ACH

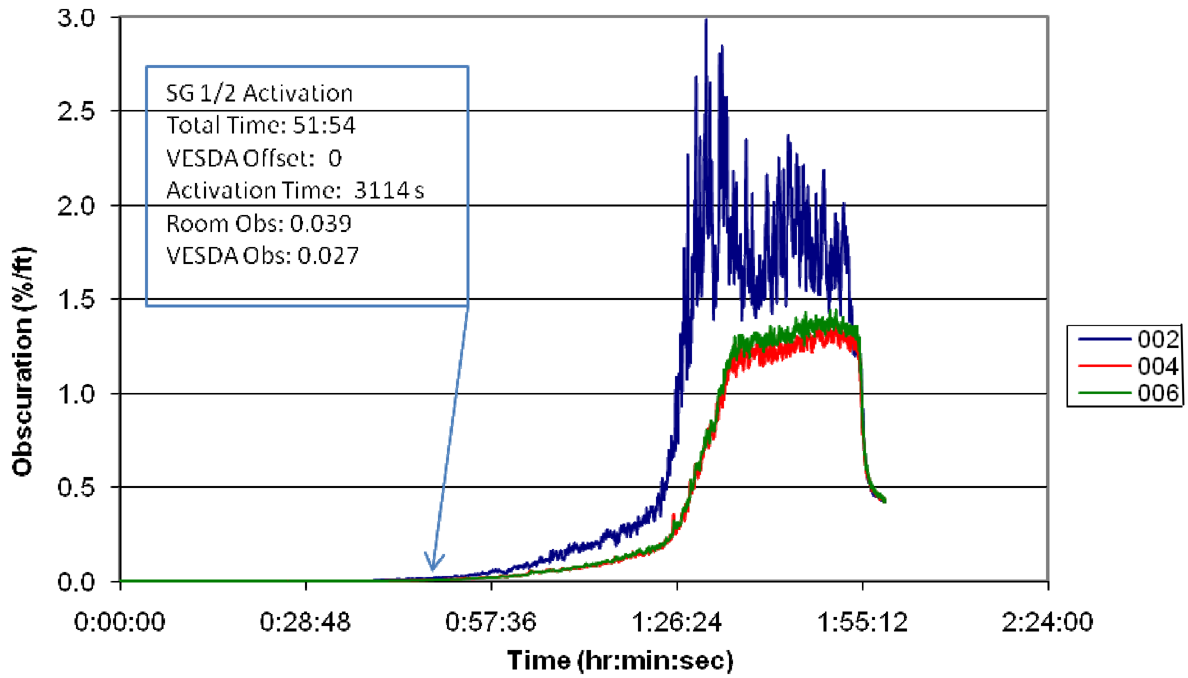

Figure 6-26: VESDA Obscuration vs. Time for Test #36. Ponderosa Pine at 6 ACH

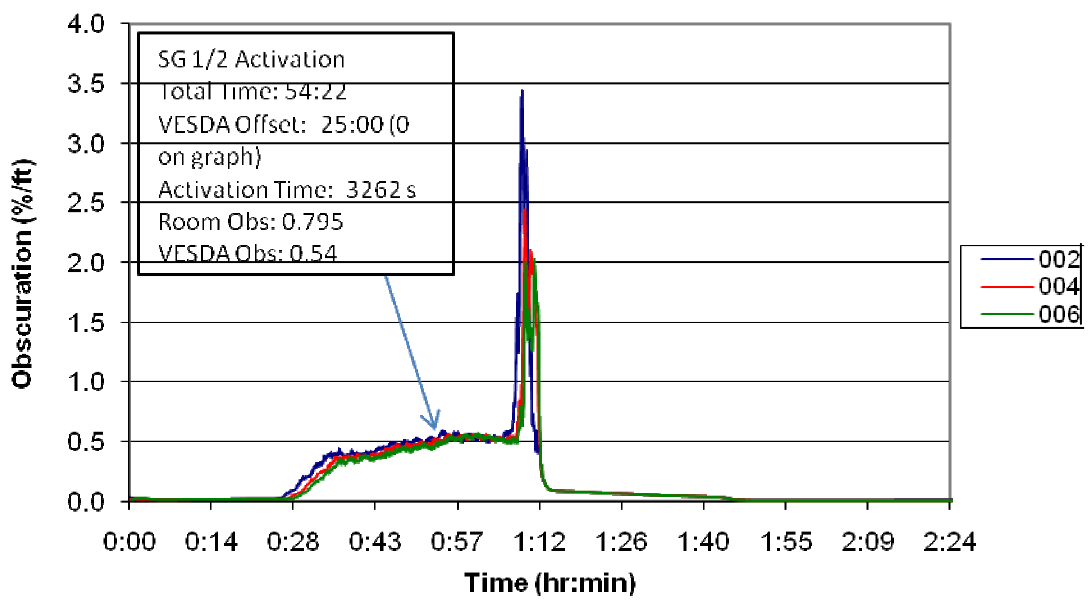

Figure 6-27: VESDA Obscuration vs. Time for Test #37. Cotton Linen Fabric at 6 ACH

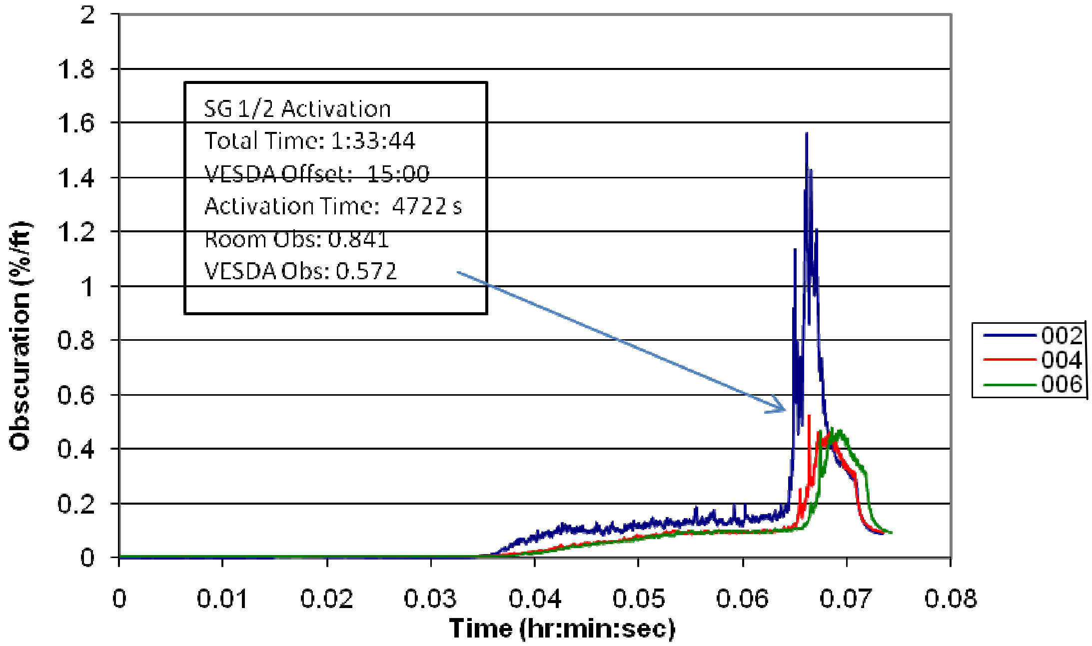

Figure 6-28: VESDA Obscuration vs. Time for Test #39. Cotton Linen Fabric at 6 ACH

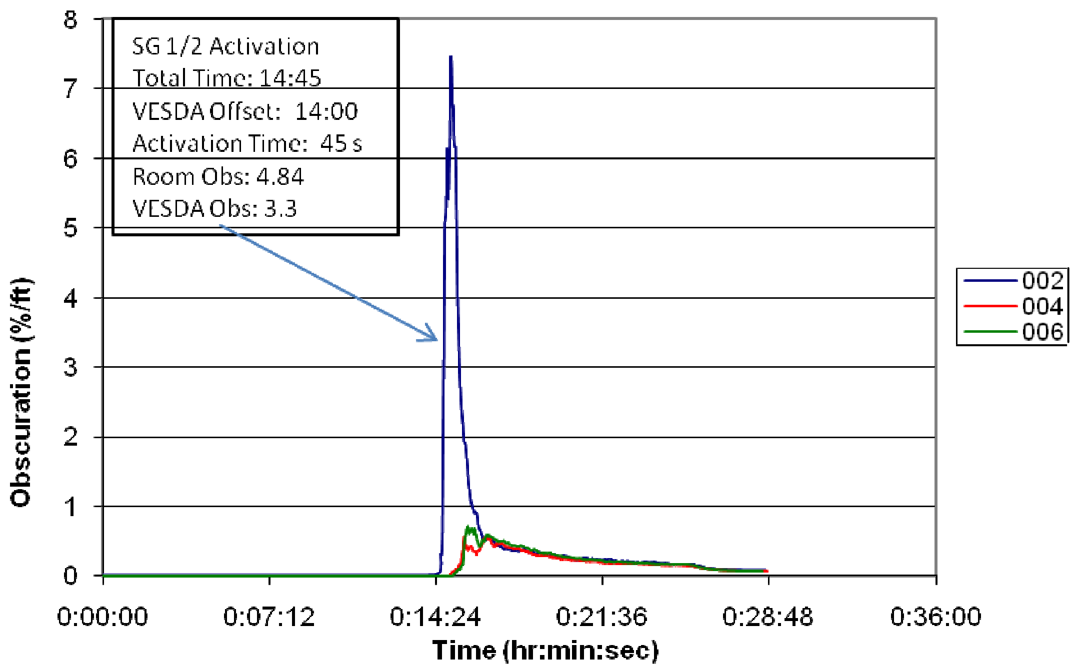

Figure 6-29: VESDA Obscuration vs. Time for Test #46. Printed Circuit Board at 6 ACH

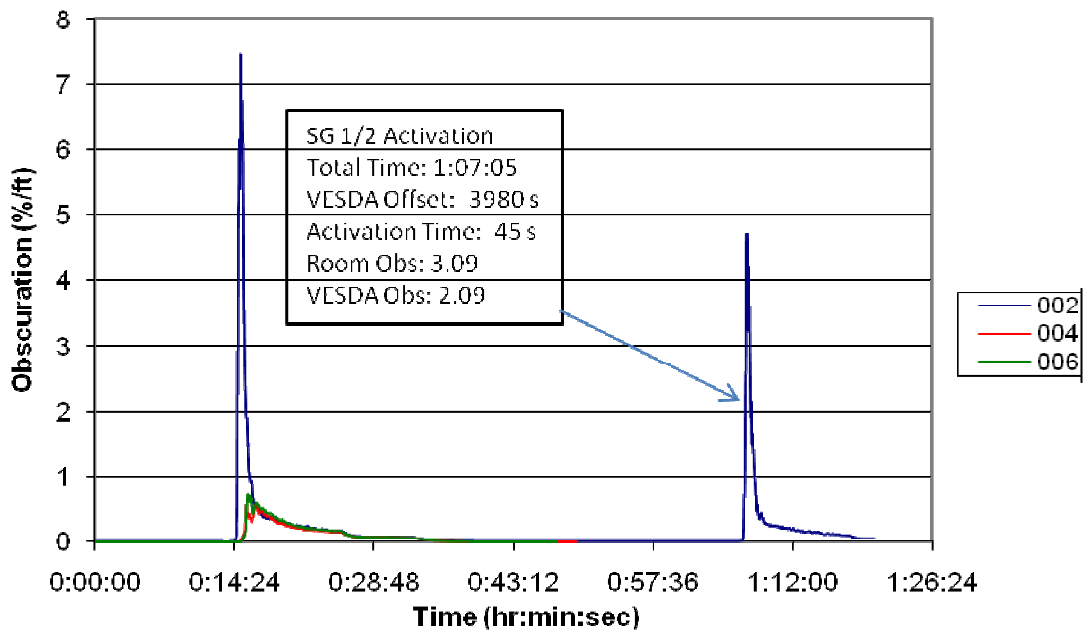

Figure 6-30: VESDA Obscuration vs. Time for Test #47. Printed Circuit Board at 6 ACH

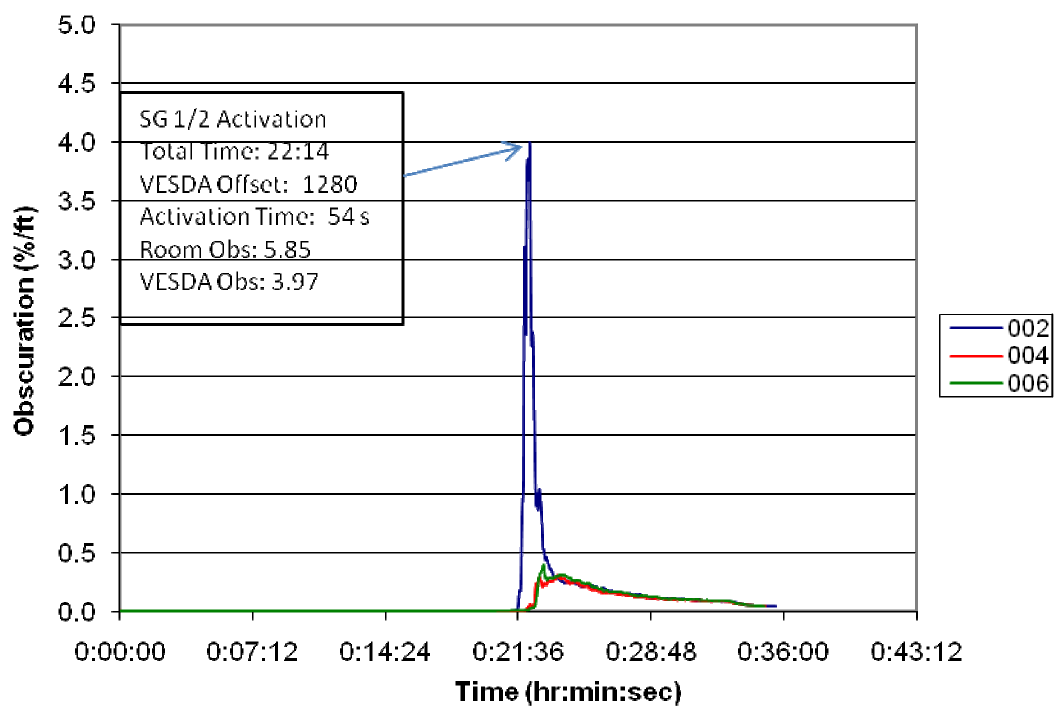

Figure 6-31: VESDA Obscuration vs. Time for Test #48. Printed Circuit Board at 6 ACH

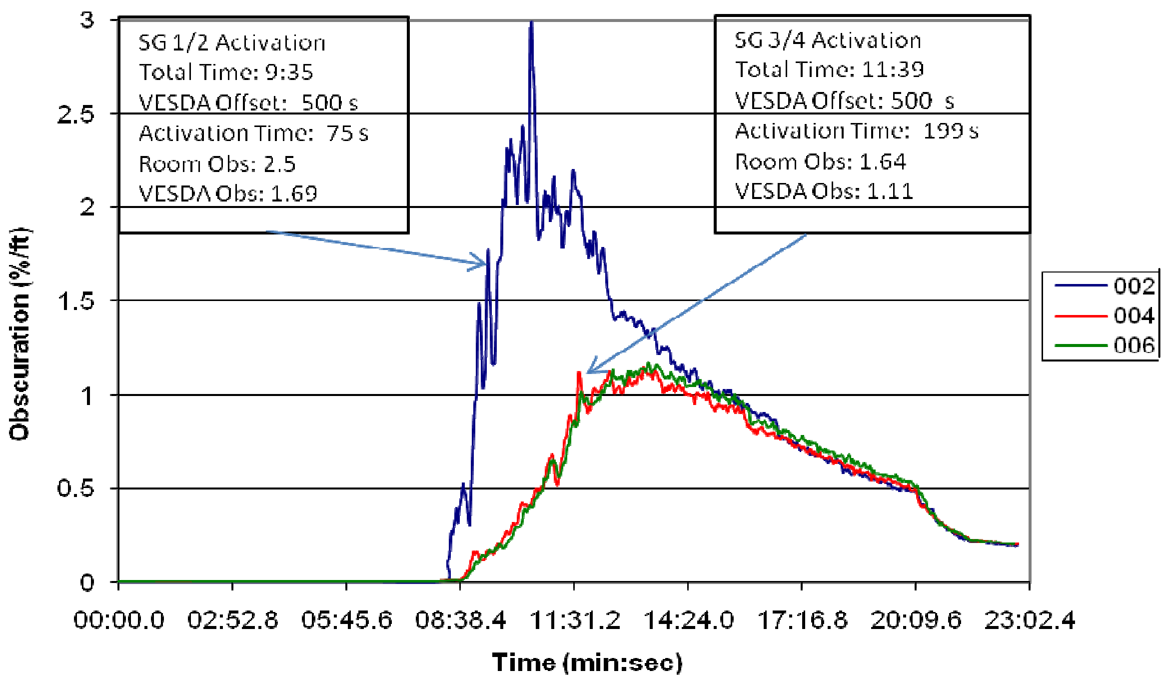

Figure 6-32: VESDA Obscuration vs. Time for Test #51. Shredded Office Paper at 12 ACH

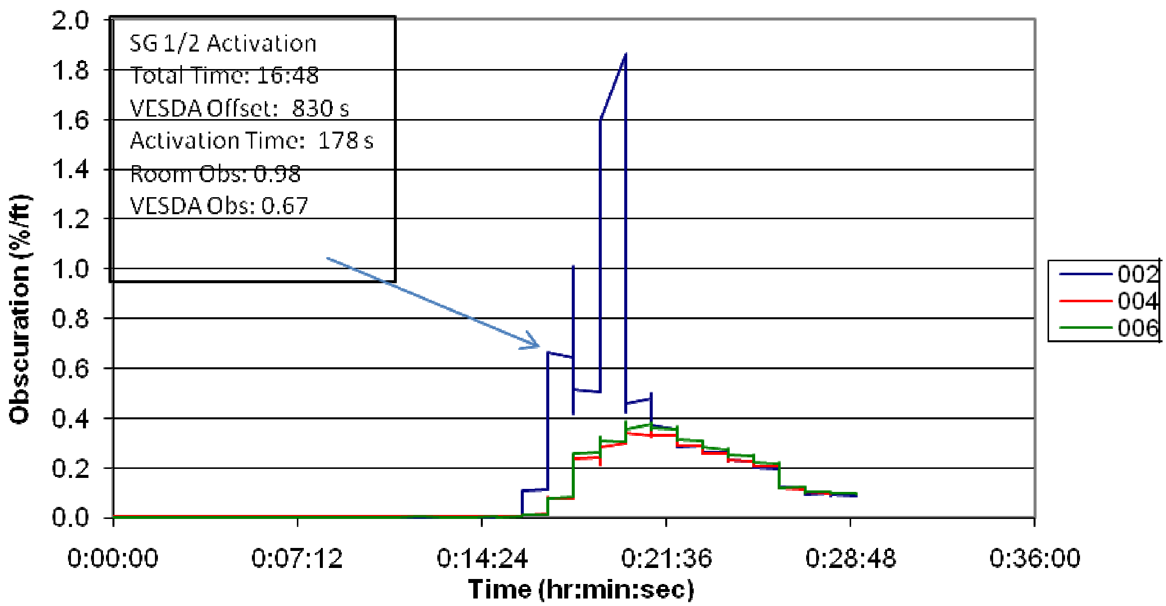

Figure 6-33: VESDA Obscuration vs. Time for Test #52. Flaming PU Foam/Microfiber Fabric at 12 ACH

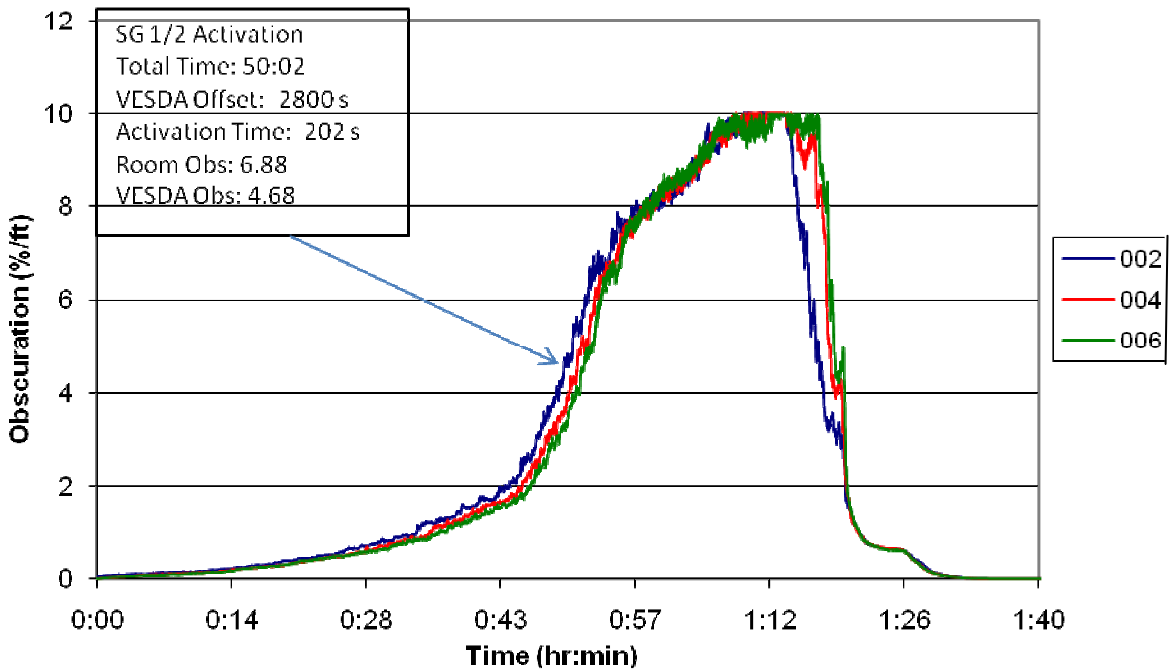

Figure 6-34: VESDA Obscuration vs. Time for Test #53. Flaming PU Foam/Microfiber Fabric at 12 ACH

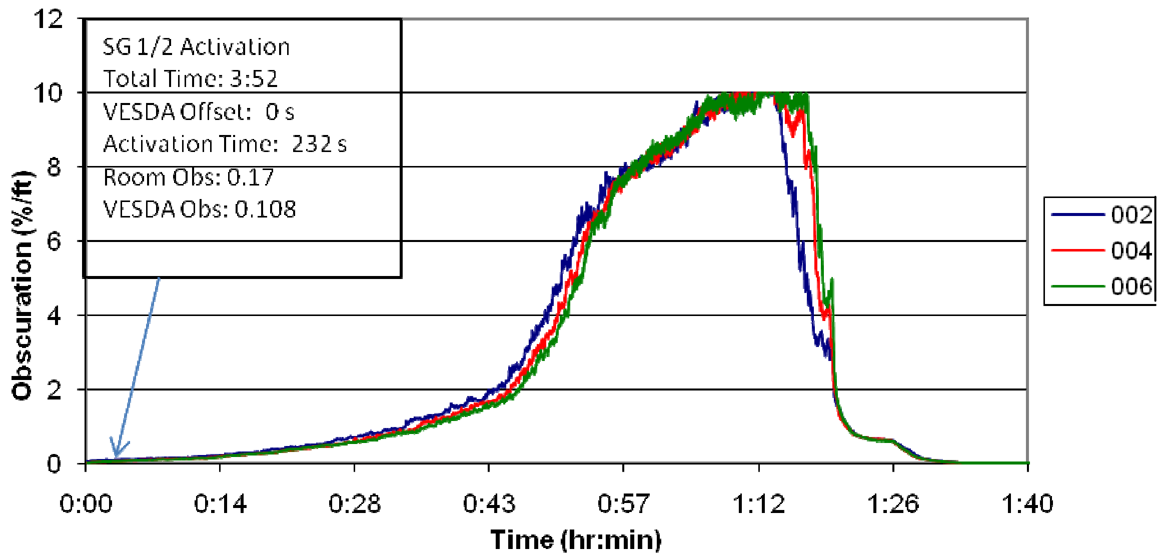

Figure 6-35: VESDA Obscuration vs. Time for Test #54. Flaming PU Foam/Microfiber Fabric at 12 ACH

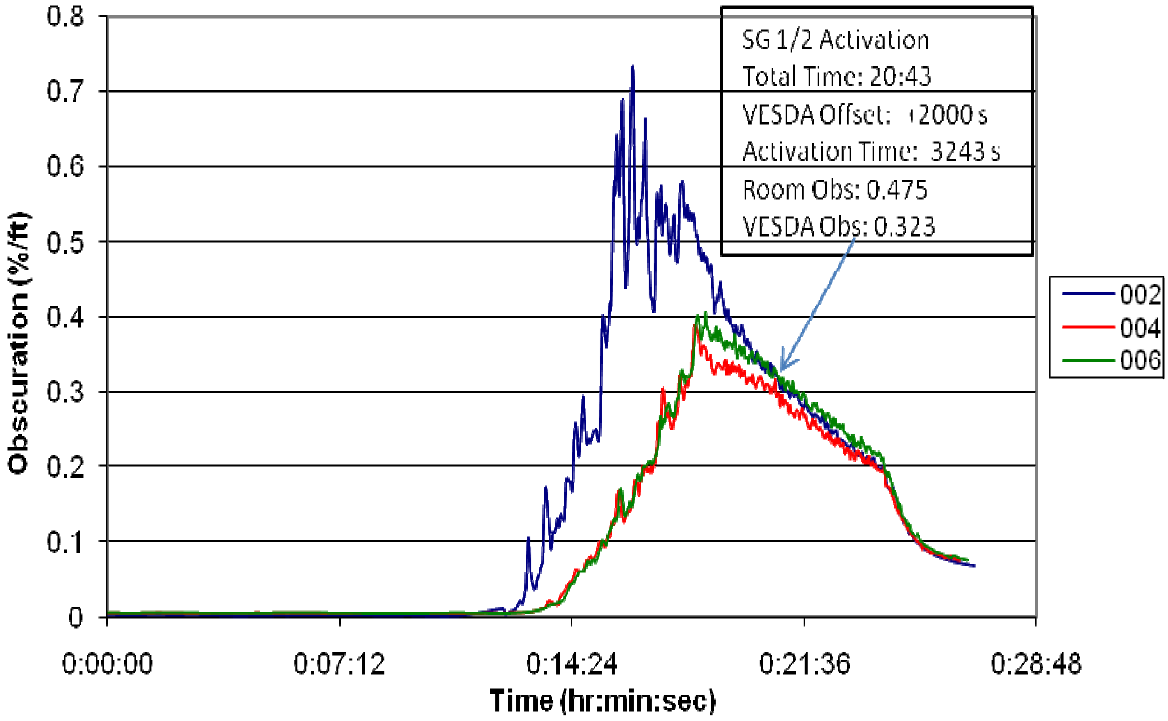

Figure 6-36: VESDA Obscuration vs. Time for Test #55. Smoldering PU Foam/Microfiber Fabric at 12 ACH

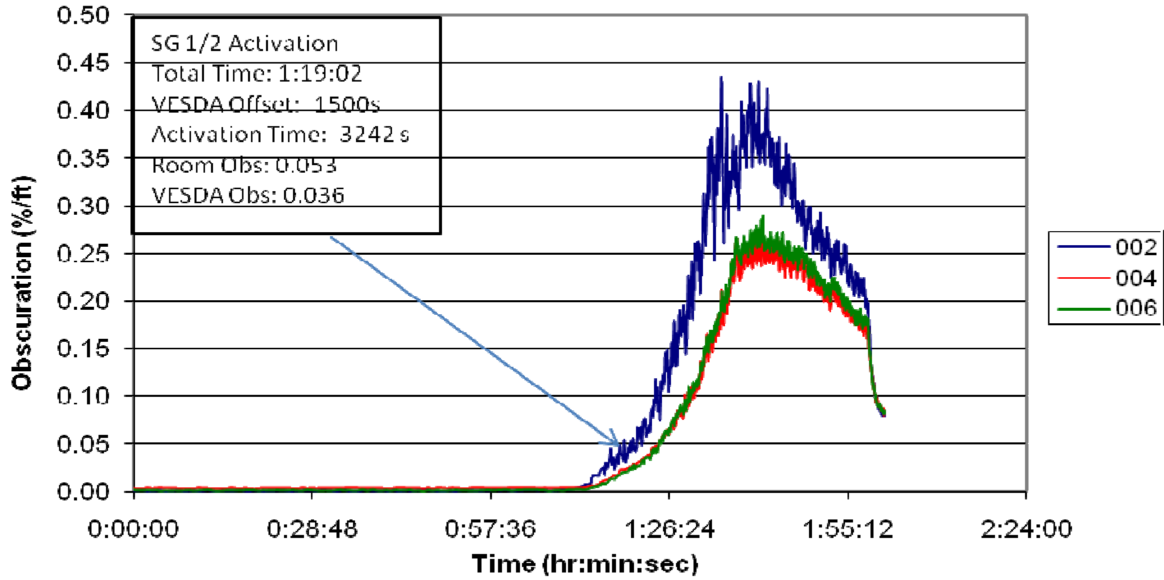

Figure 6-37: VESDA Obscuration vs. Time for Test #56. Smoldering PU Foam/Microfiber Fabric at 12 ACH

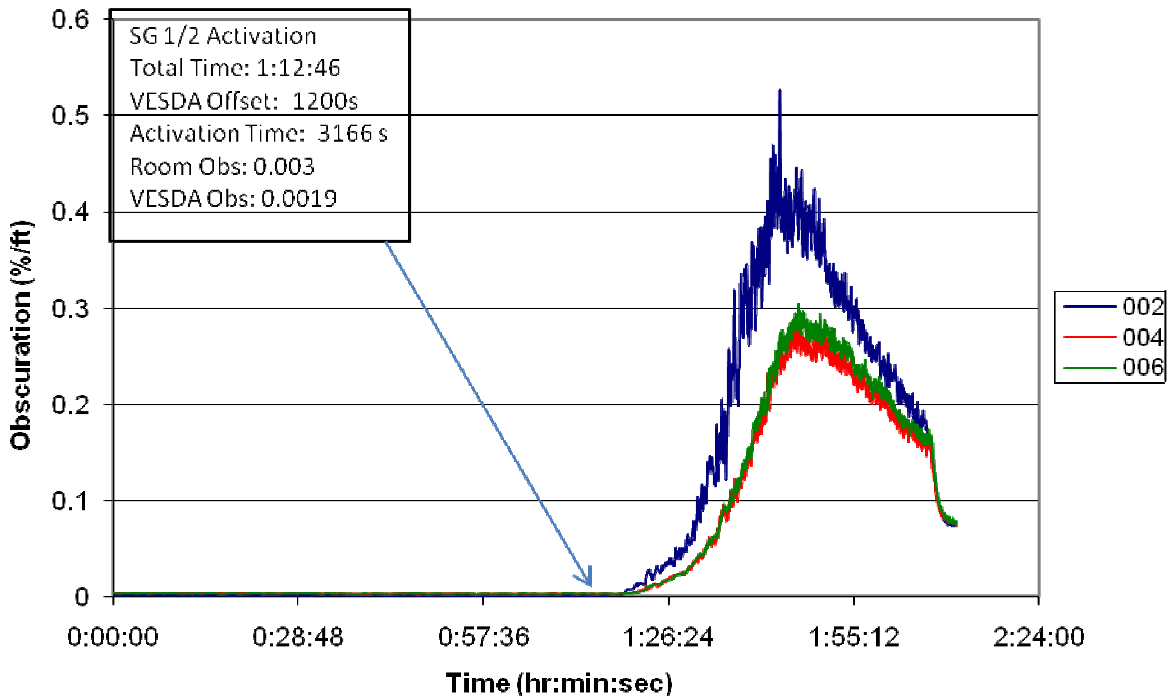

Figure 6-38: VESDA Obscuration vs. Time for Test #57. Smoldering PU Foam/MF Fabric at 12 ACH

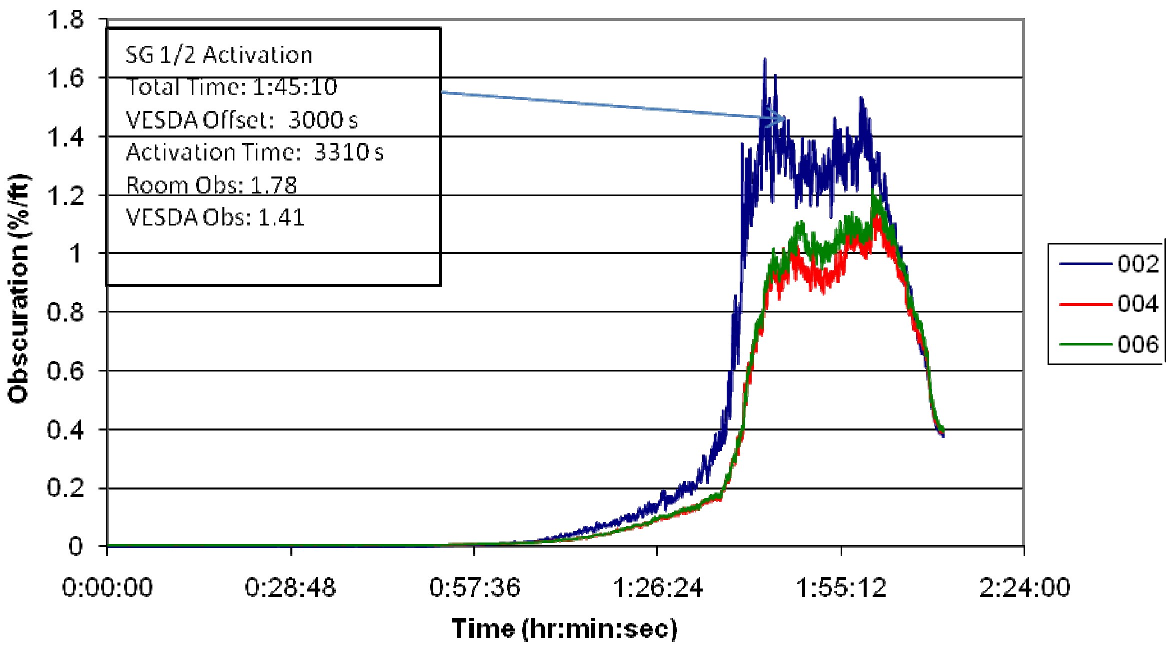

Figure 6-39: VESDA Obscuration vs. Time for Test #58. Ponderosa Pine at 12 ACH

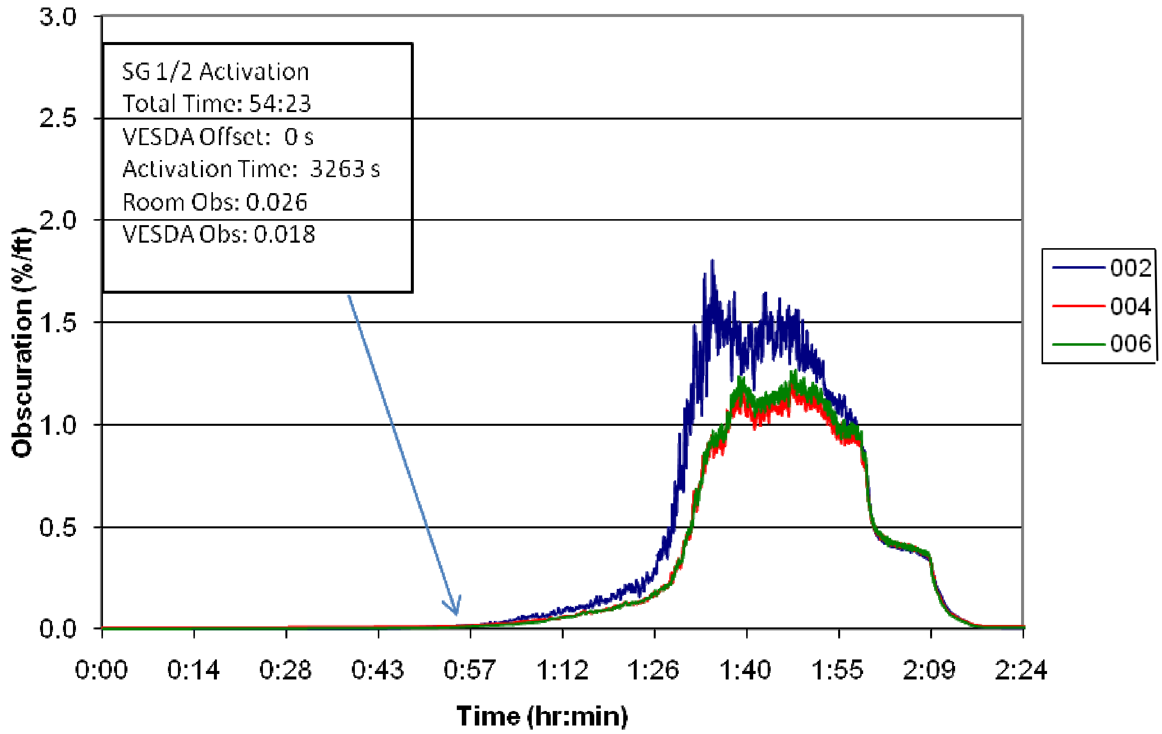

Figure 6-40: VESDA Obscuration vs. Time for Test #59. Ponderosa Pine at 12 ACH

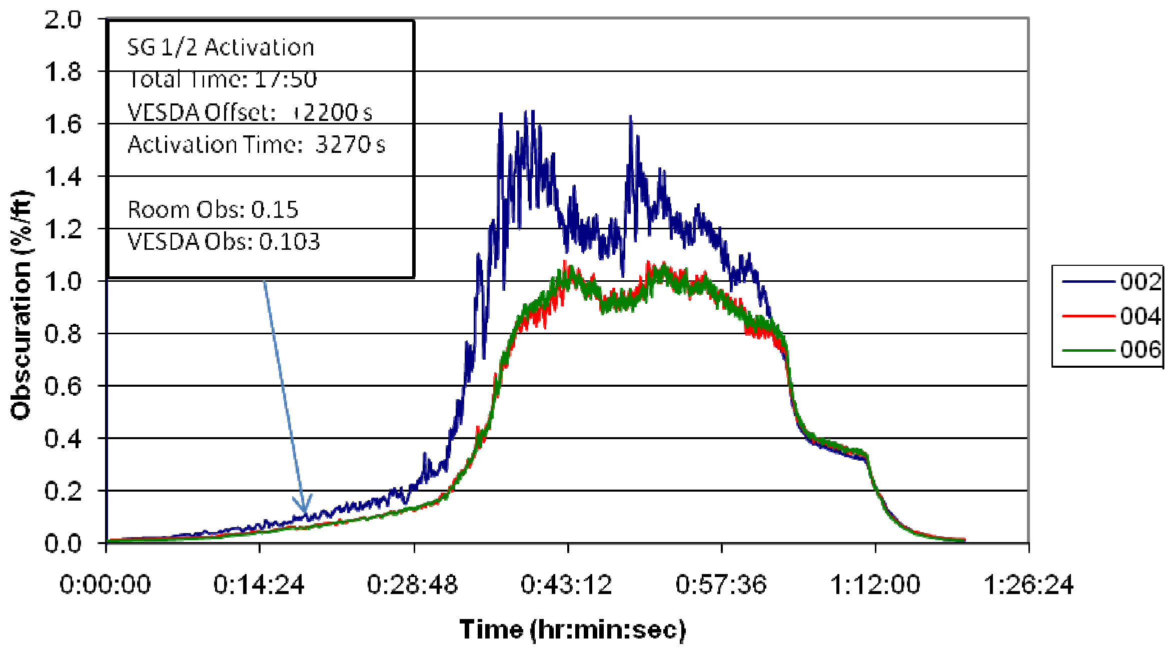

Figure 6-41: VESDA Obscuration vs. Time for Test #60. Ponderosa Pine at 12 ACH

Chapter 7: Results and Discussion

Part 1: Results and Accuracy of This Analysis

The results of this analysis were divided into sections to improve the clarity of this document. Each of the six figures obtained from this analysis will be displayed and followed by a discussion of the accuracy of each result. The results for the ventilated test room will be presented as follows:

-Obscuration (%/ft) for the flaming fires by test number and incipient fire source at 0, 6, and 12 air changes per hour (ACH)

-Obscuration (%/ft) for the non-flaming fires by test number and incipient fire source at 0, 6, and 12 air changes per hour (ACH)

The obscuration results for the spot photo-electric detector activation times based on aspirated smoke detector (VESDA) readings are displayed for the flaming fires by test number and incipient fire source at 0 ACH in Figure 7-1.

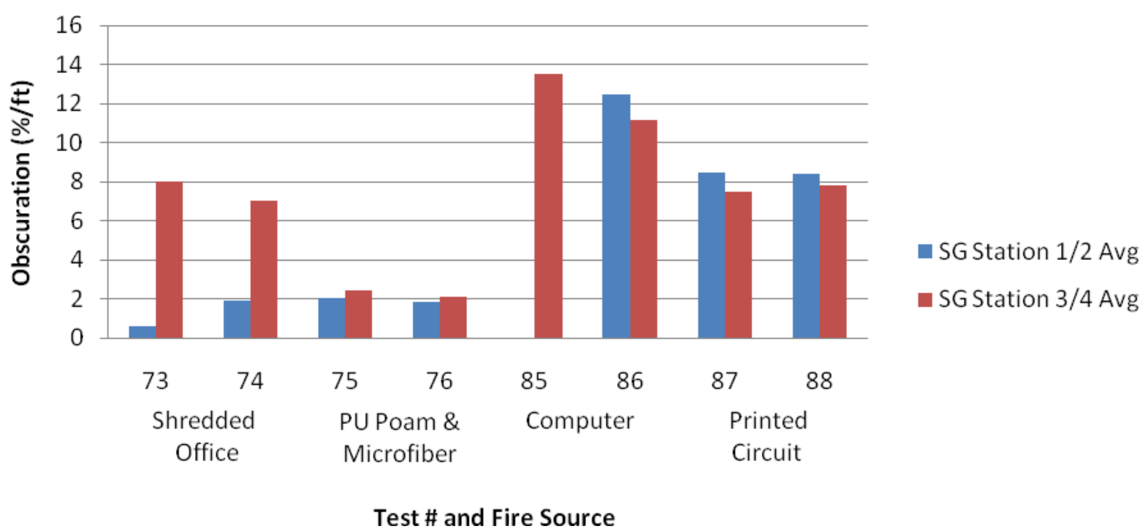

Figure 7-1: Obscuration Levels at Detector Response, Flaming Fires, Ventilated Room (0 ACH)

Figure 7-1 displays that the obscuration readings given by VESDA for the responses of the spot photo-electric detectors are very consistent for these flaming incipient fire sources at 0 ACH for each particular fuel. The only exceptions are the tests concerning the shredded office paper. The shredded office paper tests displayed an odd smoke profile, with smoldering occurring in the first minute of the test and then a spike to a very high obscuration level after the paper ignition. This odd smoke profile provides insight as to what may have occurred during these tests. The detectors at stations 1 and 2 activated just after the initial smoldering of the paper at a low obscuration level which is consistent with the data identified in this analysis (non-flaming fire data at much lower obscuration levels). The detectors at stations 3 and 4 activated at a higher obscuration level after the ignition of the paper which is consistent with the data identified in this analysis (flaming fire data at higher obscuration levels). The overall results of these flaming tests at 0 ACH indicate that the aspirated smoke detectors (VESDA) are providing accurate readings of the obscuration level at spot photo-electric detector response, and that these tests may be highly reproducible in future experiments.

The obscuration results from the spot photo-electric detector activation times based on aspirated smoke detector (VESDA) readings are displayed for the flaming fires by test number and incipient fire source at 6 ACH in Figure 7-2. The data points labeled with a (- 2) represent the obscuration level of an additional activation of the photo-electric detectors during the tests. This data was not available for all tests.

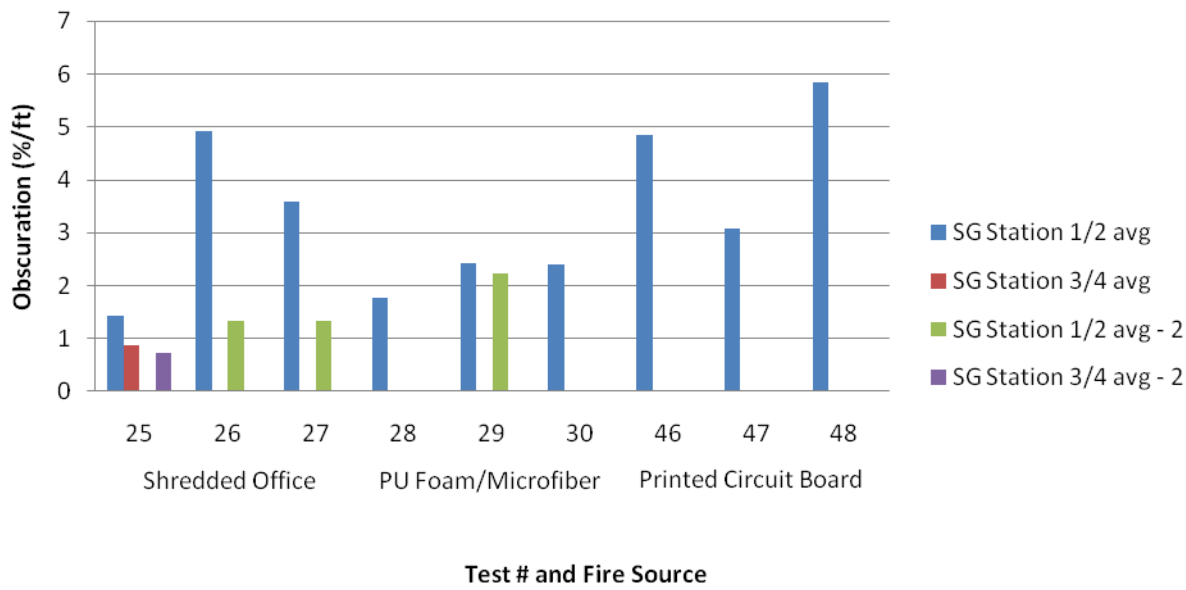

Figure 7-2: Obscuration Levels at Detector Response, Flaming Fires, Ventilated Room (6 ACH)

Figure 7-2 displays that the obscuration readings given by VESDA for the responses of the spot photo-electric detectors are very consistent for these flaming incipient fire sources at 6 ACH for each particular fuel. Some of the data for the flaming fire tests at 6 ACH was excluded due to the inability to obtain data points from the VESDA files (computer case tests). This inability to obtain data points was due to the fact that there were large time gaps in the VESDA data files at the corresponding SG photo-electric activation times. Also, many of these tests are missing data for the SG Station 3/4 Avg activation time, and this was due to the fact that these photo-electric smoke detectors did not activate for these tests. The green and purple data points on this graph (labeled with a "-2" as discussed earlier) denote the obscuration level at additional activations of the spot photo-electric smoke detectors during the test. These data points were included to display increased consistency of the results. Some of the test data displayed in the graph is inconsistent from test to test for the same incipient fire source (i.e, tests 25 and 47), and this may be due to the transient nature of the smoke in the test room or the unpredictability of fire in general (i.e. the fuel in these tests may have burned in a different way than the other tests with the same fuel). The overall results of this graph indicate that the aspirated smoke detectors (VESDA) are providing accurate readings of the obscuration level at spot photo-electric detector response, and that these tests may be reproducible in future experiments.

The obscuration results from the spot photo-electric detector activation times based on aspirated smoke detector (VESDA) readings are displayed for the flaming fires by test number and incipient fire source at 12 ACH in Figure 7-3. The data points labeled with a (- 2) represent the obscuration level of an additional activation of the photo-electric detectors during the tests. This data was not available for all tests.

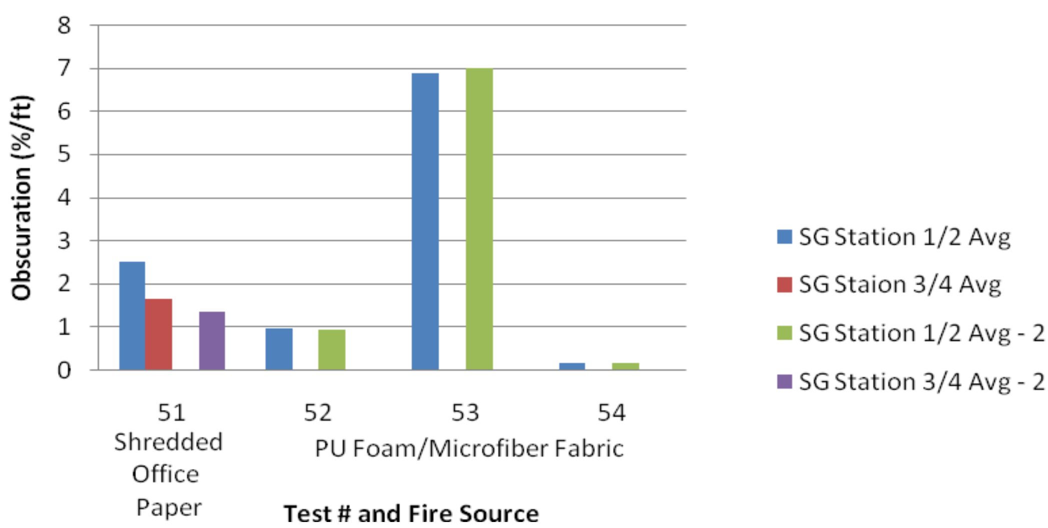

Figure 7-3: Obscuration Levels at Detector Response, Flaming Fires, Ventilated Room (12 ACH)

Figure 7-3 displays that the obscuration readings given by VESDA for the responses of the spot photo-electric detectors are relatively consistent for these flaming incipient fire sources at 12 ACH. Some of the data for the flaming fire tests at 12 ACH was excluded due to the inability to obtain data points from the VESDA files (printed circuit board and computer case tests). This inability to obtain data points was due to the fact that there were large time gaps in the VESDA data files at the corresponding SG photo-electric activation times. Also, many of these tests are missing data for the SG Station 3/4 Avg activation time, and this was due to the fact that these photo-electric smoke detectors did not activate for these tests. The green and purple data points on this graph (labeled with a "-2" as discussed earlier) denote the obscuration level at additional activations of the spot photo-electric smoke detectors during the test. These data points were included to display increased consistency of the results. Although these results are not as consistent as the 0 and 6 ACH tests, there is a small consistency apparent in the polyurethane foam/microfiber fabric tests. The disparity between data points in these tests could also be attributed to the increased ventilation level of 12 ACH. The overall results of this graph indicate that the aspirated smoke detectors (VESDA) are providing some accurate readings of the obscuration level at spot photo-electric detector response, and that these tests may be reproducible in future experiments. The recommendation from this analysis is that many tests with each incipient flaming fire source should be conducted at 12 ACH in order to show more consistency in the results.

The obscuration results for the spot photo-electric detector activation times based on aspirated smoke detector (VESDA) readings are displayed for the non-flaming fires by test number and incipient fire source at 0 ACH in Figure 7-4. The data points labeled with a (-2) represent the obscuration level of an additional activation of the photo-electric detectors during the tests. This data was not available for all tests.

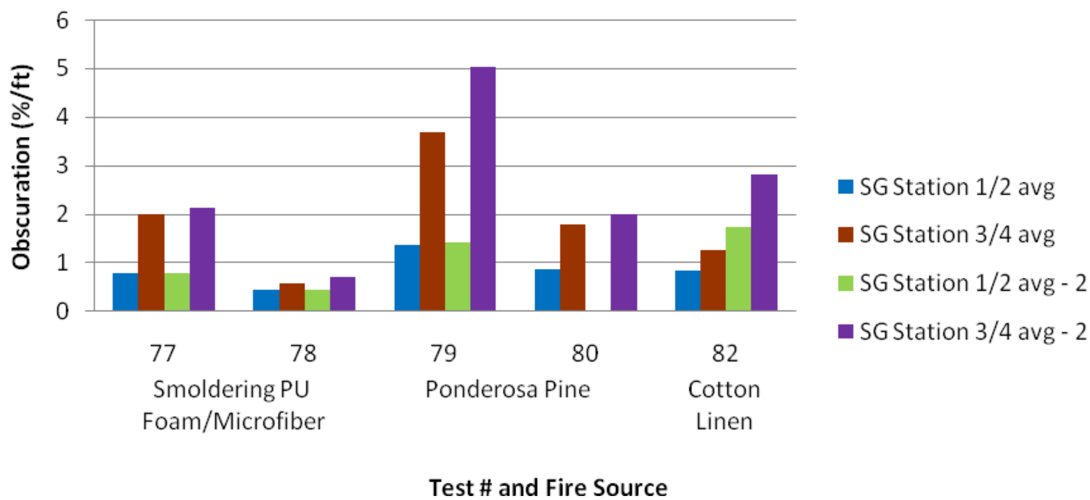

Figure 7-4: Obscuration Levels at Detector Response, Non-Flaming Fires, Ventilated Room (0 ACH)

Figure 7-4 displays that the obscuration readings given by VESDA for the responses of the spot photo-electric detectors are relatively consistent for these non-flaming incipient fire sources at 0 ACH. Some of the data for the non-flaming fire tests at 0 ACH was excluded due to the inability to obtain data points from the VESDA files. This inability to obtain data points was due to the fact that there were large time gaps in the VESDA data files at the corresponding SG photo-electric activation time. The green and purple data points on this graph (labeled with a "-2" as discussed earlier) denote the obscuration level at additional activations of the spot photo-electric smoke detectors during the test. These data points were included to display increased consistency of the results. The results displayed on this graph indicate that there is inconsistency in the obscuration level from test to test for each non-flaming fire source. However, the additional activation readings (green and purple data points) for each test suggest that there is consistency in the obscuration level throughout each test. These results suggest that VESDA is reporting the correct obscuration level for each individual test. The inconsistency associated with the obscuration levels for the same non-flaming fire source from test to test suggests that the reproducibility of these smoldering fires is very difficult.

The obscuration results for the spot photo-electric detector activation times based on aspirated smoke detector (VESDA) readings are displayed for the non-flaming fires by test number and incipient fire source at 6 ACH in Figure 7-5. The data points labeled with a (-2) represent the obscuration level of an additional activation of the photo-electric detectors during the tests. This data was not available for all tests.

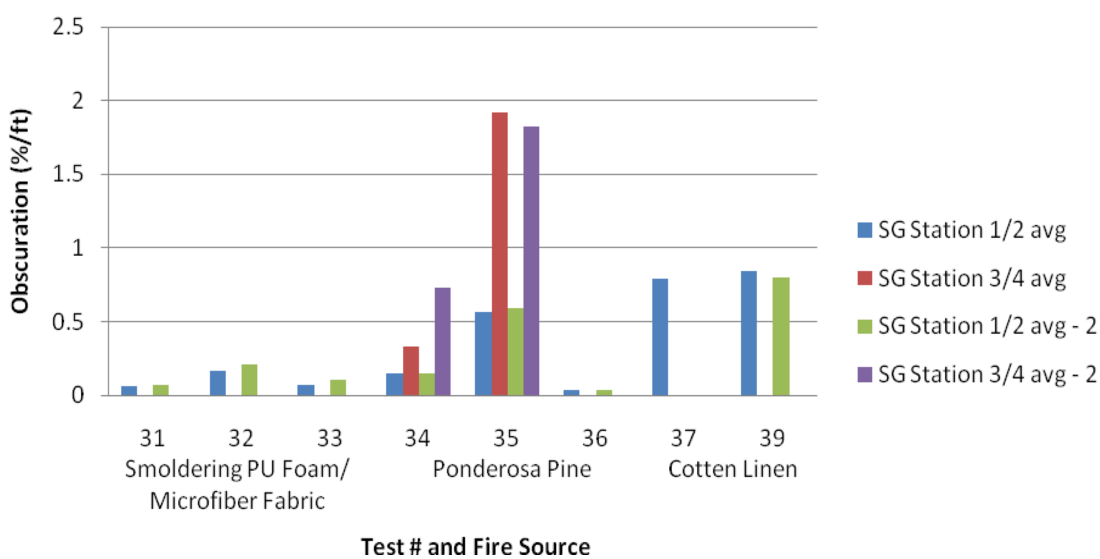

Figure 7-5: Obscuration Levels at Detector Response, Non-Flaming Fires, Ventilated Room (6 ACH)

Figure 7-5 displays that the obscuration readings given by VESDA for the responses of the spot photo-electric detectors are relatively consistent for these non-flaming incipient fire sources at 6 ACH. Some of the data for the non-flaming fire tests at 6 ACH was excluded due to the inability to obtain data points from the VESDA files. This inability to obtain data points was due to the fact that there were large time gaps in the VESDA data files at the corresponding SG photo-electric activation time. Also, many of these tests are missing data for the SG Station 3/4 Avg activation time, and this was due to the fact that these photo-electric smoke detectors did not activate for these tests. The green and purple data points on this graph (labeled with a "-2" as discussed earlier) denote the obscuration level at additional activations of the spot photo-electric smoke detectors during the test. These data points were included to display increased consistency of the results. The results displayed on this graph indicate that there is inconsistency in the obscuration level from test to test for each non-flaming fire source (specifically Ponderosa Pine for this set of tests). However, the additional activation readings (green and purple data points) for these tests suggest that there is some consistency in the obscuration level throughout each test. These results suggest that VESDA is reporting the correct obscuration level for each individual test. The inconsistency associated with the obscuration levels for the same non-flaming fire source from test to test suggests that the reproducibility of the smoldering fires is very difficult. However, this set of tests at 6 ACH is only displaying an inconsistency for the Ponderosa Pine tests, the smoldering polyurethane/microfiber fabric and the cotton linen fabric tests are displaying relatively consistent results from test to test which suggests that the reproducibility of these experiments is possible.

The obscuration results for the spot photo-electric detector activation times based on aspirated smoke detector (VESDA) readings are displayed for the non-flaming fires by test number and incipient fire source at 12 ACH in Figure 7-6. The data points labeled with a (-2) represent the obscuration level of an additional activation of the photo-electric detectors during the tests. This data was not available for all tests.

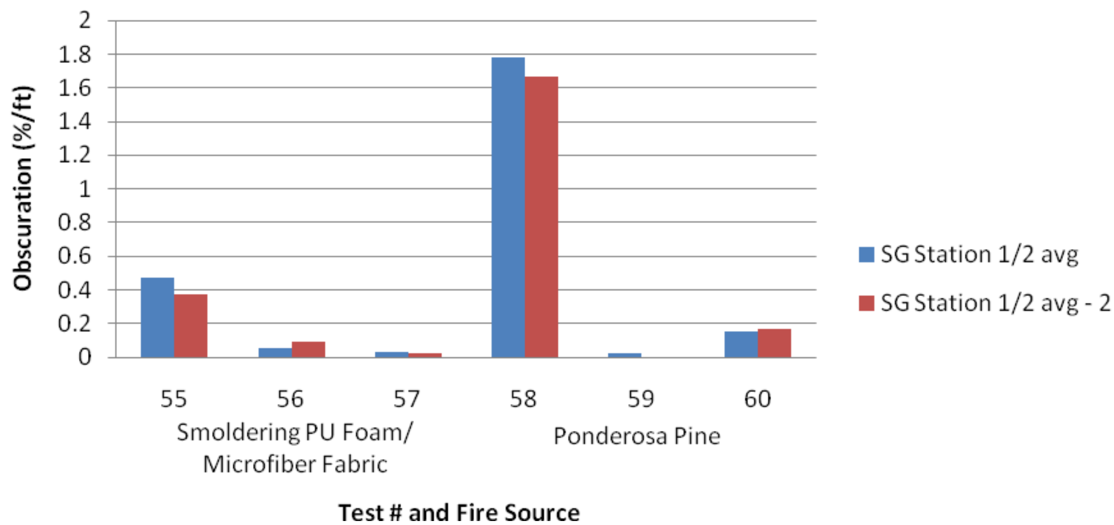

Figure 7-6: Obscuration Levels at Detector Response, Non-Flaming Fires, Ventilated Room (12 ACH)

Figure 7-6 displays that the obscuration readings given by VESDA for the responses of the spot photo-electric detectors are relatively consistent for these non-flaming incipient fire sources at 12 ACH. Some of the data for the non-flaming fire tests at 12 ACH was excluded due to the inability to obtain data points from the VESDA files. This inability to obtain data points was due to the fact that there were large time gaps in the VESDA data files at the corresponding SG photo-electric activation times. For this series of tests, there were no activation times recorded for the spot photo-electric detectors at stations 3 and 4, and only two sets of tests recorded activation times at station 1 and 2. The absence of activation times could be due to the high ventilation rate (affected stations 1 and 2) or the location of the fire source which was closer to stations 1 and 2 (affected stations 3 and 4). The red data points on this graph (labeled with a “-2” as discussed earlier) denote the obscuration level at additional activations of the spot photo-electric smoke detectors during the test. These data points were included to display increased consistency of the results. The results displayed on this graph indicate that there is inconsistency in the obscuration level from test to test for each non-flaming fire source. However, the additional activation readings (red data points) for each test suggest that there is consistency in the obscuration level throughout each test. These results suggest that VESDA is reporting the correct obscuration level for each individual test. The inconsistency associated with the obscuration levels for the same non-flaming fire source from test to test suggests that the reproducibility of these smoldering fires is very difficult.

The overall response times of the spot photo-electric detectors did show a distinct tendency based on the detector location, with the detectors at stations 1 and 2 responding more quickly than the detectors at stations 3 and 4. This was primarily attributed to the fire location being closer to stations 1 and 2 than stations 3 and 4. Also, many of the tests in this analysis did not yield alarms for the detectors at stations 3 and 4 or the comparable VESDA obscuration level was not available (mostly there was no alarm condition). A few of the tests did not yield alarms for any of the detectors. The only exception to these cases was the flaming fire tests at 0 ACH, which suggests that the transient nature of the smoke and the ventilation had a large impact on the results of these tests.

Part 2: Comparison of this Analysis with 2008 Report

The mean and standard deviation of the obscuration (%/ft) for the flaming and non-flaming fires at 0, 6, 12 ACH calculated for this analysis was compared to the same result obtained in the 2008 report titled "Validation of a Smoke Detection Performance Prediction Methodology". The two tables are displayed below for comparison.

Table 7-1: Detector response statistics from this analysis for flaming and non-flaming fires, photo-electric detector SG

	0 ACH		6 ACH		12 ACH	
Parameter	Flaming	Non-flaming	Flaming	Non-flaming	Flaming	Non-flaming
Obscuration (%/ft)						
Mean	6.37	1.62	2.53	0.5	2.41	0.44
Standard Deviation	4.1	1.16	1.56	0.55	1.56	0.69

Table 7-2: Detector response statistics from 2008 report for flaming and non-flaming fires, photo-electric detector SG [1]

	No Ventilation		6 ACH		12 ACH	
Parameter	Flaming	Non-flaming	Flaming	Non-flaming	Flaming	Non-flaming
Obscuration (%/ft)						
Mean	9.52	1.32	2.55	0.28	1.9	0.42
Standard Deviation	6.29	0.65	2.6	0.25	2.47	0.53

The obscuration level at the time of detector response is lower for the tests where ventilation was provided than in cases where the ventilation was not provided in both this analysis and the 2008 report.

For flaming fires, the obscuration level in tests without forced ventilation ranged from 1.8 to 13.5 %/ft for the spot photo-electric detectors in this analysis. This data is very similar to the data captured in the 2008 report (2.7 to 12.9 %/ft) and suggests that the obscuration guideline for flaming fires of 8 %/ft is still reasonable. For flaming fires with ventilation, the obscuration levels ranged from 0.16 to 5.9 %/ft. This data is similar to the data obtained in the 2008 report (80th percentile values of 4.3 to 4.9 %/ft) and suggests that the obscuration guideline for flaming fires could reasonably be 5 %/ft for ventilation rates ranging from 6 to 12 ACH.

For non-flaming fires, the obscuration level in tests without ventilation ranged from 0.4 to 5 %/ft in this analysis. This value is different than the values obtained in the 2008 report (80th percentile values of 1.6 to 12.1 %/ft) and suggests a different guideline of 4 %/ft (vice 10%/ft) for the obscuration level of spot photo-electric detectors for non-flaming fires without ventilation. For non-flaming fires with ventilation, the obscuration levels were all below 2 %/ft in this analysis (most below 1 %/ft if two tests excluded). This data is similar to the data obtained in the 2008 report (80th percentile values of 1 %/ft or lower) and suggests that the obscuration guideline for non-flaming fires could reasonably be 2.5 %/ft for ventilation rates ranging from 6 to 12 ACH.

The minor differences in these two analyses may be attributed to a number of factors even though they follow the same trend. These potential differences will be explained in the following section of this thesis.

Part 3: Explanation of Improved Results

The spot photo-electric detector sensitivity was set at 2.5 %/ft, which corresponds to the obscuration levels for smoke inside the sensing chamber associated with the response of the detectors. With the detector sensitivities set to this particular obscuration, it was expected that the detectors would not alarm until the obscuration outside the detector reached at least this level. The results of this analysis and the analysis conducted in the 2008 report did not display this result for many reasons. However, the results from this analysis displayed improved results when compared to the analysis completed in the 2008 report as shown in Figure 7.3.

Table 7.3: Mean spot photo-electric detector obscuration levels obtained in this analysis and the 2008 report for the flaming and non-flaming incipient fire sources at the 3 different ventilation conditions (0, 6, 12 ACH)

	0 ACH		6 ACH		12 ACH	
Parameter	Flaming	Non-flaming	Flaming	Non-flaming	Flaming	Non-flaming
Obscuration %/ft						
Expected Result	2.5	2.5	2.5	2.5	2.5	2.5
Mean (This Analysis)	6.37	1.62	2.53	0.5	2.41	0.44
Mean (2008 Report)	9.52	1.32	2.55	0.28	1.9	0.42

From this data, it can be concluded that the readings obtained from the aspirated smoke detectors (VESDA) in this analysis are closer to the expected value of 2.5 %/ft than the readings obtained from the obscuration meters used in the 2008 report.

The improved readings from this analysis are based on two major factors. The first reason for the variation in spot photo-electric detector response between this analysis and the 2008 report is the presence of ambient light in the test room. In the tests conducted in the ventilated room, fluorescent lights were left on during the tests. The photocell used in the 2008 report for the light obscuration measurements was not shielded from this fluorescent lighting. As a result, the photocells could have received additional scattered light from the smoke particles created by the incipient fire sources. This additional scattering of light could have yielded a lesser smoke obscuration measurement than what was actually present [1]. This ambient light effect was mitigated in this analysis by the use of the aspirated smoke detectors (VESDA) to measure the obscuration level in the test room. As discussed earlier in the literature survey, the aspirated smoke detectors (VESDA) take a sample of the air in the room to a test chamber where ambient light is not present. The other major contributor to the improvement of the results in this analysis is the use of light scattering technology to determine the obscuration level in the test room at the spot photo-electric detector response time. The aspirated smoke detectors (VESDA) use the same light scattering technology to determine the obscuration level as do the photo-electric detectors. This technology similarity was not present in the 2008 report considering obscuration meters were used to record the obscuration levels in the test room. This use of the same technology to determine the obscuration levels may have eliminated some of the error associated with the tenuous relationship between light obscuration and light scattering.

There are many reasons why the experimental results from this analysis and the 2008 report differ from the expected value of 2.5 %/ft for spot photo-electric detector responses. One of the reasons is that light scattering responses from the spot photo-electric detectors are not directly related to the obscuration of light as described in the literature survey section of this report. The smoke detector sensitivity of 2.5 %/ft for spot photo-electric detectors are ascertained through tests conducted in the UL 217 Sensitivity Test Smoke Box with a single smoke source which produced a light gray smoke. This test enables a relationship to be developed by the detector manufacturers to relate light obscuration to light scattering (light scattering is "measured" implicitly by recording the detector output signal). The relationship established by this test is only relevant to a particular smoke with specific characteristics relating to color, particle size, distribution, and wavelength of light used to make the measurement. The incipient fire sources used in this experiment were created with many different materials that could create many different types of smoke. As the detector is exposed to all of these different types of smoke with different characteristics, the relationship established by the UL 217 Sensitivity Test Smoke Box breaks down [1]. This relationship breakdown is one of the major contributing factors to the disparity in the obscuration levels obtained at photo-electric detector response in this analysis and the 2008 report.

Chapter 8: Conclusion

The use of aspirated smoke detectors (VESDA) in this analysis has provided improved experimental results of the obscuration level (%/ft) at the response time of spot photo-electric detectors. These results were evident in all ventilation conditions for flaming and non-flaming incipient fire sources utilized in this experiment. However, the results from this analysis still show a relatively large deviation in the expected obscuration level of 2.5% at photo-electric detector response. This error is mainly attributed to smoke characteristics created by each of the different incipient fire sources, the smoke transport, and the characteristics of the detectors.

A particular level of obscuration does not uniquely describe the characteristics of a particular type of smoke from an incipient fire source. There are situations where a smoke can have the same obscuration level at different particle sizes as discussed in the recent Smoke Characterization Project [8]. Even though the level of light obscuration is the same for a particular smoke, its detect ability by a light scattering detector would vary given that the detection technology is dependent on the square of the particle diameter [1]. This information, along with the increased ventilation rates may be another significant contributing factor in the disparity between the obscuration levels reported for the spot photo-electric detectors by the aspirated smoke detection system (VESDA).

The error in this experiment could be reduced by further study. The calibration of the SG photo-electric smoke detectors in the UL 217 Sensitivity Test Smoke Box for all of the smoke types created by the 8 incipient fire sources could improve results. This calibration would provide an expected obscuration level at response for the SG photo-electric detectors for each incipient fire source (i.e. 2.5 %/ft. will not be expected for all types of smoke). However, even with these calibrations completed, there would still be substantial error due to the ventilation conditions in some of the tests and the fact that smoke properties can change as the smoke moves away from the incipient fire source. This previous statement leads into another recommendation for further study. It was evident in this analysis and others covered in the 2008 report that the obscuration levels reported by the obscuration meters (and now the aspirated smoke detectors) decreased as the ventilation in the room increased. An investigation into the impact of mechanical ventilation on smoke properties and photo-electric detector response is warranted. Some of the details of this investigation could address the following questions:

> -Does increased ventilation aid in the agglomeration of smoke particles and how does this agglomeration affect the obscuration level reported by the photo-electric detectors at activation?

> -How does increased ventilation aid the photo-electric detectors in responding to low obscuration levels? Does the increased ventilation force the smoke particles into the detectors for sensing? Does the ventilation affect the scattering of light inside the detector mechanisms to cause detector activation at low obscuration levels?

The answers to these questions could improve the understanding of how spot photo-electric detectors respond to incipient fire sources at higher ventilation conditions.

Appendix

Tables of SG Photo-Electric Detector Activation Times and VESDA Obscuration Levels

Table A1: SG Photo-Electric Activation Times and VESDA Obscuration Levels

Obtained from this Analysis at 0 ACH for Ventilated Room Tests

Incipient Fire Source	**SG-1/2 Avg (s)**	**SG-3/4 Avg (s)**	**VESDA VLC 002 (%/ft) @ SG-1/2 Avg Time**	**VESDA VLC 004 (%/ft) @ SG-3/4 Avg Time**	**Test #**	**VESDA Offset Time (s)**
Shred Off. Paper (Flame)	63/98	114	No data/0.639	8.03	73	570
Shred Off. Paper (Flame)	112	85	1.95	7.07* (84 s)	74	1250
PU Foam/MF Fab (Flame)	169	223	2.08	2.44	75	650
PU Foam/MF Fab (Flame)	150	204	1.83* (149 s)	2.15	76	2130
PU Foam/MF Fab	3046/3084	3560/3606	0.78/0.8* (3083s)	2.0* (3561s)/2.13* (3607s)	77	2700
PU foam/MF Fab	3156/3180	3600/3691	0.433/0.433* (3181s)	0.59* (3599s)/0.71	78	2000/850
Ponderosa Pine	2100/2154	2947/3072	1.36/1.43	3.68/5.03	79	3700
Ponderosa Pine	2204	2888/3060	0.86	1.78/2.01	80	500
Cotton Linen Fabric	No Alarm	No Alarm	No Alarm	No Alarm	81	2800
Cotton Linen Fabric	4539/4633	4682/4742	0.84/1.75	1.25/2.82	82	1700
PVC Wire	No Data	No Data	No Data	No Data	83	0
PVC Wire	No Data	No Data	No Data	No Data	84	0
Computer Case (Flame)	164	328	No data	13.5	85	1200
Computer Case (Flame)	126	286	12.5	11.2	86	40
Print Circ. Board (Flame)	56/228	107	No data/8.5	7.5	87	200
Print Circ. Board (Flame)	50	106	8.4* (49s)	7.8* (107s)	88	2185/2200

*Denotes a data point at a different time than SG-1/2 Avg and SG-3/4 Avg, actual time in parenthesis
Data points with two values indicates additional activation times (s) or obscuration level (%/ft)

Table A2: SG Photo-Electric Activation Times and VESDA Obscuration Levels

Obtained from this Analysis at 6 ACH for Ventilated Room Tests

Incipient Fire Source	**SG-1/2 Avg (s)**	**SG-3/4 Avg (s)**	**VESDA VLC 002 (%/ft) @ SG-1/2 Avg Time**	**VESDA VLC 004 (%/ft) @ SG-3/4 Avg Time**	**Test #**	**VESDA Offset Time (s)**
Shred Off. Paper (Flame)	96	232/270	1.44	0.88/0.72	25	1050
Shred Off. Paper (Flame)	62/117	No Alarm	4.93/1.34	No Data	26	814
Shred Off. Paper (Flame)	44/88	No Alarm	3.6/1.34	No Data	27	285
PU Foam/MF Fab (Flame)	147	No Alarm	1.76	No Data	28	5000
PU Foam/MF Fab (Flame)	142/215	No Alarm	2.42/2.22	No Data	29	350
PU Foam/MF Fab (Flame)	160	No Alarm	2.41	No Data	30	320
PU foam/MF Fab	3415/3440	No Alarm	0.065/0.07	No Data	31	770/850
PU foam/MF Fab	3300/3388	No Alarm	0.17/0.21	No Data	32	300
PU foam/MF Fab	3312/3556	No Alarm	0.074/0.103	No Data	33	4300
Ponderosa Pine	2928/2969	4213/4602	0.153/0.146	0.335/0.73	34	300
Ponderosa Pine	3138/3187	4144/4199	0.57/0.59	1.92/1.82	35	1200
Ponderosa Pine	3114/3174	3780/3866	0.039/0.037	No Data	36	0/3900
Cotton Linen Fabric	4762	No Alarm	0.795	No Data	37	1500
Cotton Linen Fabric	No Alarm	No Alarm	No data	No Data	38	3700
Cotton Linen Fabric	4722/4765	No Alarm	0.841/0.798	No Data	39	900
PVC Wire	No Alarm	No Alarm	No data	No Data	40	0
PVC Wire	No Alarm	No Alarm	No data	No Data	41	650/850
PVC Wire	No Alarm	No Alarm	No data	No Data	42	0/980
Computer Case (Flame)	No Alarm	No Alarm	No data	No Data	43	9650
Computer Case (Flame)	No Alarm	No Alarm	No data	No Data	44	N/A
Computer Case (Flame)	No Alarm	No Alarm	No data	No Data	45	850
Print Circ. Board (Flame)	45	No Alarm	4.84* (44s)	No Data	46	840/890
Print Circ. Board (Flame)	45	No Alarm	3.09* (46s)	No Data	47	3980
Print Circ. Board (Flame)	54	No Alarm	5.85	No Data	48	1280/1290

*Denotes a data point at a different time than SG-1/2 Avg and SG-3/4 Avg, actual time in parenthesis

Data points with two values indicates additional activation times (s) or obscuration level (%/ft)

Table A3: SG Photo-Electric Activation Times and VESDA Obscuration Levels

Obtained from this Analysis at 12 ACH for Ventilated Room Tests

Incipient Fire Source	**SG-1/2 Avg (s)**	**SG-3/4 Avg (s)**	**VESDA VLC 002 (%/ft) @ SG-1/2 Avg Time**	**VESDA VLC 004 (%/ft) @ SG-3/4 Avg Time**	**Test #**	**VESDA Offset Time (s)**
Shred Off. Paper (Flame)	70	208	No data	No data	49	0
Shred Off. Paper (Flame)	78	211	No data	No data	50	0
Shred Off. Paper (Flame)	75	199/210	2.5	1.64/1.37	51	500
PU Foam/MF fabric (Flame)	178/224	No Alarm	0.979* (190s)/0.949* (250s)	No data	52	830/870
PU Foam/MF fabric (Flame)	202/253	No Alarm	6.88* (224s)/7.0* (246s)	No data	53	2800
PU Foam/MF fabric (Flame)	232/327	No Alarm	0.17* (220s)/0.176* (334s)	No data	54	0
PU foam/MF fabric	3243/3336	No Alarm	0.475/0.376	No data	55	2000/850
PU foam/MF fabric	3242/3473	No Alarm	0.053/0.09	No data	56	1500
PU foam/MF fabric	3166/3214	No Alarm	0.003/0.001	No data	57	1200/1685
Ponderosa Pine	3310/3370	No Alarm	1.78/1.67	No data	58	3000/4000
Ponderosa Pine	3263/3336	No Alarm	0.026 (avg)	No data	59	0
Ponderosa Pine	3270/3319	No Alarm	0.15/0.17	No data	60	2200
Cotton Linen Fabric	No Alarm	No Alarm	No data	No data	61	2150
Cotton Linen Fabric	No Alarm	No Alarm	No data	No data	62	0/5650
Cotton Linen Fabric	No Alarm	No Alarm	No data	No data	63	0
PVC Wire	No Alarm	No Alarm	No data	No data	64	0/2700
PVC Wire	No Alarm	No Alarm	No data	No data	65	650
PVC Wire	No Alarm	No Alarm	No data	No data	66	550
Computer Case (Flame)	No Alarm	No Alarm	No data	No data	67	1520
Computer Case (Flame)	No Alarm	No Alarm	No data	No data	68	850
Computer Case (Flame)	No Alarm	No Alarm	No data	No data	69	1685
Print Circuit Board (Flame)	No Alarm	No Alarm	No data	No data	70	4650
Print Circuit Board (Flame)	No Alarm	No Alarm	No data	No data	71	630
Print Circuit Board (Flame)	No Alarm	No Alarm	No data	No data	72	4600/4400

*Denotes a data point at a different time than SG-1/2 Avg and SG-3/4 Avg, actual time in parenthesis
Data points with two values indicates additional activation times (s) or obscuration level (%/ft)

Bibliography

[1] Milke, J. A., Mowrer, F. W., & Gandhi, P. (2008). *Validation of a Smoke Detection Performance Prediction Methodology.* Quincy: Fire Protection Research Foundation.

[2] Bukowski, R. W., & Moore, W. D. (2003). *Fire Alarm Signaling Systems, Third Edition.* Quincy: National Fire Protection Association, Inc.

[3] National Fire Protection Association. (2006, August 17). NFPA 72: National Fire Alarm Code, 2007 Edition. Quincy, Massachusetts, United States of America: NFPA.

[4] Xtralis. (2009, August 01). *Air Sampling Smoke Detection.* Retrieved August 17, 2009, from xtralis: http://xtralis.com/p.cfm?s=22&p=244

[5] U. S. Nuclear Regulatory Commission. (2004, December). *Chapter 11: Estimating Smoke Detector Response TIme.* Retrieved April 10, 2010, from Fire Dynamics Tools (FDTs) Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program (NUREG-1805): http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/

[6] Custer, R. L., Meachum, B. J., & Schifiliti, R. P. (2008). Design of Detection Systems. In SFPE, The SFPE Handbook of Fire Protection Engineering, Fourth *Edition* (pp. 4-1 through 4-44).

[7] Schifiliti, R. P., & Pucci, W. E. (1996). *Fire Detection Modeling, State of the Art.* Bloomfield: Fire Detection Institute.

[8] Fabian, T. Z., & Ghandi, P. D. (2007). *Smoke Characterization Project.* Northbrook: Underwriters Laboratories Inc.

[9] Jiang, Y. (2010, January 14). VESDA Sensitivity. (J. H. Miller, Interviewer)

[10] Vythoulkas, J. (2009, November 17). Sychronization of Data. (J. H. Miller, Interviewer)

[11] Geiman, J. A. (2003). *Evaluation of Smoke Detector Response Estimation Methods, MS Thesis.* College Park: University of Maryland.

[12] Heskestad, G., & Delichatsios, M. A. (1977). *Environments of Fire Detectors – Phase 1: Effect of Fire Size, Ceiling Height and Material, Measurements Vol I (NBS-GCR-77-86), Analysis Vol II (NBS-GCR-77-95).* Springfield: National Technical Information Service.