ABSTRACT

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Matthew James Brookman, M.S., 2008

Directed By: Associate Professor Frederick W. Mowrer, Department of Fire Protection Engineering

This thesis describes the experimental and analytical methods used to characterize the heat and smoke release rates of eight different incipient fire sources. These characterizations are part of a larger effort to evaluate the current smoke detection prediction capabilities of the Fire Dynamics Simulator (FDS) version 5.1.0. FDS is a computational fluid dynamics model of fire development based on the concept of large eddy simulation; the FDS model is under ongoing development at the Building and Fire Research Laboratory of the National Institute of Standards and Technology.

The experimental aspect of this thesis includes developing a repeatable test protocol and characterizing each of the fuel sources. The experimental data produced from this phase is then input into FDS and the results of these simulations are compared to these experimental data. FDS has provided a range of accuracy near 5 % of the input values for smoke characteristics. The lag times associated with the output data can

largely be attributed to the uncorrected experimental data. The time scaled inputs for FDS are based on the time that the instrumentation within the exhaust duct detected the smoke release from the material and the transport time required to move the smoke from the specimen to the instrumentation is not compensated for. Some variations in detection and data acquisition are expected.

SMOKE CHARACTERIZATION OF INCIPIENT FIRE SOURCES FOR FDS MODELING

By

Matthew James Brookman

Thesis submitted to the Faculty of the Graduate School of the
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Advisory Committee:
Associate Professor Frederick W. Mowrer, Chair
Professor James A. Milke
Assistant Professor Peter B. Sunderland

Dedication

This thesis is dedicated to my Father, Larry Brookman, and my family because without their guidance and support, I would not be in such a rewarding field.

Acknowledgements

My sincerest gratitude is extended to Professor Frederick Mowrer and the Fire Protection Research Foundation for their support and assistance. Dr. Mowrer's guidance during the course of my research was an invaluable asset, and this would not have been possible without him and the support of the FPRF.

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I would also like to thank Dan Steppan, Pravin Gandhi, and Tom Fabian at Underwriter's Laboratories Inc. for their support during and after the experimental phase of this project. Very special thanks go out to Tom Lackhouse and Gunnar Campbell for their dedication and persistence with this project. There were many late nights and even more early mornings. Thanks to my friends from UL Northbrook, Illinois, Gary, Jen, and Joey Holmes and Manny and Leah Hurtado, for keeping me entertained during occasional downtime in and out of the office.

I wish to express my sincerest appreciation to my long time partner, Katie Eppig, who, through her own studies and her support, has given me the strength and will to maximize my potential.

My appreciation is extended to Adam Goodman as well, for his assistance with running so many simulations.

To my schoolmates and friends, those of you who made sure I was hard at work and those of you who persistently distracted me, I offer my deepest gratitude for keeping me sane. Thank you all.

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Chapter 1: Introduction and Background

This thesis describes the experimental and analytical methods used to characterize the heat and smoke release rates of eight different incipient fire sources. These characterizations are part of a larger effort to evaluate the current smoke detection prediction capabilities of the Fire Dynamics Simulator (FDS) version 5.1.0. FDS is a computational fluid dynamics model of fire development based on the concept of large eddy simulation; the FDS model is under ongoing development at the Building and Fire Research Laboratory of the National Institute of Standards and Technology.

The experimental research for this thesis was performed within the Fire Protection Department at Underwriters Laboratories, Inc., in Northbrook, Illinois. Computer modeling was performed at the University of Maryland, College Park, within the Department of Fire Protection Engineering in the A. James Clark School of Engineering using the UL Fire Modeling Lab. These computer simulations were conducted using Fire Dynamics Simulator (FDS) version 5.1.0 and Smokeview version 5 (McGrattan, et. al., 2007).

1.1 Research Goals

The purpose of this research is to provide guidance on methods to characterize incipient fuel sources to be used in simulations using Fire Dynamics Simulator (FDS), as well as to evaluate the capability of FDS to simulate the relevant phenomena for predicting smoke detector activation. The specific goals of this project are as follows.

The initial objective is the development of a process to characterize both flaming and smoldering fuel sources for input into FDS. Subsequently, FDS modeling of the previous process is studied to evaluate the ability of the program to accurately reproduce the appropriate phenomena. Finally, the variations between the models and the initial characterization are quantified to evaluate the range of accuracy.

1.2 Research Scope

The focus of this research is on flaming and smoldering incipient fires from sources that are common to commercial occupancies. This research is broken up into two phases. Phase 1 of the project examines the characteristics of each of the fuel sources chosen for evaluation. Phase 2 of the project focuses on the validation of the specific parameters in FDS that will determine the output of the models. These phases are developed further in the following subsections.

1.2.1 Phase 1 – Fuel Source Characterization

Each of the eight fuel sources chosen for this project is characterized under UL's IMO intermediate-scale calorimeter, which is based on the principle of oxygen consumption calorimetry. Three tests are performed for each fuel source to obtain replicate data sets. The information collected includes mass loss (for flaming sources), heat release rate (for flaming sources), smoke release rate, smoke particle size and count, and gas effluents. The fuel packages are designed to share similar physical characteristics to how they would be used in manufactured goods.

The flaming tests are performed using various predefined ignition sources from existing fire test standards. For each of these tests, mass loss and heat release rates are recorded for comparison and input into FDS.

The smoldering fuel sources require a different approach from the flaming packages. The test apparatus for these fuel sources prevented accurate measurement of real-time mass loss rates. However, pre-test and post-test weight measurements of test samples were recorded for each experiment.

Measurements of environmental conditions are also taken during the fire tests. These measurements include exhaust duct velocity and temperature, and room temperature and humidity. Exhaust duct velocity and temperature are used during the comparisons of the simulations to the experiments. The room temperature is used to establish the baseline temperature for the model.

1.2.2 Phase 2 – Model Development and Analysis

Upon completion of Phase 1, a model of UL's IMO intermediate-scale calorimeter is created using FDS and each of the fuel package fire test scenarios is simulated. A grid resolution study is performed and the model is instrumented similarly to the original experiment. The data collected from the original experiments is used to determine the uncertainty and the level of accuracy required from these models.

The fuel characteristics determined under the intermediate-scale calorimeter are used in the input file of FDS. The eight sources are modeled using a species ID for the smoke so that the smoke generation can follow the profiles measured in the IMO apparatus tests. The inputs for this method include the heat release rate profile, or temperature profile for the smoldering sources, and the smoke release rate profile. The mixture fraction model was used initially, which uses the heat release rate, smoke yield, and heat of combustion as inputs. This method is based on a correlation between heat release rate and smoke release rate. The exhaust velocity and room temperature are also used as initial inputs. This method does not allow for an accurate recreation of the phenomena involved with incipient fire sources due to the independent nature of the initial smoke production relative to the heat release rate.

1.3 Thesis Organization

This thesis will first discuss the experimental phase of this project, then the model development, followed by the data analysis and comparison between the experimental and modeling data.

The experimental portion will be discussed in the order that it was performed. The fuel source characterization, including instrumentation, measurements, calculations, and procedures will be discussed. Next will be a display of the results, followed by a discussion of these experimental results. Each section provided above is appropriately divided into subsections for each of the eight fire sources.

Upon completion of the analysis of the experimental results, the modeling procedures will be analyzed. The model configuration, input calculations, and output calculations are discussed separately. The modeling results and comparative analysis have been combined in this section.

To conclude, a summary of this analysis and a discussion of the performance of FDS are provided. The general procedures are reiterated and summary charts are provided to display the trends of accuracy.

The appendix provides additional charts displaying values produced in the experimental phase of this project. These values include experimental procedures, exhaust velocities, sample weight and weight loss, heat of combustion, peak heat release rate, peak smoke release rate, FTIR and WPS dilution ratios, peak carbon monoxide and carbon dioxide, smoke yield, specific extinction area, total smoke release, and total heat release. These values are direct calculations from the experimental data. Other data collected during the experimental work that is not directly related to this thesis is included here. In addition to this data, the input files used for the modeling phase are provided.

Chapter 2: Fire Source Characterization

The heat and smoke release rates of eight fuel sources are characterized through fire tests performed in the IMO intermediate-scale calorimeter located in UL's small-scale fire test laboratory in Northbrook, IL. The eight fuel sources include shredded office paper, polyurethane foam wrapped in micro-fiber fabric (used as a flaming and smoldering source), printed circuit board, computer case ABS plastic, ponderosa pine, cotton linen fabric, and PVC insulated wire. The IMO apparatus consists of a square skirted hood, 1.22 m on each side, and an exhaust duct measuring .18 m in diameter. Illustration 1 shows the layout of the IMO apparatus and the position of the measurement devices.

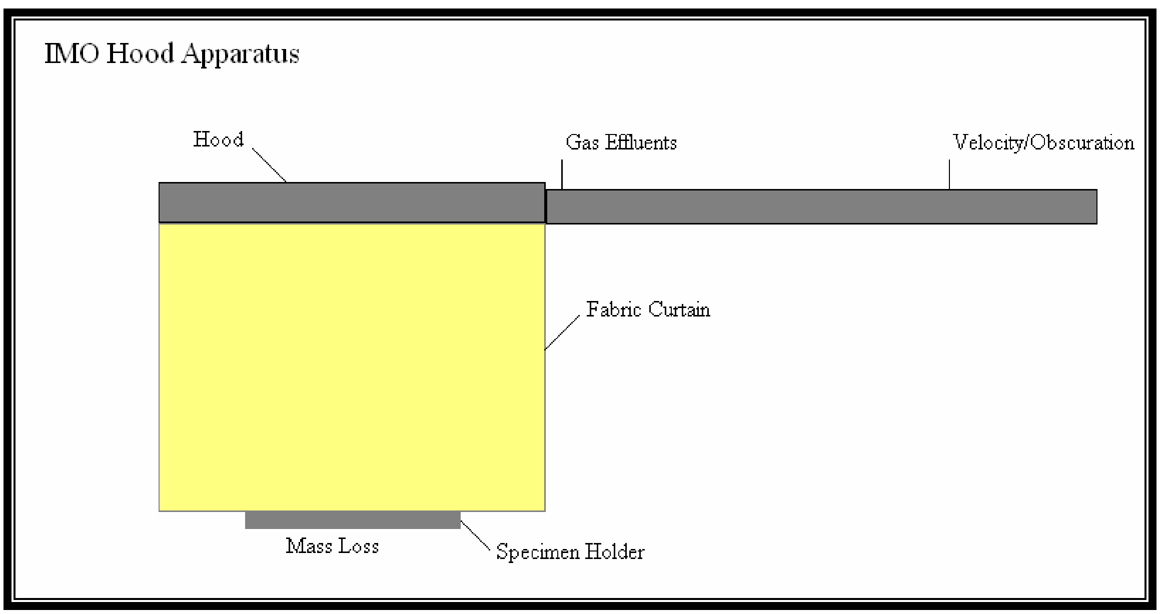

Illustration 1 - IMO apparatus.

2.1 Instrumentation

2.1.1 Smoke Characterization

The IMO intermediate-scale hood is instrumented with a sampling port near the entrance of the exhaust duct from the hood. This port is used to provide smoke samples to a Model WPS 1000XP wide range particle size spectrometer (WPS spectrometer) and a MIDAC #I 1100 Fourier Transform Infrared (FTIR) spectrometer equipped with a 10 meter path length optical cell. The exhaust duct is also equipped with a light obscuration device to measure optical density 2 m from the entrance of the duct.

The WPS spectrometer characterizes the smoke particle size and count by combining laser light scattering, electrical mobility, and condensation particle counting technologies. This produces a measurable size range from 10 to 10,000 nm in diameter. A 1 L/min sample flow is divided between the dynamic mobility analyzer (DMA) and the light particle spectrometer (LPS) to develop the size distribution measurement. The LPS measures particles larger than 200 nm and the DMA measures particles ranging from 10 to 500 nm. Measurement sensitivity is limited to particle concentrations not greater than 2×10^7 particles/cc (Fabian and Gandhi, 2007).

The FTIR spectrometer characterizes gas effluent composition using a gas calibration library to calculate the concentration of the gases detected. It is capable of measuring

600 to 4000 cm^{-1} wavenumber and has a resolution of 0.5 cm^{-1} (Fabian and Gandhi, 2007).

The light obscuration device (smoke eye) consists of a Huygen Corp. Model 856 BB (Blue Blue) Type 2 photocell and a GE 4405 spot-lamp. The smoke eye is located 2 m from the entrance of the exhaust duct leading from the collection hood. The total beam length is 0.6 m with a 0.18 m beam length within the exhaust duct. The data collected from this instrument is converted to an extinction coefficient and a percent obscuration.

2.1.2 Fuel Characterization

The IMO intermediate-scale calorimeter is equipped with an oxygen analyzer and a load cell. The oxygen analyzer is a Siemens Oxymat 6 and the load cell, which is only used for the flaming fuel source packages, is a Fire Testing Technology Limited load cell assembly. For the smoldering sources, a Wenesco Model HP1212YX hotplate is used with a programmable thermostat from Cal Controls. A power supply is needed for the PVC insulated wire test performed during this research. A Sorensen DCS 60-50 power supply is used for this purpose.

The oxygen analyzer uses a paramagnetic effect by the alternating pressure method to measure oxygen levels. This provides reliable linearity and allows parameterization of small measuring ranges of 0 to 0.5%. The detection limit is 50 ppm.

The load cell is placed in the center of the hood and various platforms have been fabricated to support the range of fuel sources being tested. The capacity of this load cell is 2.8 kg with an accuracy of 1 g.

The hotplate used for the smoldering tests is a Wenesco Model HP1212YX hotplate with a 30.4 by 30.4 by 1.3 cm thick stainless steel surface used along with a CAL95B11PA000 programmable thermostat from Cal Controls. This hotplate has a 240 volt, 6480 watt power supply, capable of producing temperatures up to 815 ˚C. The UL 217 hotplate temperature ramp is programmed into this controller and monitored by a thermocouple imbedded in the hotplate.

The Sorensen DCS 60-50 power supply is used only for the PVC insulated wire test. This instrument is capable of providing a range of power from 0 to 60 volts and 0 to 50 amps. It can also be programmed to maintain a continuous current by varying the voltage to compensate for changing resistance, which is required for the PVC insulated wire test protocol.

2.1.3 Environmental Measurements

In addition to the fuel and smoke instrumentation, thermocouples are located within the exhaust duct and in the ambient room. A bidirectional probe is located in the exhaust duct for velocity measurements.

The thermocouple in the exhaust duct is used to measure the exhaust gas temperatures near the smoke eye. The thermocouple in the room is used to measure the initial air temperature to provide a baseline starting ambient temperature for FDS input.

The bidirectional probe in the exhaust duct is a Baratron Model 220CD connected to a pressure transducer with a range of 1 torr. This probe is placed in the center of the duct to obtain the maximum velocity by converting the measured pressure differential. This velocity measurement is used to ensure that the exhaust flow in the model is similar to the exhaust flow produced in the experiments.

2.2 Experimental Calculations

Heat Release Rate – The heat release rate is calculated based on oxygen measurements performed during the tests and the characteristics of the combustion process from which the C factor is derived. This factor correlates the values produced from the measurements within the hood to a known value for methane. This correlated factor is then used in the equation for the heat release rate within a specified range. The C factor is obtained by burning a prescribed flow of methane under the hood and calibrating the oxygen analyzer to the appropriate values. The stoichiometric ratio from this calibration is used in the calculation of the heat release rate of the materials being tested.

$$\dot{Q} = C\Delta H_{O_2}\left(\frac{MW_{O_2}}{MW_{Air}}\right)\dot{m}_{Exhaust}\left(\frac{X_{0,O_2} - X_{O_2}}{E - \left(X_{product,O_2} X_{O_2}\right)}\right)$$

Where:

$\dot{Q}$ = Heat release rate (kW)
C = Calibration constant (0.91)
ΔH_{O_2} = Air heat of combustion (13,100 kJ/kg$_{O_2}$)
MW_{O_2} = Molecular weight of oxygen (32 g/mol)
MW_{air} = Molecular weight of air (29 g/mol)
$\dot{m}_e$ = Mass flow rate in exhaust duct (kg/s)
$X_{O_2,o}$ = Ambient oxygen mole fraction (0.2095)
X_{O_2} = Oxygen mole fraction in exhaust stream
E = Chemical expansion factor (1.105)
$X_{\exp}$ = Stoichiometric expansion factor (1.5)

Extinction Coefficient – The extinction coefficient is derived from the relationship between the voltage output from the photocell in the exhaust duct and the light beam intensity. For the equipment installed for these tests, the relationship is linear.

$$k = \frac{1}{l}\ln\left(\frac{I_0}{I}\right)$$

Where:

k = Extinction coefficient (m^{-1})
l = 0.18 m (Beam length in exhaust duct)
I_0 = Initial clear beam light intensity (mV)
I = Light intensity at time (t) (mV)

Obscuration – Light obscuration is based on the same data as the extinction coefficient and can be derived from it.

$$\lambda = 100\left(1 - e^{-kl}\right)$$

Where:

λ = Percent obscuration (%)
k = Extinction coefficient (m^{-1})

l = Beam length in exhaust duct (0.18 m)

Smoke Release Rate – The smoke release rate is derived from the extinction coefficient.

$$\dot{S} = kv_{Exhaust}A_{duct}$$

Where:

$\dot{S}$ = Smoke release rate (m^2/s)
k = Extinction coefficient (m^{-1})
$v_{Exhaust}$ = Exhaust velocity at photocell (m/s)
A_{duct} = 0.0248 m^2

Smoke Yield – The accumulating average smoke yield is calculated by dividing the extinction crossectional area by the specific extinction coefficient.

$$Y_s = {}^{\varepsilon}\!/_{\sigma}$$

Where:

Y_s = Accumulating average smoke yield (g_s/g)
ε = Total smoke @ t/Total mass loss @ t Extinction cross-sectional area
σ = Specific extinction coefficient (8.7 m^2/g_s)

Velocity – A pressure measurement is made in the exhaust duct near the photocell with a pressure transducer. The pressure readings are then converted to velocity. There is a correction factor required for this conversion ; This factor is 0.806.

$$v_{Exhaust} = 0.806\sqrt{PT_{duct}}$$

Where:

$v_{Exhaust}$ = Exhaust velocity (m/s)

P = Pressure transducer reading (torrs)
T_{duct} = Duct temperature at time (t) (K)

2.3 Experimental Procedures

2.2.1 Shredded Office Paper

The shredded office paper test arrangement includes a solid metal wastebasket measuring 35.5 cm tall by 28 cm in diameter at the top by 22 cm in diameter at the bottom, standard office paper cut into strips measuring 6.35 mm wide by 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.

Shredded office paper, conditioned for a minimum of 24 hours at 23 ± 0.5 ˚C and 50 ± 5 % relative humidity, with a total weight of 75 g is placed loosely into a wastebasket and then tamped down to approximately 10 cm from the base using a circular disk that covered most of the surface of the paper. This procedure is shown in Figure 1. A 2.5 cm diameter hole is drilled into the side of the trash can near the bottom to allow insertion of the TB 604 burner (TB 604, 2004), as shown in Figure 2.

The ignition source for this test is the burner tube described in TB 604, *Test Procedure and Apparatus for the Flame Resistance of Filled Bedclothing*. It consists of a 200 ± 5 mm length of stainless steel tube with an 8.0 ± 0.1 mm outer diameter and a 6.5 ± 0.1 mm inner diameter connected to a cylinder containing ultra high purity propane. The stainless steel tube is connected to a two stage regulator via clear flexible tubing 2.5 to 3.0 m in length and 7.0 ± 1.0 mm inner diameter. The flame height for testing is 35 mm when the burner is held horizontally and allowed to burn freely in air.

Figure 1 – Tamping disk (left). Disk and paper at required height (center). Tamped paper (right).

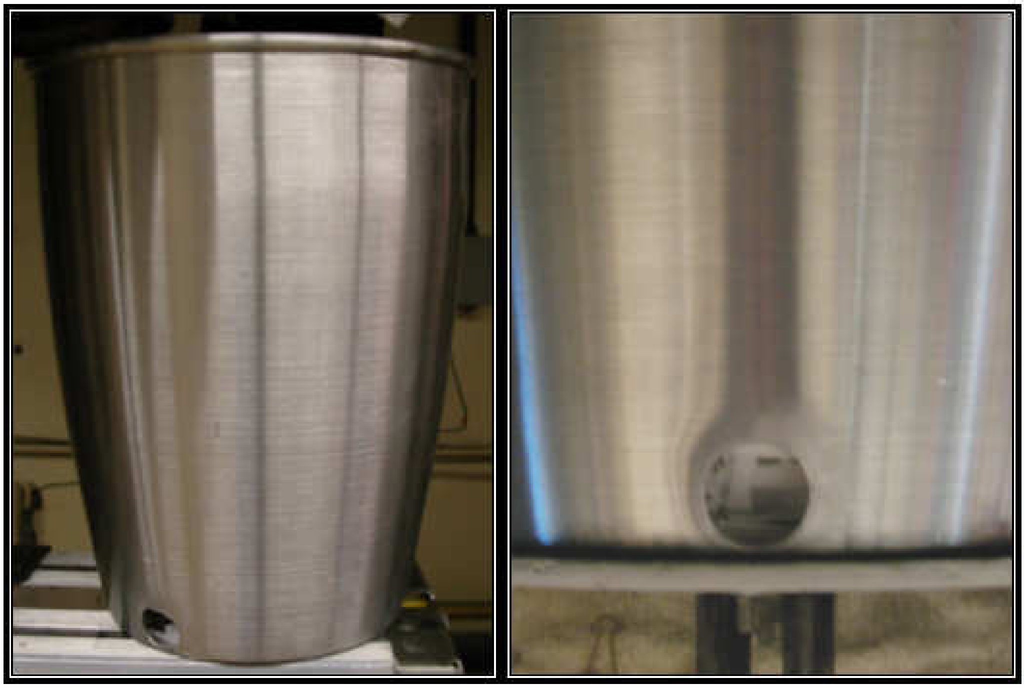

Figure 2 – 2.5 cm hole for insertion of the TB 604 burner.

The prepared wastebasket is placed on top of the load cell on a platform approximately 24 cm in diameter. The position of the base of the wastebasket is level with the bottom of the hood curtain to ensure that all of the smoke is collected by the exhaust duct. Prior to test initiation, all instruments are calibrated, the load cell is zeroed, and all instruments are rechecked. To initiate the test, all recording instruments are started and the burner is inserted horizontally 25 mm into the hole near the bottom of the wastebasket for 5 seconds. The burner is then removed and the paper is allowed to burn until smoke production stops. This procedure is repeated for a total of three tests.

2.2.2 PU Foam with Micro-fiber Fabric (Flaming)

PU foam with micro-fiber fabric is used to simulate a typical commercial upholstery assembly. The TB 604 ignition source, the same ignition source used for the shredded office paper tests, is used for this test. This ignition source is similar to a butane cigarette lighter flame.

Two blocks of PU foam measuring 20 by 8 by 10 cm are wrapped in a 50 by 60 cm sheet of micro-fiber fabric in the manner shown in Figure 3 to create a block of material that measures 20 by 16 by 10 cm. Both materials are conditioned prior to assembly for a minimum of 24 hours at 23 ± 0.5 ˚C and 50 ± 5 % relative humidity. A foil tray is positioned beneath the specimen during testing to contain the liquefied PU foam. The specimen is placed on the foil tray with the 20 by 16 cm side down, which incorporated the pinned fabric.

Figure 3 – Front view of PU foam block (left). Side view of PU foam block (center). Non-combustible straight pins hold fabric to foam at the base (right).

The PU foam assembly and foil tray are placed on a 0.60 by 0.60 m noncombustible platform on top of the load cell such that the base of the material is at the same height as the bottom of the hood curtain. Initiation of the test begins with igniting the TB 604 burner and establishing a 35 mm tall flame with the burner held horizontally. Once the flame has been stabilized, all recording instruments are started and the burner flame is placed against the base of the front side of the PU foam assembly near the center for 20 seconds. As the foam liquefies and the micro-fiber fabric burns away, the flame is kept in contact with the material, adjusting for the deformation during the 20 second ignition period. Three tests were conducted to evaluate test repeatability.

2.2.3 Printed Circuit Board

The printed circuit board tests use the ATIS T1.319 (ATIS T1.319, 2003) line burner for ignition. This test is used to determine the fire propagation risk of telecommunications equipment assemblies. In this standard, when adjacent printed circuit boards ignite, the assembly has failed. In the test described below, ignition of the printed circuit board is intentional.

Two 7.5 by 7.5 by 1.57 mm printed circuit boards conditioned to 23 ± 0.5 ˚C and 50 ± 5 % relative humidity for a minimum of 24 hours are placed 2 cm apart in a vertical orientation. The line burner is centered 1.5 cm below the PC board assembly, perpendicular to the PC boards. This setup is shown in Figure 4 and Figure 5. The specimen assembly is elevated 2.5 cm off of the platform of the load cell to accommodate the location of the line burner. The line burner valley is 3 cm wide and the valley running parallel to the PC boards is 2.5 cm wide. The specimen assembly is placed such that the PC boards are over the 2.5 cm valley. The requirements for the line burner are described in section 5 of ATIS T1.319. It is constructed of type 304 stainless steel tubing with a nominal 9.5 mm diameter and one end welded closed. Eleven holes, 2.78 ± 0.1 mm in diameter, with 13 mm spacing on center are drilled through one side of the tube, starting 13 mm from the welded end of the tube. Compression fittings are used to connect the burner to the output of the fuel assembly. Ultra high purity methane is used.

Figure 4 – Specimen assembly placed over the line burner on top of the load cell.

Figure 5 – Line burner attached to ring stand.

The PC board assembly and line burner are positioned as described above. The position of the base of the material is approximately 2.5 cm higher than the base of the hood curtain. To begin this test, the line burner is ignited, and the methane flow is brought up to 5 scfh to provide a 65 mm flame height. All recording instruments are initiated and the flame of the line burner is allowed to burn for 1 minute to stabilize before the printed circuit boards are placed on top. The PC boards are placed above the center of the line burner, oriented perpendicular to the line burner. The line burner remains on for the duration of the test because the PC boards will not sustain a flame without an external heat source. The tests are run until smoke production from the printed circuit boards stops. This procedure is shown in Figure 6. Three tests are conducted to evaluate test repeatability.

Figure 6 – Line burner stabilizing (left). PC board assembly at beginning of ignition (center). Assembly post-smoke production with line burner (right).

2.2.4 Computer Case ABS Plastic

The computer case material is representative of the materials used as external casing for electronics equipment. The 50 W ignition source specified in UL 94 is used and the specimen setup is also similar to that specified in UL 94.

The specimen is 125 mm tall by 13 mm wide by 3.5 mm thick and is conditioned for a minimum of 24 hours at 23 ± 0.5 ˚C and 50 ± 5 % relative humidity. The specimen is wrapped in a 6 by 15 cm piece of hexagonal wire mesh to prevent dripping, which causes significant inconsistencies with smoke output and mass loss readings. The additional length of hexagonal wire mesh is held by a clamp and the material is suspended above the UL 94 bunsen burner. The top of the burner is positioned 1 cm from the bottom of the specimen. The specimen, test setup, and test are shown in Figure 7.

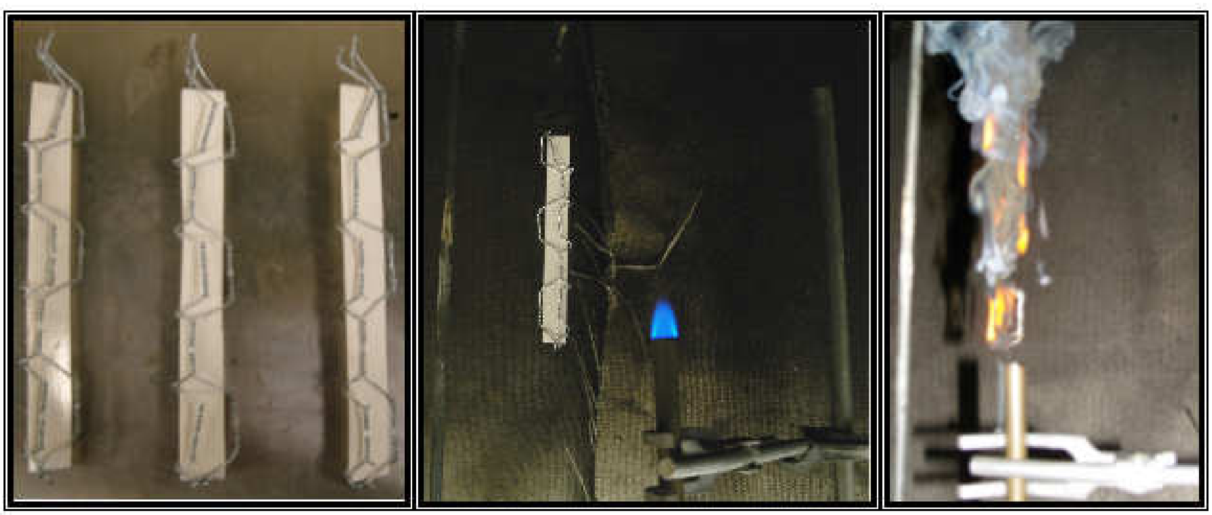

Figure 7 – Computer case specimens (left). Test setup with 20 mm premixed flame from UL 94 burner (center). Smoke production during test (right).

The ring stand and clamp are placed on top of the load cell platform and the computer case specimen is secured into the clamp. The specimen is positioned so that it is completely vertical. The second ring stand and test tube clamp are placed on top of the load cell on the opposite side of the specimen from the other ring stand. The UL 94 burner is clamped onto the ring stand and positioned 1 cm from the base of the plastic strand. The burner is then swung away from the assembly and the methane flow is adjusted to 105 ml/min with a backpressure of less than 10 inches of water. A 20 mm flame is produced and then adjusted until the yellow tip disappears. The flame is then re-measured to ensure the proper height. All recording instruments are activated and the burner is swung back into place beneath the material, approaching from the wider side. The burner maintains 1 cm from the bottom of the specimen and remains ignited for the duration of the test. If any material begins to sag down from the wire, the burner is pulled down slightly to maintain the 1 cm distance to prevent the material from getting into the burner tube. Three tests are operated for 5 minutes until smoke production stops.

2.2.5 PU Foam with Micro-fiber Fabric (Smoldering)

The smoldering test for the polyurethane foam with micro-fiber fabric uses the UL 217 smoldering smoke test temperature profile and the Wenesco HP1212YX hotplate. The material is placed in a 22.8 by 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 by 8 by 10 cm are wrapped in a 50 by 60 cm sheet of micro-fiber fabric in the manner shown in Figure 3 to create a block of material that measured 20 by 16 by 10 cm. Both materials are conditioned prior to assembly for a minimum of 24 hours at 23 ± 0.5 ˚C and 50 ± 5 % relative humidity. The assembled specimen is then placed in a 22.8 by 22.8 in. steel pan lined with foil to protect the hotplate. Additional thermocouples are placed between the pan and the hotplate and between the foil lining and the pan to ensure the appropriate temperature profile. The specimen on the hotplate as well as the material smoldering during the test and the post-test material condition are shown in Figure 8.

Figure 8 – PU foam assembly on hotplate (left). Smoldering during test (center). Posttest material condition (right).

The hotplate surface is approximately level with the bottom of the hood curtain to ensure that the low buoyancy smoke produced from this smoldering source is completely collected by the exhaust duct. The test begins by placing the 22.8 by 22.8 cm tray on the center of the hotplate, sliding the additional thermocouples into position, and placing the specimen inside of the tray. All recording devices are activated and the proportioning temperature controller switched on when the recording devices complete the 15 second countdown. The controller has been preprogrammed to follow the specified temperature profile from UL 217, which is shown in Table 1 and Figure 9. This test is performed in triplicate for a minimum duration of 4500 seconds with pre-test and post-test weights recorded.

Table 1 – Hotplate Temperature (UL 217)

Time (minutes)	Hot plate temperature
0	23 ±2°C (73 ±4°F)
0 – 3	Increased 60.7°C (109°F) per minute to 205°C (401°F)
3 +	Increased 3.2°C (5.8°F) per minute for remainder of test

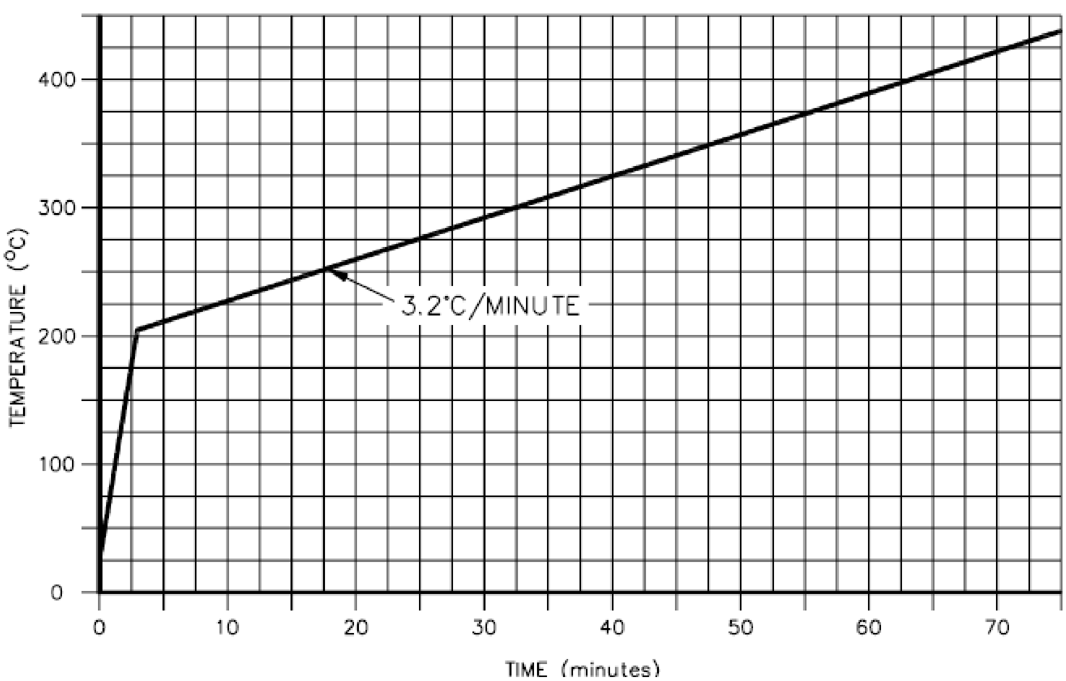

Figure 9 – Hotplate temperature profile (UL 217).

2.2.6 Ponderosa Pine Wood

Ponderosa Pine is used in the smoldering smoke test detailed in UL 217 (UL217, 2006). This test evaluates smoke detector performance for spot-type detectors. The UL 217 hotplate and temperature profile is used for this test.

Ten ponderosa pine sticks, free from knots and pitches, are placed in a spoke pattern on the hotplate so that the sticks are 36 degrees apart. The sticks are 7.6 by 2.5 by 1.9 cm with the 1.9 by 7.6 cm side in contact with the hotplate. Each stick is conditioned for a minimum of 48 hours at 52˚C (125˚F) in an air-circulating oven. The hotplate, controller, and stick positioning are shown in Figure 10.

Figure 10 – Hotplate position (left). Proportioning temperature controller (center). Ponderosa pine sticks placed in UL 217 spoke pattern (right).

The hotplate surface is approximately level with the bottom of the hood curtain to ensure that the low buoyancy smoke produced from this smoldering source is completely collected by the exhaust duct. The test is initiated by placing the ponderosa pine sticks on the hotplate in the specified spoke pattern, activating all recording instruments, and switching on the preprogrammed proportioning temperature controller. This test is performed in triplicate for 6300 seconds with pre-test and post-test weights taken for each test. The sticks lose most of their original mass and much of what is left is only char.

2.2.7 Cotton Linen Fabric

The cotton linen fabric test is intended to represent a cloth material such as a napkin or tablecloth that is too close to a heat source and begins to smolder. The hotplate described previously is used for this test, with the temperature profile specified in UL 217.

Two 30 by 30 cm sheets of cotton linen fabric, conditioned for a minimum of 24 hours at 23 ± 0.5 ˚C and 50 ± 5 % relative humidity, are placed on the hotplate and smoothed out over the surface. The sheets nearly covered the entire heated surface. The proportioning temperature controller maintains the UL 217 temperature profile. Figure 11 shows the precut cotton linen fabric, the positioning on the hotplate, and the fabric smoldering during testing.

Figure 11 – Two-ply cotton linen fabric (left). Cotton linen fabric sheets on hotplate surface (center). Fabric during testing (right).

The hotplate surface is approximately level with the bottom of the hood curtain to ensure that the low buoyancy smoke produced from this smoldering source is completely collected by the exhaust duct. To begin this test, the two sheets of fabric are stacked and adjusted so that the edges and corners match up. They are then placed on the hotplate, pressed flat and smoothed out across the heated surface. All recording instruments are started and the proportioning temperature controller is switched on to the preprogrammed temperature profile. The test is performed in triplicate for a minimum duration of 5400 seconds, which allowed for total consumption of the cotton sheets. Prior to testing, each set of sheets is weighed and post-test weight is assumed to be zero.

2.2.8 PVC Insulated Wire

The PVC insulated wire test is representative of smoke produced from an electrical overload. This test generally follows the procedures detailed in NFPA 76 Appendix B, *Performance Test Procedures for Very Early Warning and Early Warning Fire Detection Systems*. The smoke produced from this test simulates the smoke that might be produced during the early stages of a telecommunications fire.

The North American Wire Test is used as the procedure for this test. A 1 m long PVC insulated solid 22 AWG copper wire with a radial insulation thickness of 1.1 mm is 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 is conditioned for a minimum of 24 hours at 23 ± 0.5 ˚C and 50 ± 5 % relative humidity, cut to the 1 m length, and no more than 12 mm of insulation is removed from the ends of the wire. The wire is placed on a foil covered surface in a manner that prevented kinks or crossovers that could interfere with the current application. The ends are connected to a reef bar that is connected to the Sorensen DCS 60-50 power supply through 10 AWG stranded wire. This setup is shown in Figure 12.

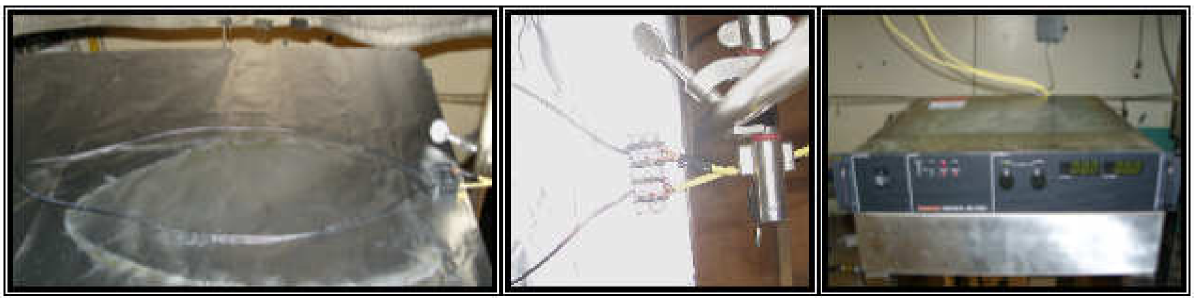

Figure 12 – PVC insulated wire (left). Reef bar connection (center). Sorensen DCS 60-50 power supply (right).

The foil surface for this test is level with the base of the hood curtain to limit the potential for smoke loss from the hood. To begin this test, the wire is connected to the reef bar. The power supply is then switched on and set to a constant current of 28 amps. The recording instruments are activated and the voltage is activated to impose the current. The current is applied for 1 minute as the voltage increases to maintain 28 amps. Data is taken until the wire ceases to produce any more smoke after the current is shut off.

Chapter 3: Experimental Results

The experimental results described in this chapter are produced from fire tests performed following the procedures explained in Chapter 2. These tests were completed during the summer of 2007 with assistance and provisions from Underwriters Laboratories, Inc., in Northbrook, Illinois. The data provided in this section consists of mass loss (for flaming sources only), heat release rate (for flaming sources only), and smoke release rate.

3.1 Shredded Office Paper

The shredded office paper tests are performed for 360 seconds, which allowed for enough time for the smoke generation to reach its peak and return back to zero. Figures 13-15 show the results for the three replicated tests.

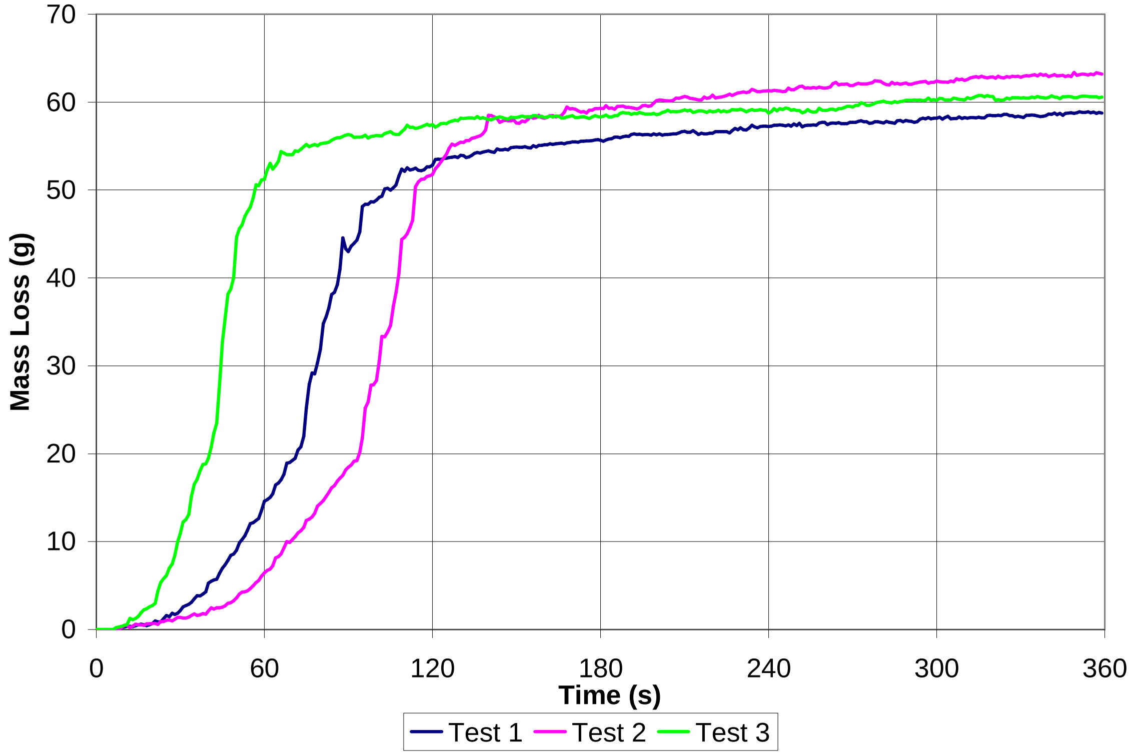

Figure 13 – Shredded office paper mass loss.

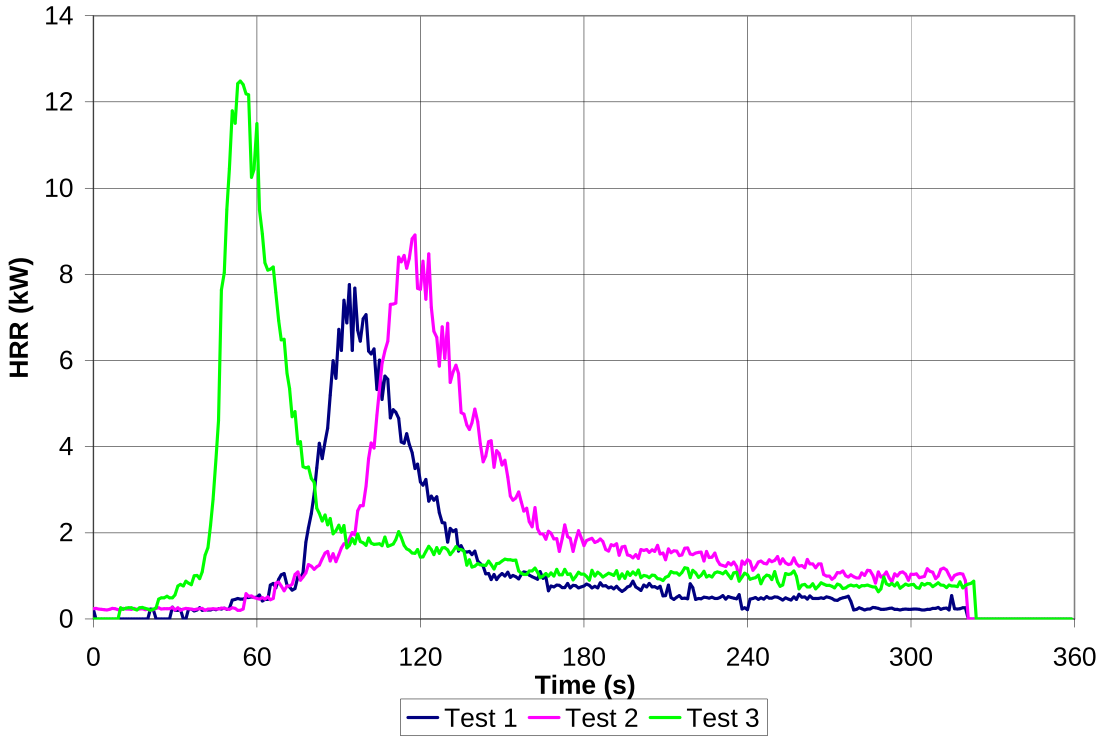

Figure 14 – Shredded office paper heat release rate.

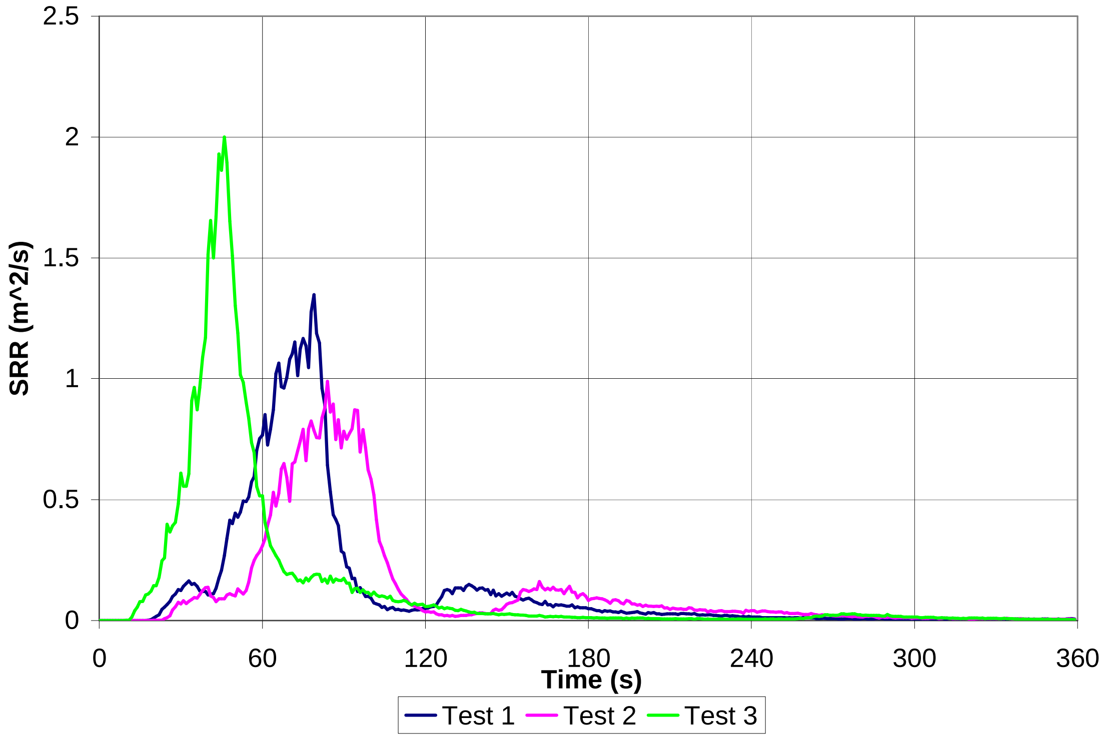

Figure 15 – Shredded office paper smoke release rate.

3.2 PU Foam with Micro-fiber Fabric (Flaming)

The PU foam with micro-fiber fabric package flaming test is performed for 640 seconds to capture the complete smoke production from the material. Figures 16-18 show unique characteristics and produce consistent data.

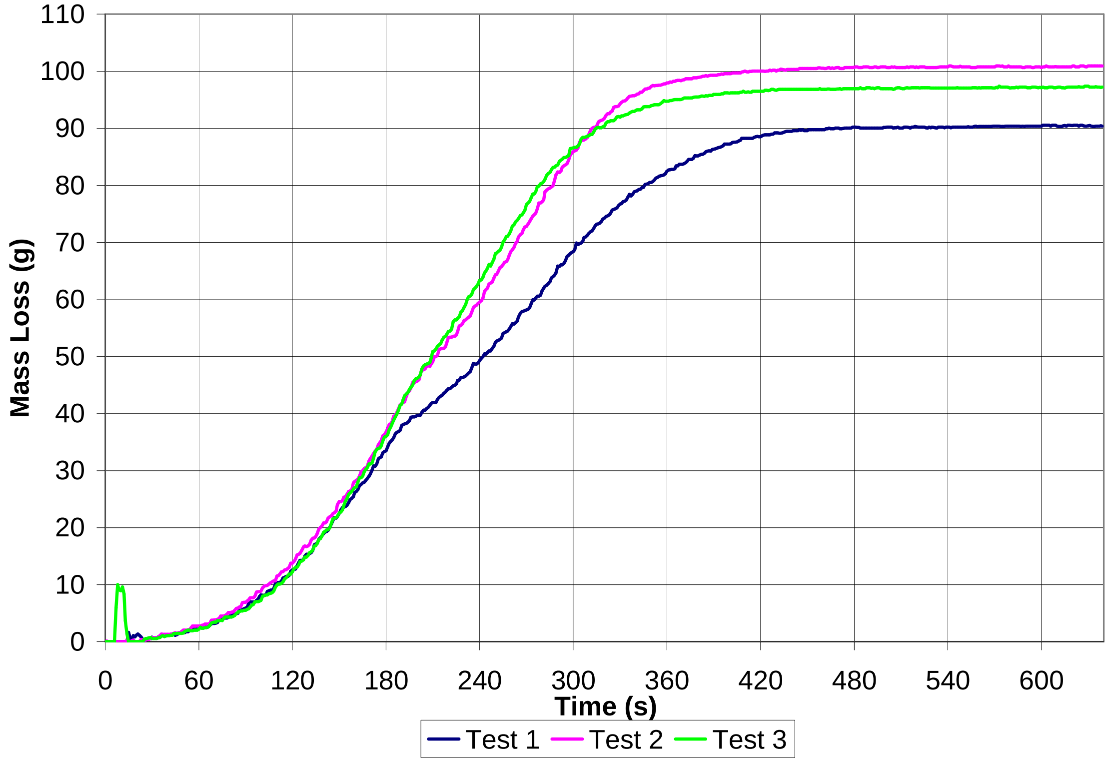

Figure 16 – Flaming PU foam with micro-fiber fabric mass loss.

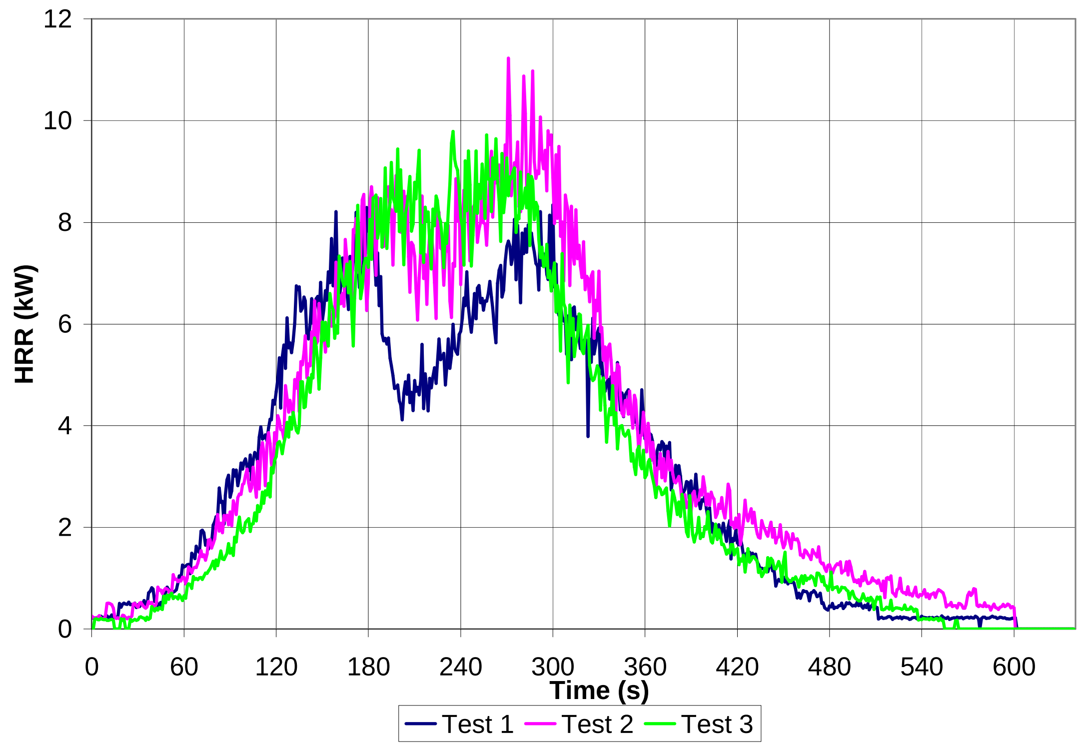

Figure 17 – Flaming PU foam with micro-fiber fabric heat release rate.

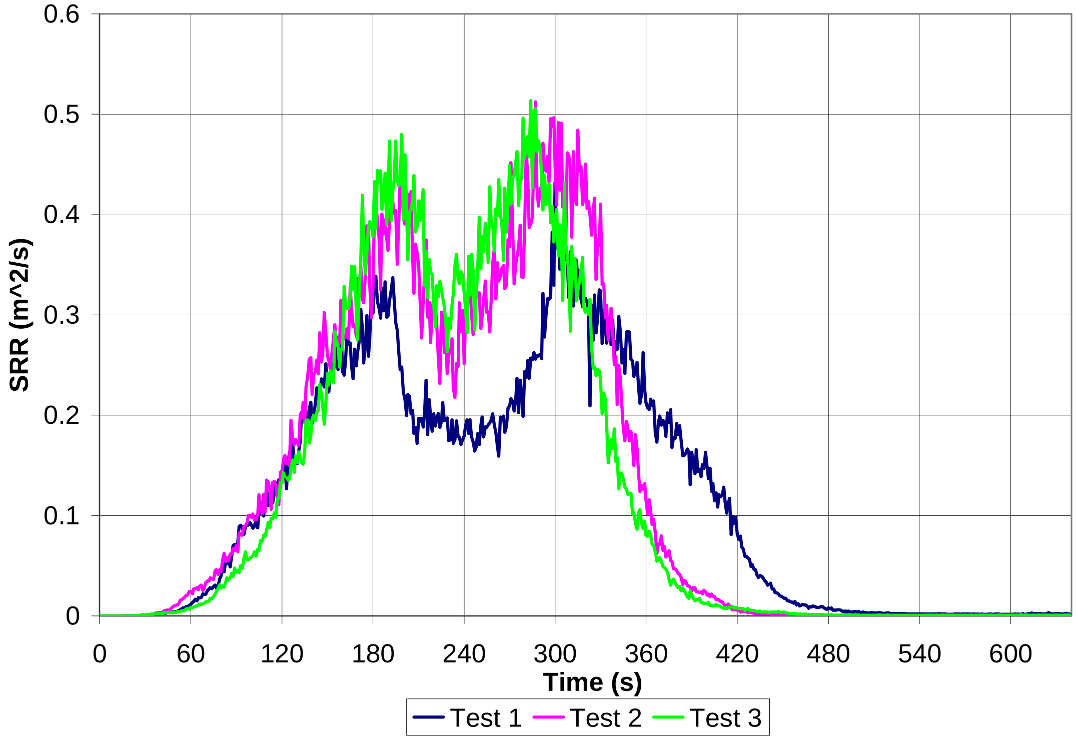

Figure 18 – Flaming PU foam with micro-fiber fabric smoke release rate.

3.3 Printed Circuit Board

The printed circuit board test is performed for 540 seconds to allow for the material to be significantly affected by the burner. The PC boards intumesce and do not sustain ignition without an external heat source. Figures 19-21 display data that includes the contributions of the line burner.

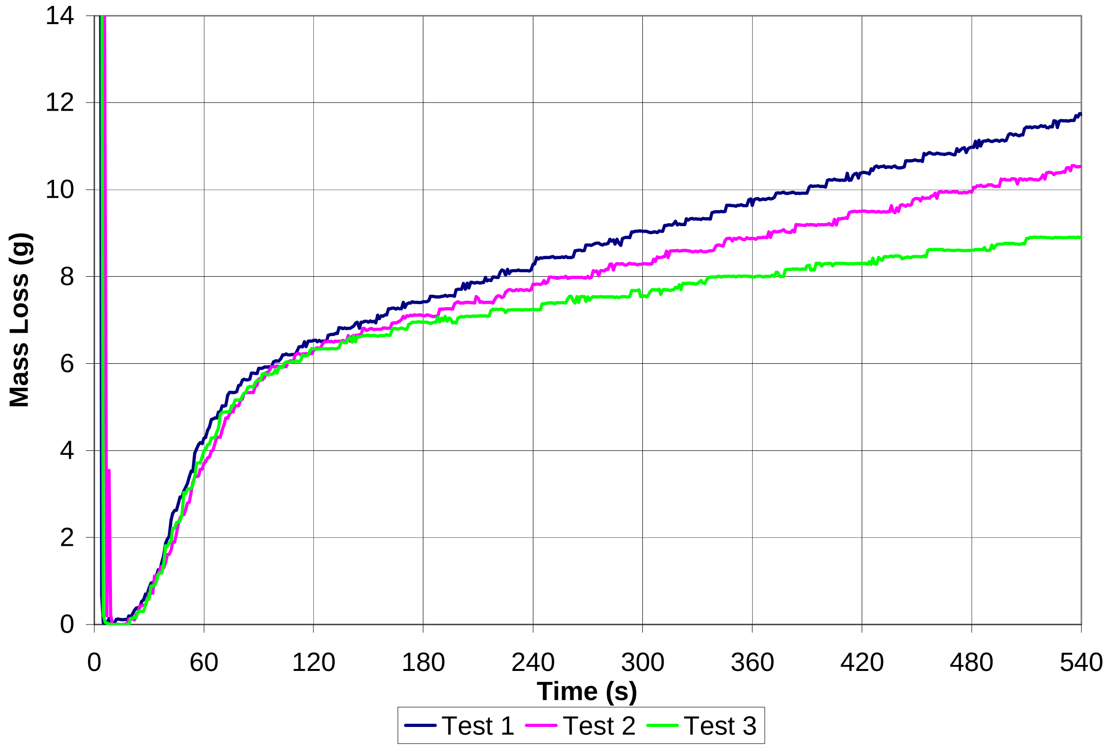

Figure 19 – Printed circuit board mass loss.

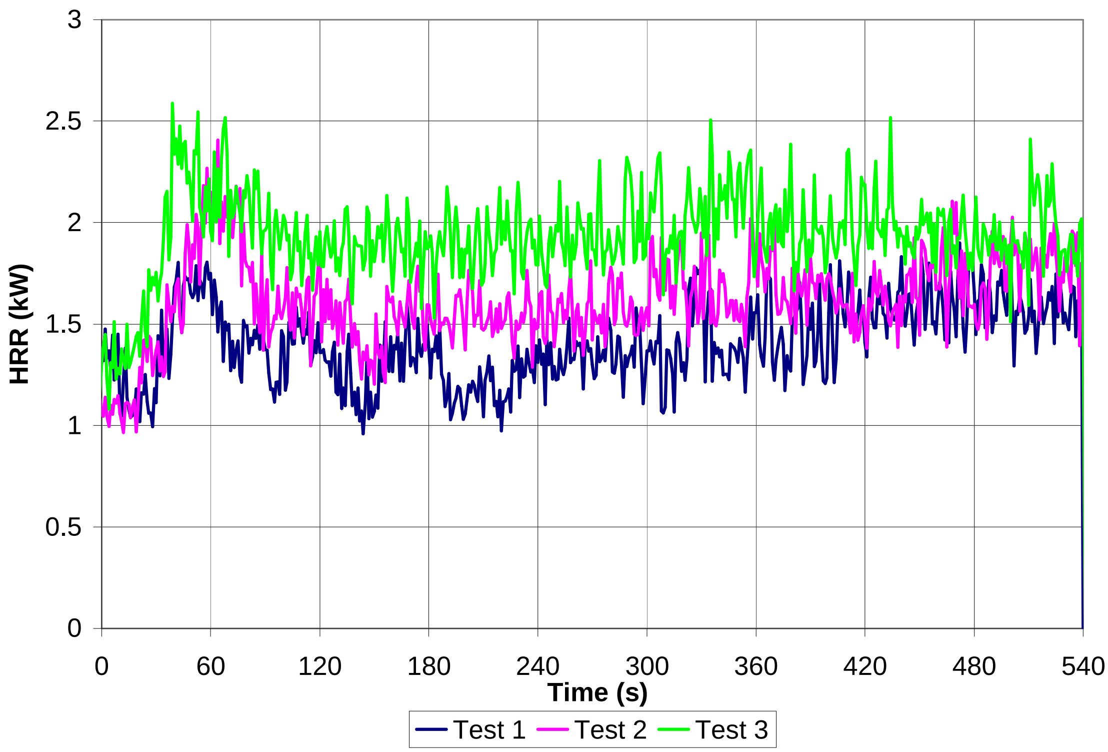

Figure 20 – Printed circuit board heat release rate.

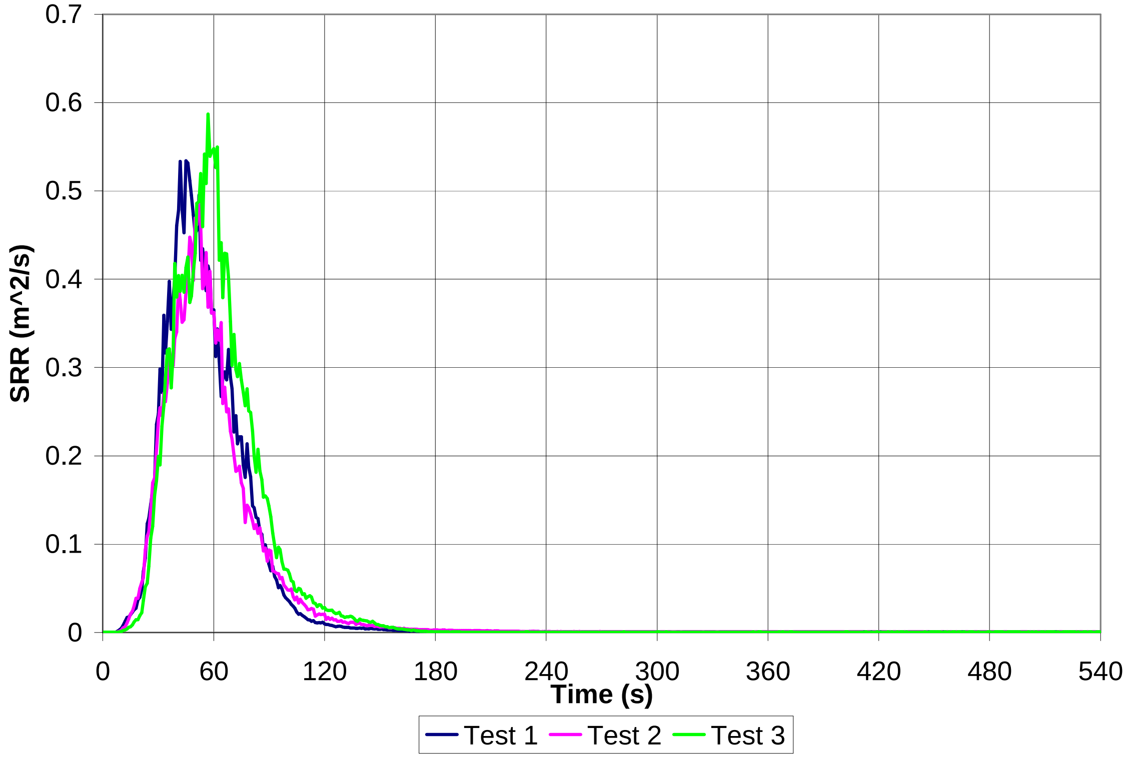

Figure 21 – Printed circuit board smoke release rate.

3.4 Computer Case ABS Plastic

The computer case ABS plastic test is performed for 340 seconds to allow for complete smoke production and affect from the burner. The computer case material deforms significantly during the test, which may have caused some of the variations. Figures 22-24 show the results of the three replicated tests.

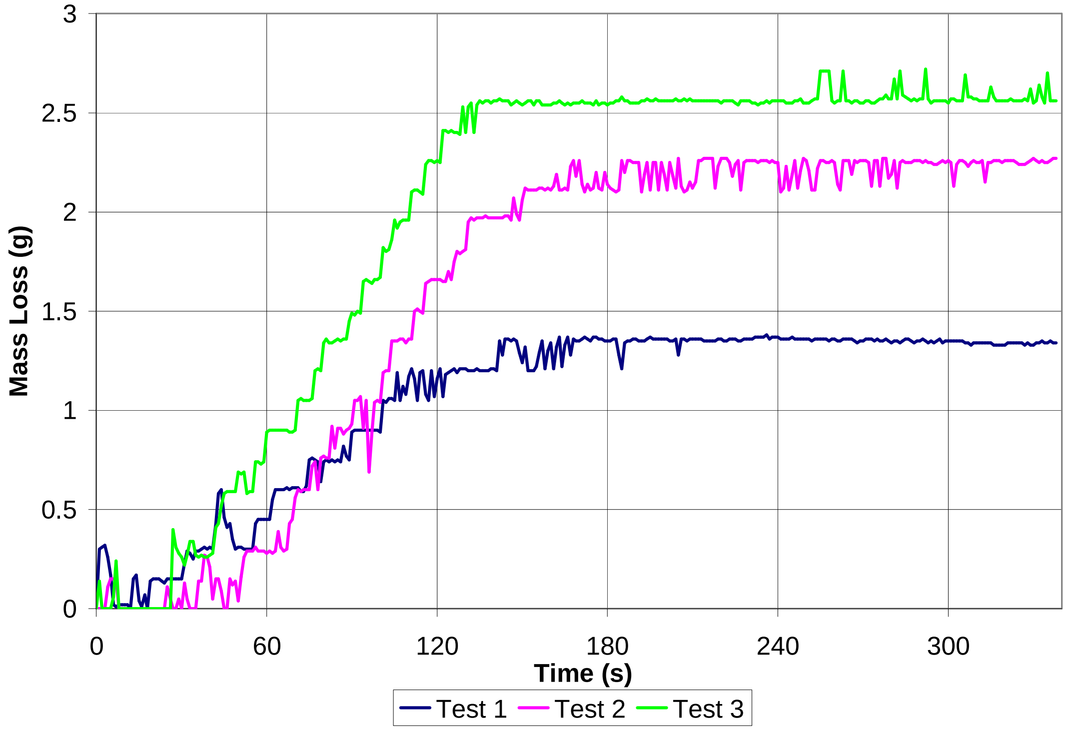

Figure 22 – Computer case ABS plastic mass loss.

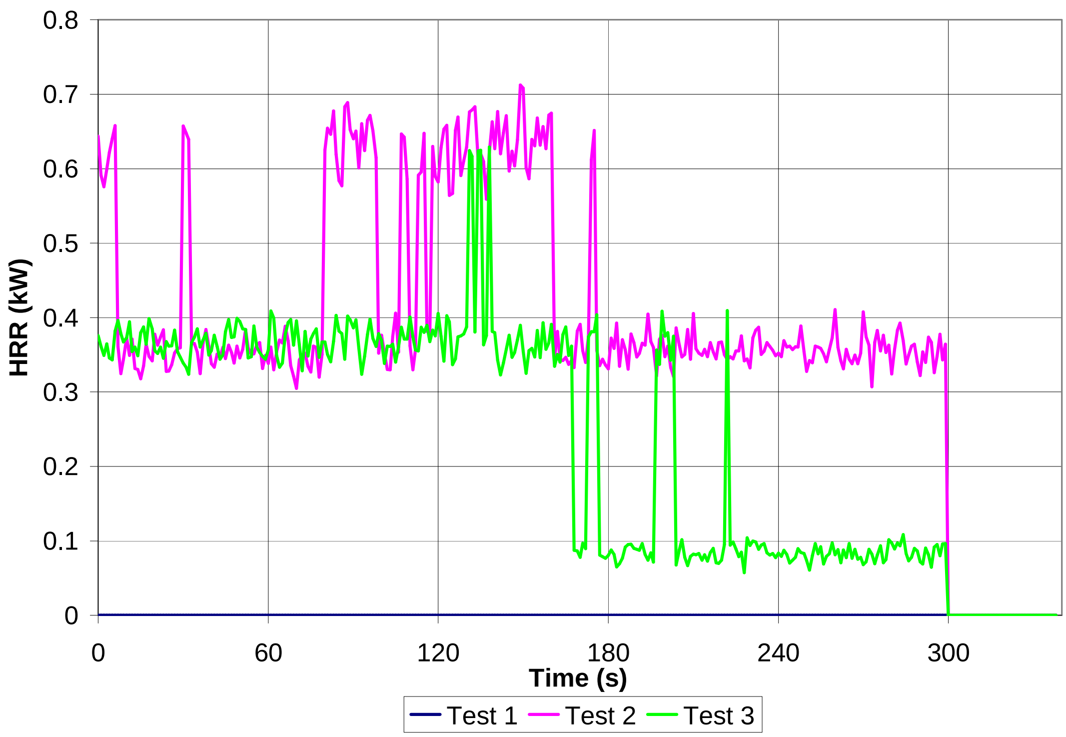

Figure 23 – Computer case ABS plastic heat release rate.

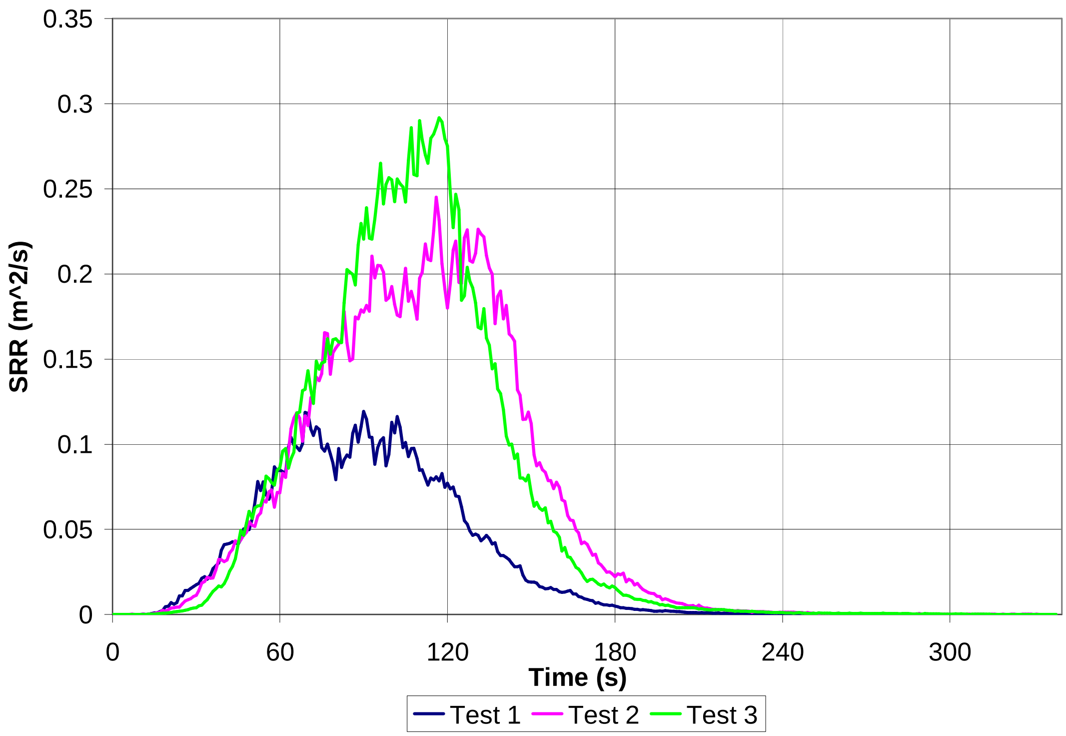

Figure 24 – Computer case ABS plastic smoke release rate.

3.5 PU Foam with Micro-fiber Fabric (Smoldering)

The smoldering PU foam with micro-fiber fabric package test is performed for a minimum of 4500 seconds to capture the increase and decay of smoke production. Figure 25 shows the smoke release rate curves for the three tests.

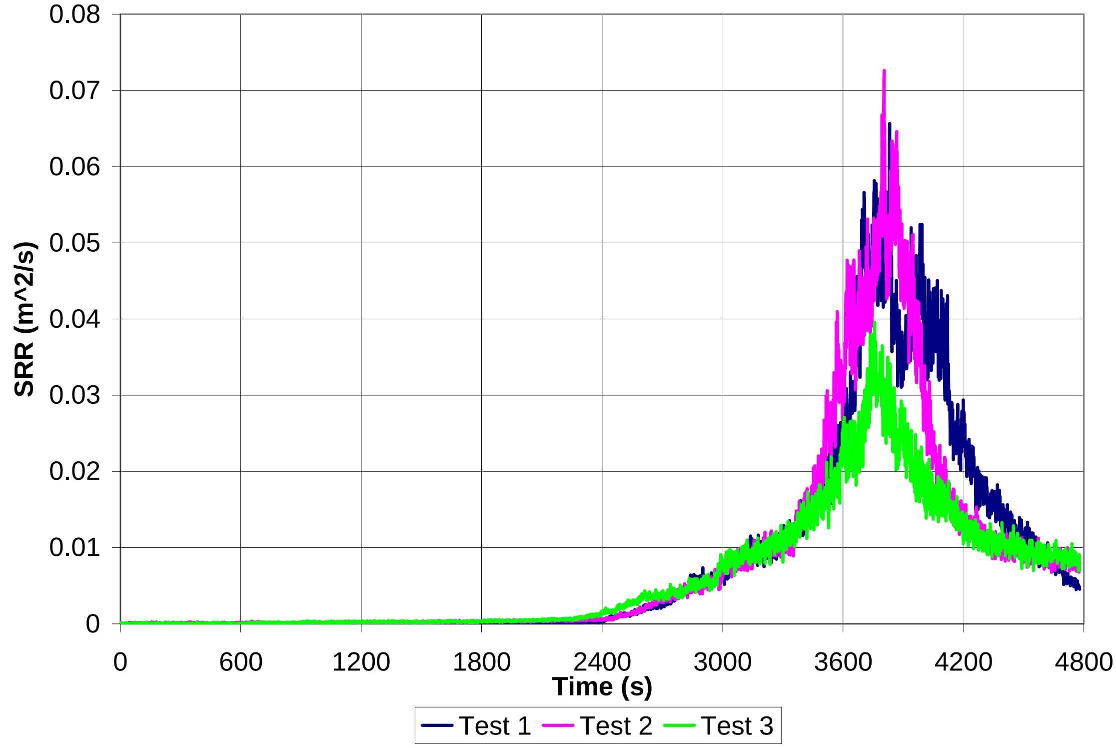

Figure 25 – Smoldering PU foam w/ micro-fiber fabric smoke release rate.

3.6 Ponderosa Pine Wood

The ponderosa pine wood stick test is performed for 6400 seconds to capture the full smoke release rate curve. This test is based on the UL 217 Smoldering Smoke Test and is very consistent between data sets. Figure 26 shows the smoke release rate data from the three tests.

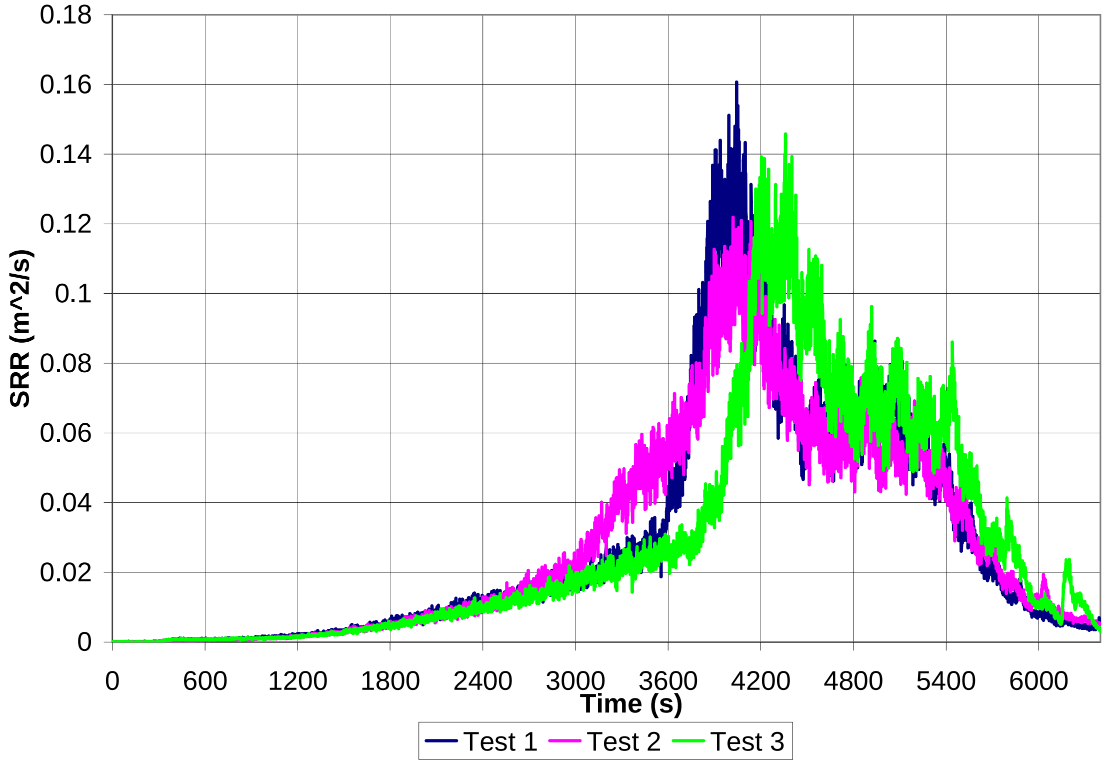

Figure 26 – Ponderosa pine smoke release rate.

3.7 Cotton Linen Fabric

The cotton linen fabric test is performed for 6000 seconds to ensure that the smoke data is completely characterized. Figure 27 shows the smoke release rate curves of the three tests.

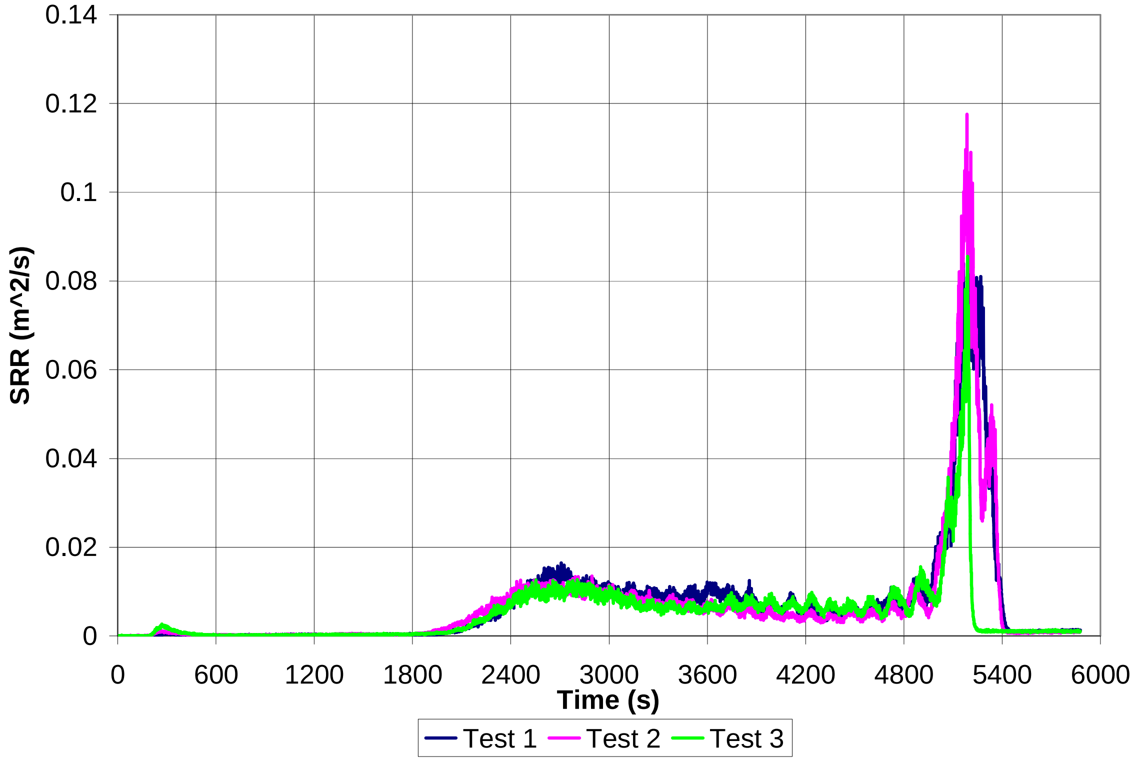

Figure 27 – Cotton linen fabric smoke release rate.

3.8 PVC Insulated Wire

The PVC insulate wire test is unique to this test set. It does not have an external heat source provided by a hotplate and does not generate a significant amount of heat itself. This characteristic means that the smoke produced will not be very buoyant. This test is only performed for 240 seconds because the smoke production is quick. Figure 28 shows the smoke release rate curves for the three replicated tests.

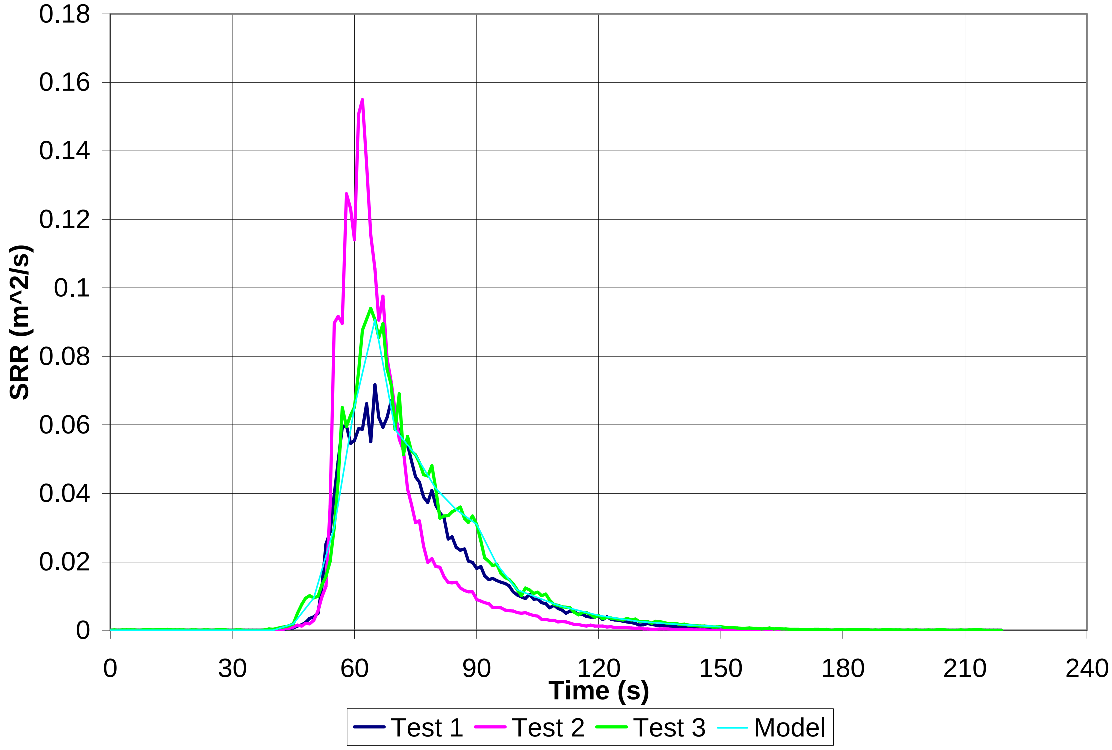

Figure 28 – PVC insulated wire smoke release rate.

Chapter 4: Analysis of Experiments

4.1 Shredded Office Paper

The shredded office paper test shows similarities between the tests, but there is some inconsistency. The primary cause of the inconsistency is 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. Figure 29 shows the test before and after flame-through. This event can also be seen with the peak in the heat release rate curves shown in Figure 14. The flame-through time is significantly affected by the packing density of the paper. This characteristic is not uniform throughout the assembled package and causes inconsistencies. If the packing density is low near the ignition orifice, then flame-through occurs earlier; whereas, if it is high near the ignition source, the flame-through tends to take longer because the material smolders longer. The effects of this characteristic are noted throughout all of the data presented from these tests.

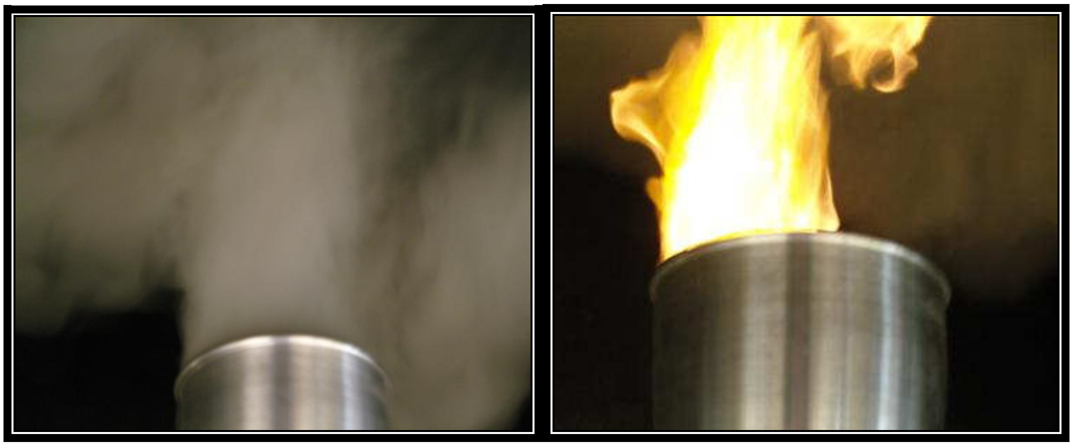

Figure 29 – Shredded office paper prior to flame-through (left). Flames present just after flame-through (right).

The mass loss from the shredded office paper tests is similar in rate, but differs in time due to the inconsistent packing density. Most of the mass is consumed during these tests and the remaining mass consists of char, a few remaining strands, and water residue produced from the combustion. For each of the tests, most mass consumption occurs between approximately 30 seconds and 120 seconds as is shown in Figure 13. In the initial part of this graph, the material does not begin to significantly burn until approximately 10 seconds. This time interval includes the 5 second ignition source application to the base of the material. The smoke release rates produced from these tests shows the effect of the packing density as well.

The smoke release rate data is consistent in nature to the heat release rate and the mass loss data. All tests show that the smoke release rate peaks just before the heat release rate. This is consistent with the observations during testing. The material initially smolders and produces a significant amount of smoke without a high heat release rate, followed by flame-through where smoke production drops and the heat release rate increases. There is a lag time associated with the smoke release rate measurement based on the distance between the flaming source and the smoke eye, the buoyancy produced by the source, and the induced exhaust velocity. Visually, during the tests, the smoke production is high in the beginning from the smoldering phenomenon, then, as flame-through occurs, the additional heat pushes the smoke up at a much higher rate and the smoke production decreases. The thermal push created by the flame-through event has an effect on the measured smoke release rate. The smoke release rate is calculated from the extinction coefficient produced from the smoke eye, and the volumetric flow rate measured by the bidirectional probe.

The smoke release rate data is shown in Figure 15. Smoke production peaks from approximately 50 seconds to 90 seconds through each data set and has a rapid increase and decay. The shredded office paper tests produced an average smoke yield of 0.091 g_s/g_f.

4.2 PU Foam with Micro-fiber Fabric (Flaming)

The flaming PU foam with micro-fiber fabric test produced unique results due to the thermal response of the polyurethane foam. In general, the data is consistent and the tests were repeatable.

Figure 16 shows the mass loss data produced from these tests. The tests are almost identical until approximately 180 seconds where the material begins to melt away from the ignited areas and the mass loss rate becomes slower. This transition to a liquid pool fire is unique to this material as compared to the rest of the fuel sources and is shown in Figure 30. The fuel package loses approximately 80 % of its mass during the tests and the remaining material consists of sticky clumps of char and residue from the PU foam. The remains of the fuel package are shown in Figure 31. The initial spike in the mass loss data shown in Figure 16 is due to the TB 604 igniter coming in contact with the load cell. The igniter is applied for 20 seconds.

Figure 30 – PU foam with micro-fiber fabric test transitioning to liquid pool dominated fire (left). Test dominated by pool fire (right).

Figure 31 – Remains of PU foam fuel package near end of test.

The heat release rate curves produced from these tests show similar traits. Figure 17 shows that each test produces two distinct peaks. The first peak is reached when the flames begin to move across the solid fuel package, igniting a significant portion of the material. The heat release rate then begins to decrease as the heat output from the ignited portion begins to melt the remaining material and allow it to move away before it can ignite. As the fuel begins to melt down completely, it transitions to a liquid pool fire and the heat release rate begins to increase again, creating the second peak. The heat release rate at this point is higher because the preheated material is collected on the foil surface and more of it is able to burn. The transition to liquid fuel dominated combustion begins just after the first heat release rate peak at approximately 180 seconds. This is consistent with the mass loss data.

The smoke release rate follows a similar profile to that of the heat release rate. Figure 18 shows these results. The smoke generation from this fuel package is not significant until after 60 seconds. The flame propagation rate is relatively slow in the beginning as the material is initially of low density, with many air pockets, resulting in low thermal conductivity. Once a significant portion of the materials is ignited, the smoke production increases dramatically. During the transition to liquid fuel dominated combustion, the smoke release rate decreases consistently with the mass loss rate. Once the materials is mostly melted, the heat release rate begins to increase as the liquid pools ignite, increasing the mass loss rate and the smoke release rate similarly. Significant smoke production occurs from approximately 60 seconds until 480 seconds. The PU foam with micro-fiber fabric tests produce an average smoke yield of 0.0952 g_s/g_f.

4.3 Printed Circuit Board

The printed circuit board tests show 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 this test include the contributions of the line burner. The heat release rate from this ignition source is approximately 1.3 kW.

Figure 20 shows that the PC boards create a peak in the heat release rate just before 60 seconds and then provide a minor contribution for the remainder of the test. This small, continual contribution can be associated with the propagation of the heat laterally across the surface of the PC boards. The material intumesces and chars, closing the 2 cm gap between them. This event causes the heat from the burner to become more restricted as it passes through the assembly. The material pops and sparks as it decomposes. Figure 32 shows the PC boards after the material has been significantly deteriorated and the center portions of each board are swollen and charred. The peak heat release rate from the PC boards, subtracting the line burner contribution is approximately 1.3 kW. The line burner will remain part of the data for this fuel package for incorporation into the input file for the modeling portion of this research.

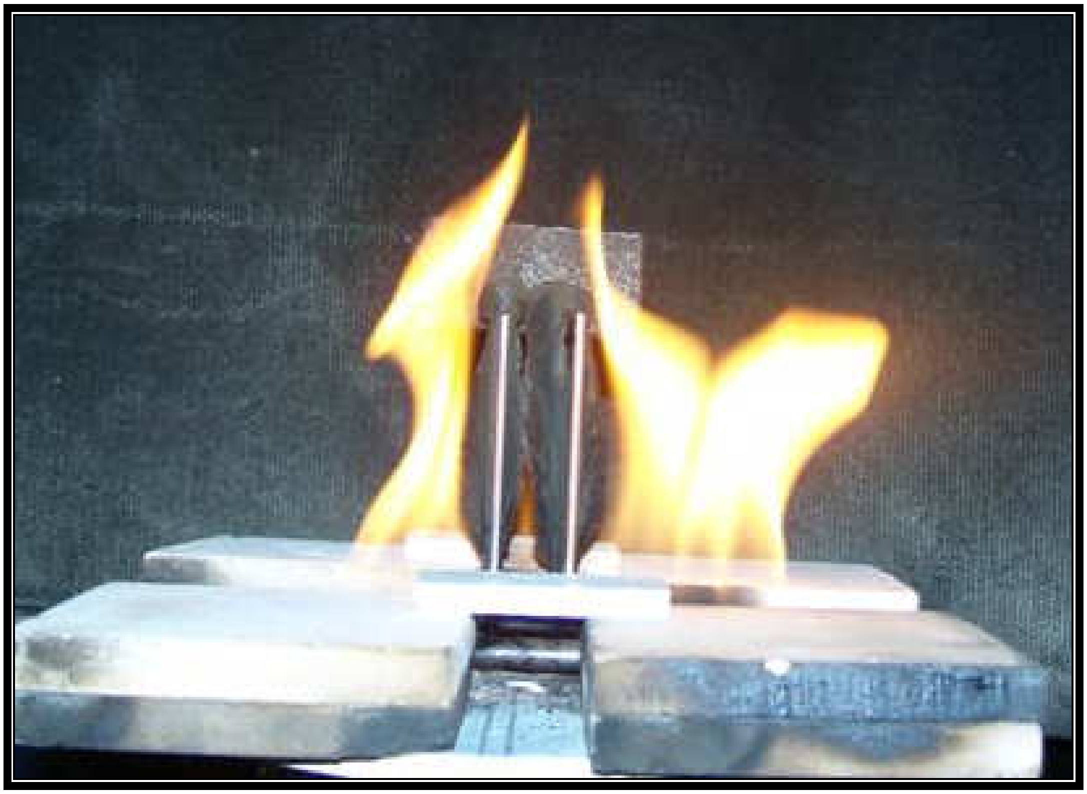

Figure 32 – PC boards during testing. Note the charred bulges from the center of the boards.

The mass loss data from these tests is shown in Figure 19. The mass loss is consistent between the tests and shows that the fuel consumption rate is highest from approximately 20 seconds to 90 seconds. The average mass loss percentage from the PC boards is 15.5%. The large spikes at the beginning of the test data in Figure 19 are from placing the fuel package on the load cell after the 60 second ignition stabilization time.

The smoke release rates, Figure 21, are consistent and peak just prior to 60 seconds. The majority of the smoke production is during the first two minutes of the test.

After approximately 180 seconds, the smoke production is zero, but it is shown that mass is still being lost. The material continued to be consumed for some time after the peak smoke output, but did not produce a rapid rate of smoke production. The smoke yield averaged 0.252 g_s/g_f.

4.4 Computer Case ABS Plastic

The computer case ABS plastic test results in some data that is below the accuracy of the instrumentation. The graphs presented in the results chapter show the complications. Some instruments would not register any changes and therefore, some data may seem to be missing from the graphs.

The mass loss from these tests ranged from approximately 1.4 g to 2.6 g. This equates to an average mass loss percentage of approximately 18.2 %. All mass loss profiles in Figure 22 become constant after approximately 130 seconds. The data shows that mass loss stopped after this point.

The heat release rate curves in Figure 23 show that the heat output including the contribution of the 50 W burner is below the accuracy of the IMO intermediate-scale calorimeter. Test 1 does not produce data, test 2 and 3 show that the heat release rate is nearly constant at just below 0.4 kW until 180 seconds where test 3 drops to below 0.1 kW.

The smoke release rate data provided in Figure 24 shows that tests 2 and 3 are consistent and test 1 produced less smoke. This is consistent with the mass loss trends. Test 1 is produced less smoke and lost the least amount of mass because the material began to drip during testing and the burner had to be moved to avoid contaminating the burner tube or extinguishing the flame. The smoke production from the computer case ABS plastic tests is shown in Figure 33. The smoke release rate for tests 2 and 3 peaks approximately before 120 seconds. Smoke production returns to zero after 240 seconds for all tests.

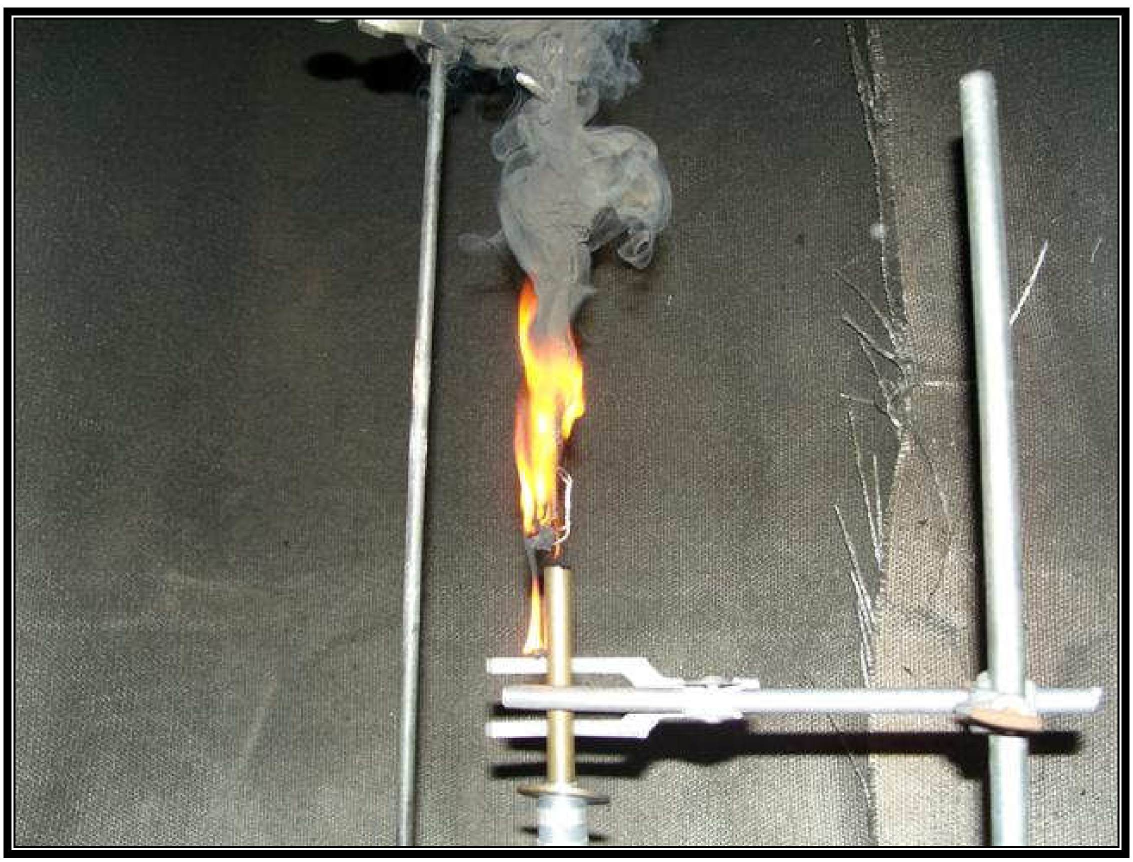

Figure 33 – Computer case ABS plastic smoke production.

The smoke yield average is 0.961 g_s/g_f. This is very high compared to typical smoke yields. The cause for this is that the measured mass loss is very low, but the smoke production is high. The accuracy of the load cell is 1 g and therefore the calculation of the smoke yield is not valid. A smoke yield this high would suggest that the material is simply vaporizing, which is not the case.

4.5 PU Foam with Micro-fiber Fabric (Smoldering)

The smoldering test for the PU foam with micro-fiber fabric produced consistent data. The carbon monoxide and carbon dioxide data for tests 2 and 3 are incomplete due to an instrument malfunction.

The smoke release rate from these tests, Figure 25, shows that significant smoke generation does not occur until approximately 2300 seconds. At this point, the smoke release rate continues to rise and peaks at approximately 3700 to 3800 seconds. The material is left very brittle as is shown in the procedures chapter. The smoke release rate is low compared to the flaming tests, but total smoke generation is significantly higher. Test 3 is lower than Test 1 and Test 2, but follows the same profile.

4.6 Ponderosa Pine Wood

The ponderosa pine tests are consistent and show similar trends between tests. Test 1 shows slightly higher values for some of the data, but remains similar.

The smoke release rate of smoldering ponderosa pine begins much earlier than the PU foam package. Figure 26 shows that the smoke release rate begins to increase near 500 seconds. This curve peaks near 4000 seconds and then falls dramatically to a point where it plateaus for a bit and then continues to decrease. This trend is shown in each of the data sets in Figure 26. The total smoke produced during this test is approximately 182 m^2.

4.7 Cotton Linen Fabric

The cotton linen fabric test shows two peaks, similar to the flaming PU foam package, but not nearly as dramatic. The dual peaks are noticeable in the smoke release rate, the particle count density, and the carbon monoxide production.

The smoke release rate begins to increase near 200 seconds and creates a primary peak near 2600 seconds. This peak is caused by the lower sheet deteriorating and the upper sheet shriveling upward and moving away from the heated surface. As the sheets begin to heat up, they begin to produce smoke and deform. As they deform, a majority of their surface loses contact with the heated surface and the smoke release decreases temporarily. This is shown in Figure 27. As the hotplate temperature continues to rise, the lower sheet becomes significantly charred and the upper sheet begins to decompose under the higher heat. Near 5000 seconds, the upper sheet rapidly smolders, creating the peak that is seen in this graph. The material is eventually completely consumed and small piles of char remain. The shriveled upper sheet and the post-test remains are shown in Figure 34. Figure 35 shows the mid-test decomposition of the lower sheet as compared to the upper sheet. The lower sheet is significantly more decomposed and is almost completely consumed by the time the upper sheet begins to rapidly decompose.

Figure 34 – Cotton linen fabric upper sheet shriveled (left). Note the darker valleys where it remains in contact with the hotplate. Post-test remains (right).

Figure 35 – Upper sheet (top) and lower sheet (bottom) shown in mid-test conditions.

4.8 PVC Insulated Wire

The PVC insulated wire test is unique to the smoldering tests in that it is of short duration and has no significant heat source.

The smoke release rate data is provided in Figure 28. Smoke generation does not begin until after 60 seconds. At this point it rapidly increases, creating a peak in the smoke release rate data that is consistent in time and duration for the tests. The magnitude of smoke release rate is significantly higher in test 2 and test 1 is the lowest. Smoke production occurs for approximately 100 seconds. The buoyancy characteristics of the smoke are very low. The movement is laminar and slow. This is shown in Figure 36.

Figure 36 – PVC insulated wire laminar smoke production.

Chapter 5: Modeling of Test Data

The software used for this modeling is Fire Dynamics Simulator (FDS). FDS is a Computational Fluid Dynamics (CFD) model of fire-driven fluid flow (McGrattan, et al., 2007). This model numerically solves the Navier-Stokes equations with an emphasis on smoke and heat transport from fires (McGrattan, et al., 2007).

Common applications of FDS include fire reconstruction, sprinkler and detector activation studies, smoke transport analysis, and fundamental fire dynamics and combustion studies. With the data produced in Phase 1 of this project, the calculations performed by FDS will be studied and compared to the results of the IMO intermediate-scale calorimeter tests. The simulation performed in FDS will be based on the IMO intermediate-scale calorimeter dimensions and instrumentation. Fuel characteristics such as smoke yield, heat of combustion, and heat release rate will be used as inputs for the FDS simulation as appropriate.

5.1 Model Configuration

For these simulations, the IMO intermediate-scale calorimeter is modeled as closely as possibly under the constraints of the chosen grid size. The dimensions of the IMO intermediate-scale calorimeter are the basis for the domain characteristics of the model.

A grid resolution study has been performed and the grid size that will be used for this model is 2.5 cm. Using a smaller grid cell size only provided a slight increase in data resolution with a significant increase in physical simulation run time. A large grid cell size did not provide an appropriate level of data resolution. Accordingly, the dimensions of the IMO in the model are within 2.5 cm of the actual physical dimensions of the apparatus at Underwriter's Laboratories. The height of the hood specified in the model is 1.25 m; the length on each side is 1.15 m. The exhaust duct is connected to the top center of one of these sides and measures 2.5 m long. The duct is 0.15 m by 0.15 m wide of free flow dimension. The area of the duct in the model is 9.4 % smaller than the physical duct due to the constraints of the grid. The duct is 2.5 m long to allow for proper instrument locations. To compensate for the variation in duct size between the model and the IMO tests, the model specifies a volume flux to maintain the same flow past the instrumentation.

The instrumentation is also closely modeled. Carbon monoxide, carbon dioxide, extinction coefficient, oxygen mass fraction, and soot density are measured near the entrance of the exhaust duct for simulations using the mixture fraction model. The light obscuration measurement, as well as a velocity measurement, is taken 2 m from the entrance of the exhaust duct. Thermocouples have been placed above the fuel source to monitor the plume temperatures. These thermocouples were not in place during fuel characterization in Phase 1 because of the variation caused by the exhaust duct velocity.

The environmental aspects of the room have also been taken into consideration. The ambient temperature of the room, 25 ˚C, has been used as an input into the model.

The exhaust velocity is represented by specifying a volume flux within the model at the end of the duct. The exhaust velocity is different for each of the tests performed and is uniquely specified for each model. The completed model is shown in Figure 37.

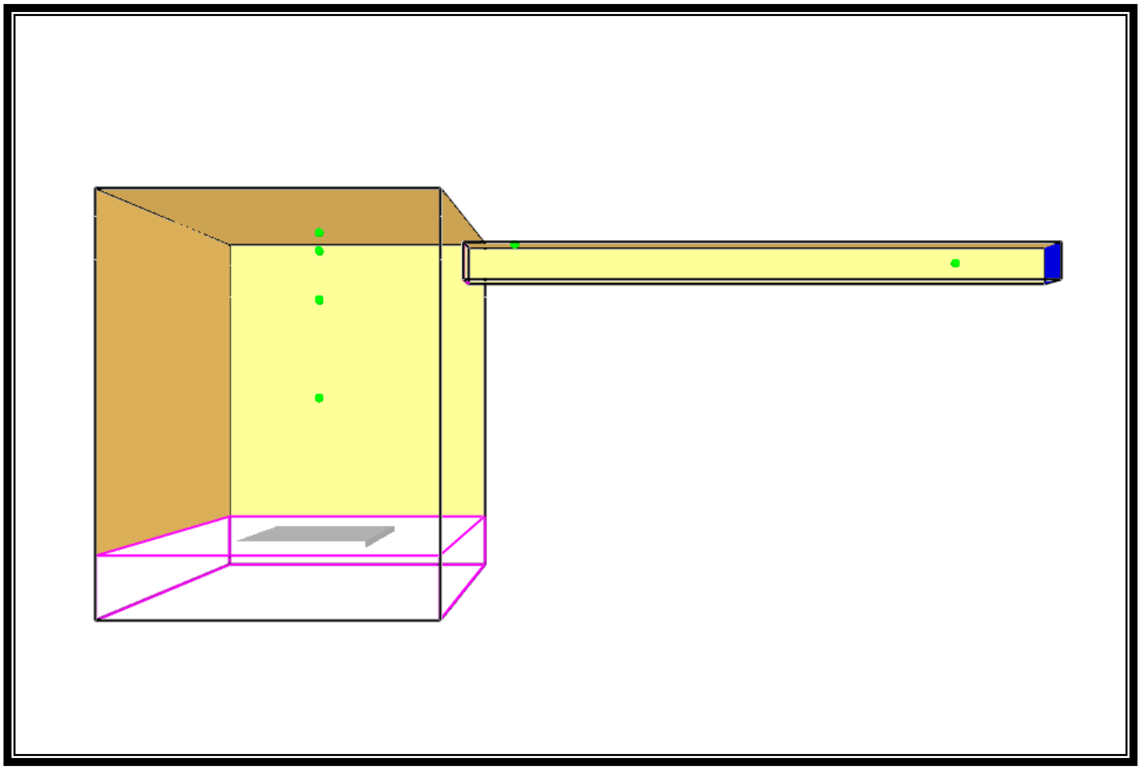

Figure 37 – IMO intermediate-scale hood in FDS.

5.2 Model Input Calculations

All of the 8 sources are modeled using a species ID for the smoke so that the smoke generation can follow the profiles of the IMO tests. The smoke generation for some of the flaming sources did not correlate directly with the heat release rate. When using the mixture fraction model in FDS, the smoke release rate is dependent on the heat release rate and therefore may not follow the appropriate profile from the IMO tests. Specifying the smoke as a separate species allows the model to ramp the smoke and heat independently. This method is also used for the smoldering models where there is no significant heat release but simply an induced temperature from the hotplate.

Using the mixture fraction model requires inputs from the IMO tests such as the average soot yield, the heat of combustion, and the heat release rate ramp. The soot yield and heat of combustion are averaged over the three tests to obtain a representative value for the model. The heat release rate ramp follows the profile of one test that is representative of the middle of the test data and shows characteristics that are found in each test. The flaming polyurethane foam with micro-fiber fabric source was simulated using the mixture fraction model for comparison to the species ID method.

The flaming sources modeled with the species ID method do not use the mixture fraction model, but a heat release rate ramp is specified along with a mass flux ramp corresponding to the smoke release rate profiles from the IMO tests. The smoldering models use the temperature profile specified in UL 217 to create buoyancy and the mass flux ramp for the smoke release rate, similar to the flaming sources. The mass flux ramp is developed by converting the units of the smoke release rate to units of mass flux. Then the maximum value is multiplied by a value from zero to one to specify the mass flux at a given time to follow the profile of the smoke release rate.

The smoke is then injected into the domain via a vent that is on the top surface of the source material. Below is the calculation for the mass flux curve.

$$\dot{m}'' = \frac{SRR/\sigma}{A_{Vent}}$$

Where:

$\dot{m}''$ = Mass flux (kg/m^{2}s)
SRR = Smoke release rate (m^2/s)
σ = 8700 (m^2/kg)
A_{Vent} = Fuel source vent area for smoke injection (m^2)

The exhaust velocity is based on an average of all three tests and is then converted to a volume flux and created by a vent at the end of the exhaust duct.

5.3 Model Output Calculations

Heat Release Rate – The heat release rate is measured directly by FDS in all flaming source models. The smoldering source models do not produce a significant heat release.

Duct Velocity – The exhaust duct velocity is measured 2 m from the inlet at the hood. This is a direct calculation of FDS.

Extinction Coefficient – The extinction coefficient is calculated from a simulated measurement of the species obscuration taken in the duct near the original obscuration measurement from the actual IMO hood. This calculation is unnecessary when the mixture fraction model is being used because FDS provides a direct measurement of the extinction coefficient. When calculating the extinction coefficient, the experimental exhaust duct diameter is used to compensate for the difference in diameters between experimental and simulated domains. This correction removes the variation in the relationship between the simulated data and the experimental data when converting from obscuration to extinction coefficient.

$$k = -\frac{\ln\left(1 - \lambda/100\right)}{x}$$

Where:

k = Model extinction coefficient (m^{-1})
λ = Percent obscuration (%)
x = 0.18 m (Experimental exhaust duct diameter, Beam path length)

Obscuration – The beam obscuration measurement is directly calculated in FDS.

Smoke Release Rate – The smoke release rate can be derived from the extinction coefficient and the appropriate volume flux specified in the input file that is unique to each fuel source.

$$\dot{S} = k\dot{V}_{Exhaust}$$

Where:

$\dot{S}$ = Smoke release rate (m^2/s)
k = Extinction coefficient (m^{-1})
$\dot{V}_{Exhaust}$ = Volume flux at simulated measurement (m^3/s)

5.4 Model Results and Analysis

5.4.1 Shredded Office Paper

The figures below show the results from the shredded office paper model in comparison to the data from the IMO tests. The source is modeled as a 30 by 30 by 45 cm tall volume with a 30 by 30 cm vent on top to provide the represented heat and smoke production.

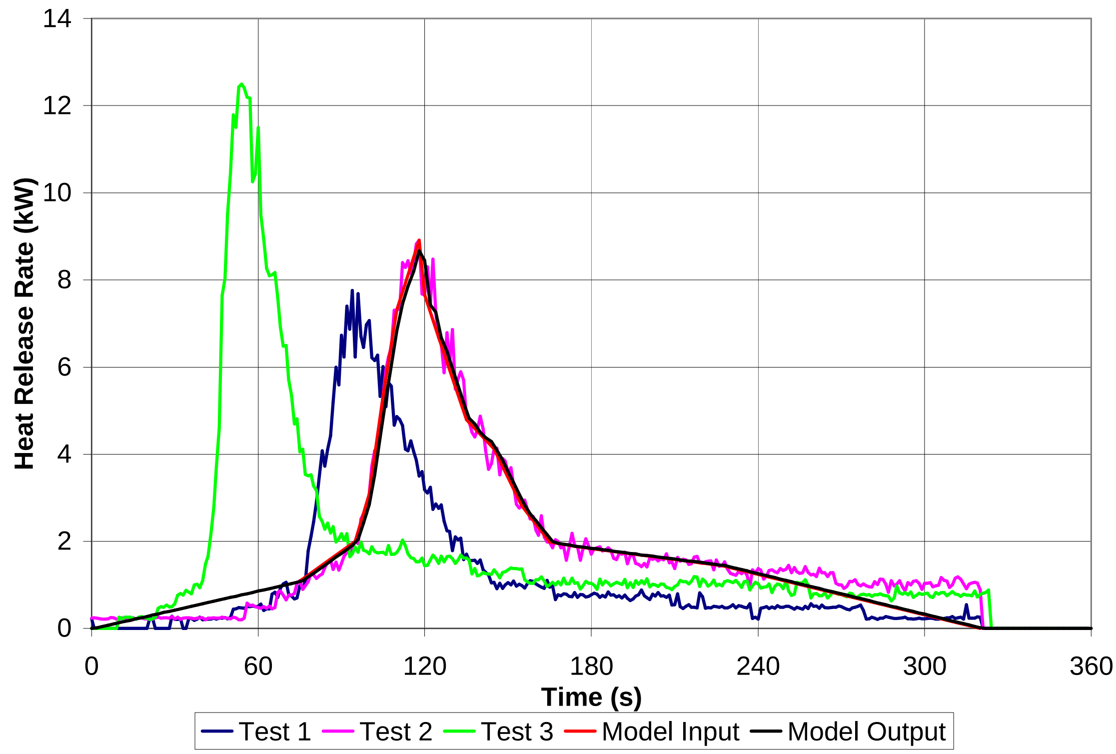

Figure 38 – Shredded office paper heat release rate.

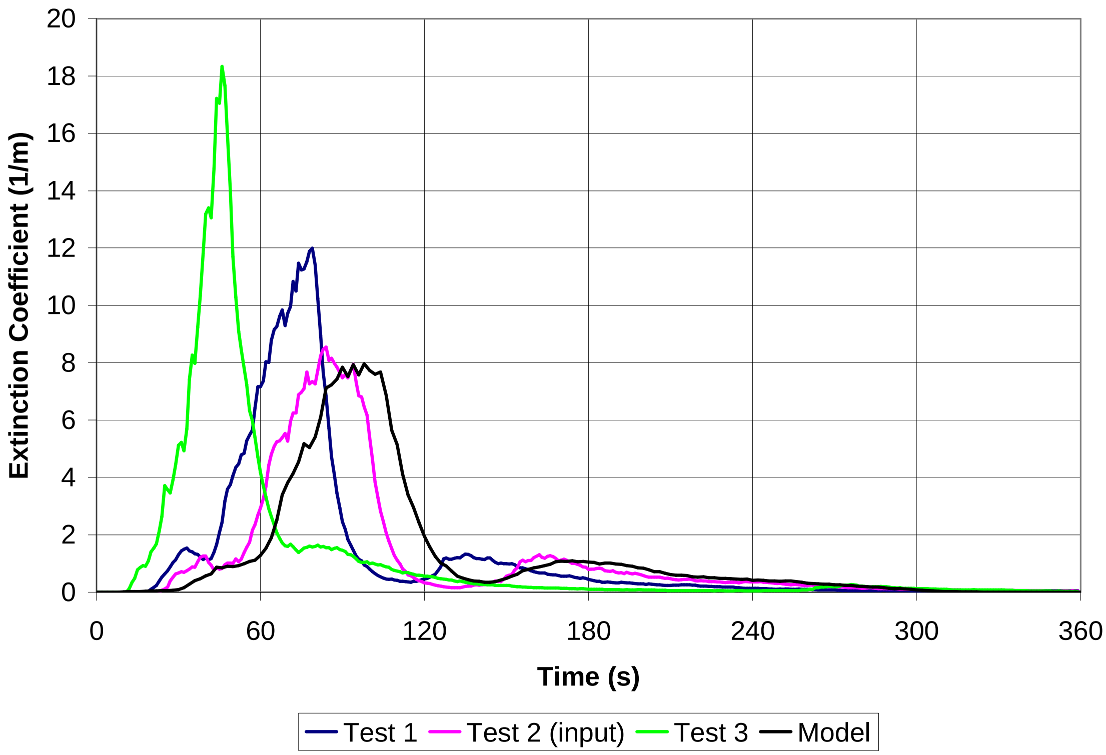

Figure 39 – Shredded office paper extinction coefficient.

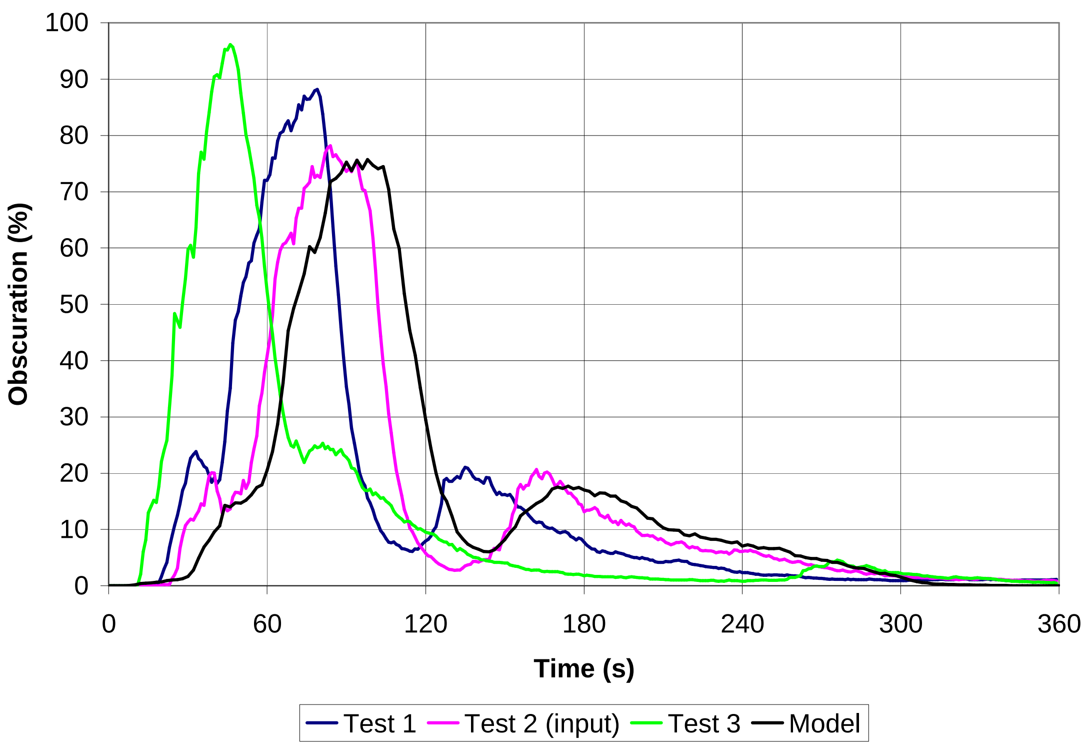

Figure 40 – Shredded office paper obscuration.

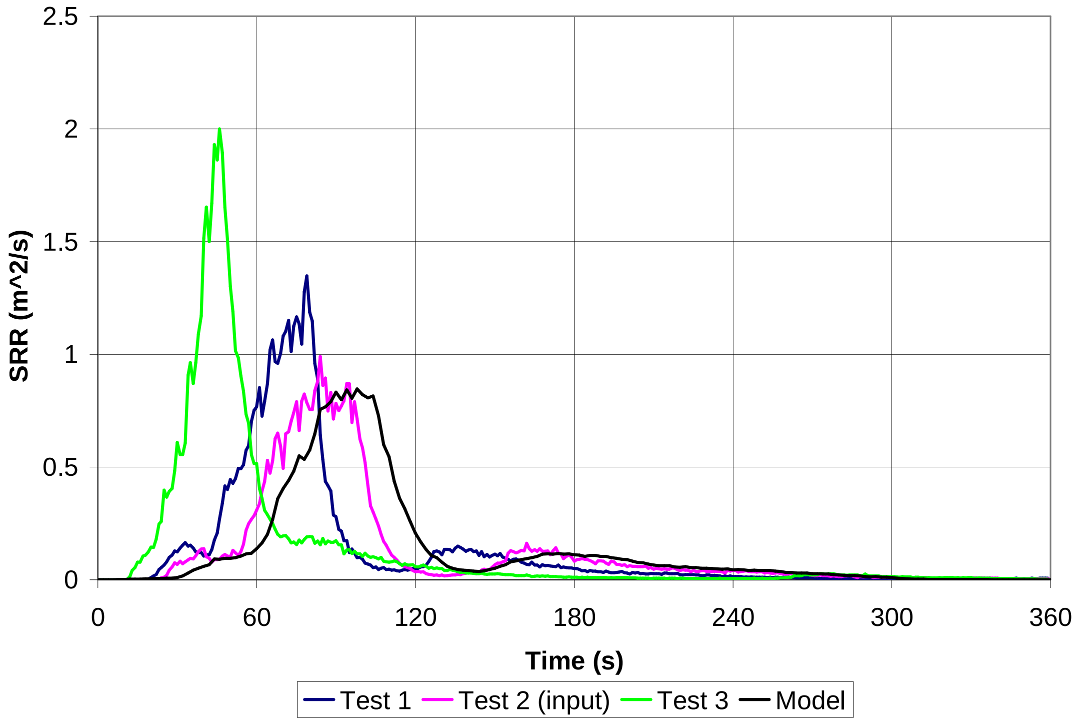

Figure 41 – Shredded office paper smoke release rate.

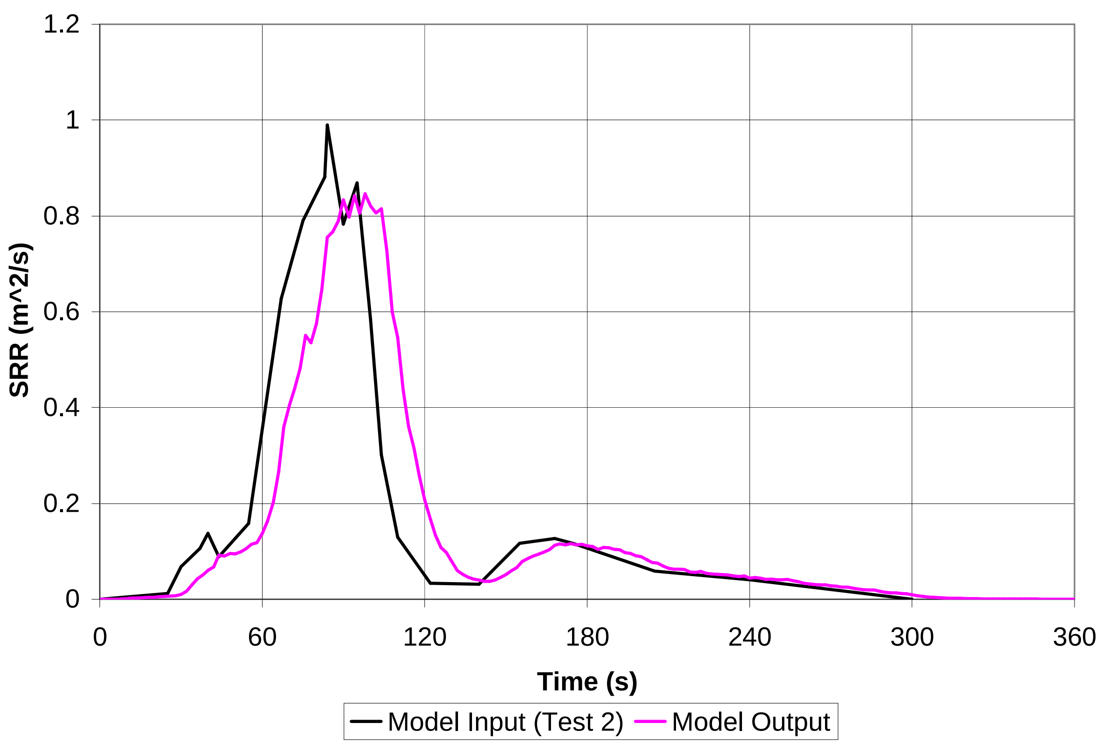

Figure 42 – Shredded office paper model input and output.

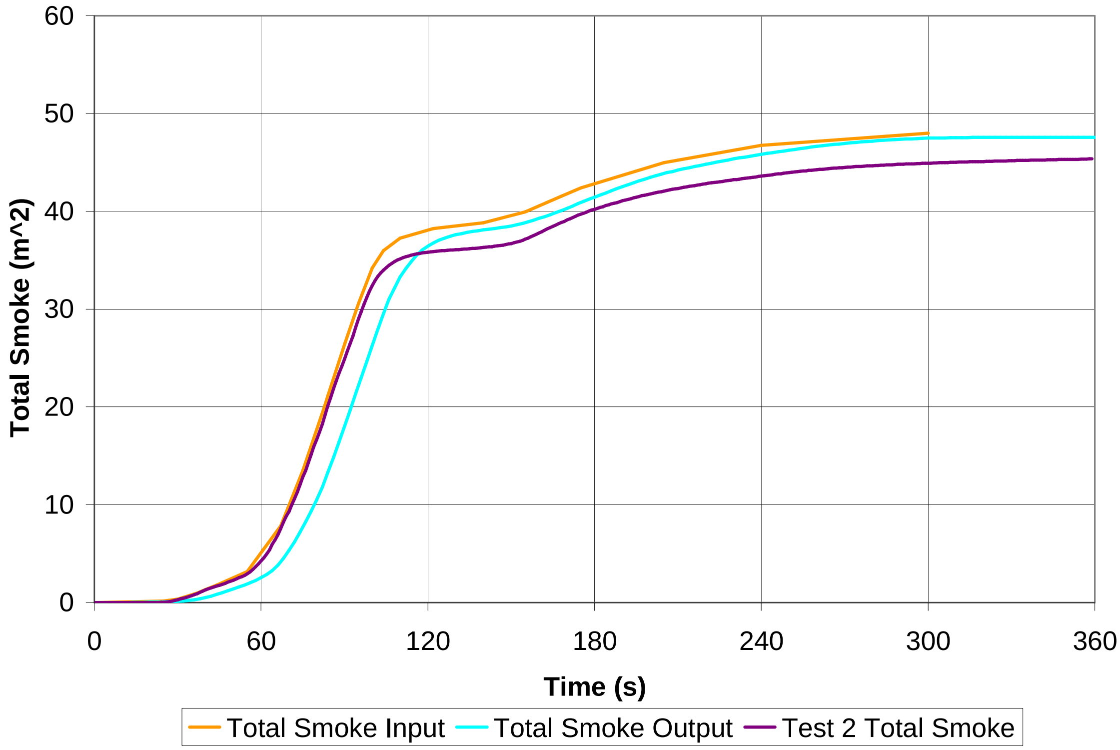

Figure 43 – Shredded office paper total smoke.

Figures 39-42 show that the Species ID method used for this model creates lag between the input (Test 2) and the output (Model) for measurements related to the species. Figure 38 shows that the heat release rate does not follow this trend and the input and output for the model are identical. This lag is created by the lack of correction for transport lag in the experimental measurement. The time of experimental measurement is used as the time of release from the fuel source. This lag is simply the transport time from the fuel source to the measurement point within the duct. The heat release rate data has corrected for the transport lag in the experimental data. A review of the data and the experimental setup showed that the transport lag in the experimental phase was approximately 15 seconds.

Figure 39 and Figure 40 show the extinction coefficient and the obscuration. The obscuration is a direct calculation from FDS and the extinction coefficient is derived from these values. The peak values and profiles are shown to be similar to the experimental inputs.

Figure 41, Figure 42, and Figure 43 are all calculated from the extinction coefficient calculation and the velocity derived from the volume flux value in the input file. The lag and difference in peak values between the input and the output of the model is shown in these three figures. The model output is up to 15 seconds behind the input and this is translated through each of the figures. Figure 41 shows that the peak smoke release rate output does not accurately reproduce the peak specified by the input. The peak from the input is short in duration and the transport phenomena in FDS may have diluted this value prior to the point of simulated measurement. Figure 43 shows that the total smoke produced in the model is 47.6 m^2, whereas Test 2 produces 45.4 m^2. The model produces 4.8 % more smoke than the actual test. The smoke release rate curve specified for this model, shown in Figure 42, produces a total smoke of 47.99 m^2. The output is 0.81 % less than the specified input. The lag between the smoke species input and output is associated with the transport lag from the source to the measurement within the exhaust duct.

5.4.2 PU Foam with Micro-fiber Fabric (Flaming, Mixture Fraction Model)

Figures 44-47 show the results from the flaming PU foam with micro-fiber fabric model in comparison to the data from the IMO tests. The source is modeled as a 20 by 15 by 10 cm tall volume with a 20 by 15 cm vent on top to provide the represented heat and smoke production using the mixture fraction model within FDS.

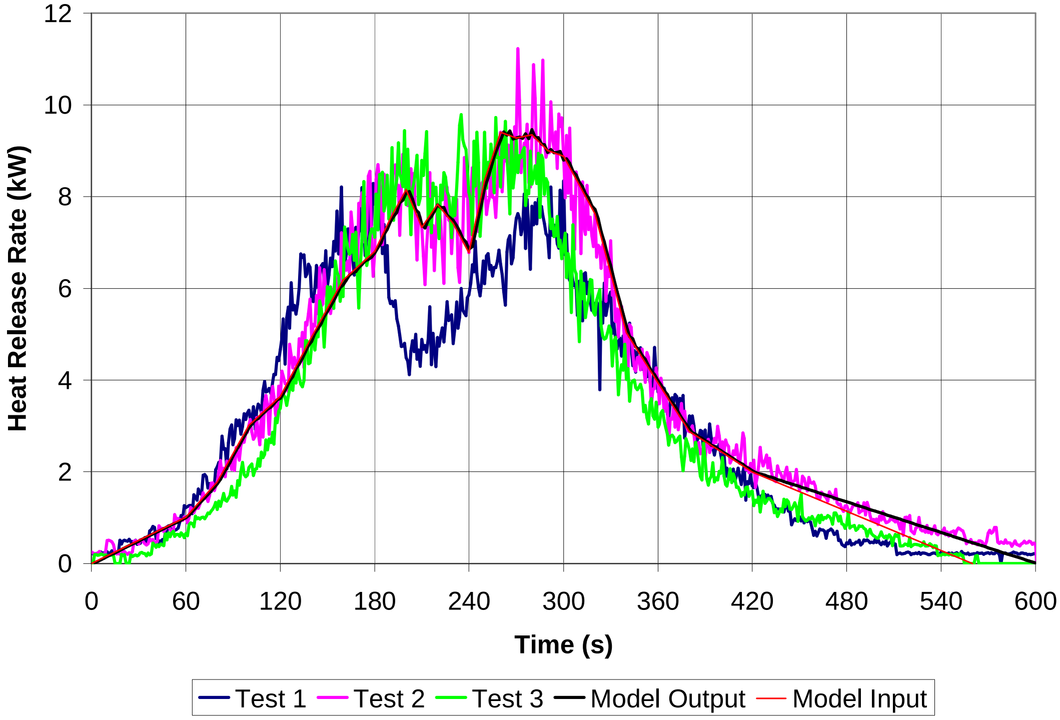

Figure 44 – Flaming PU foam with micro-fiber fabric heat release rate.

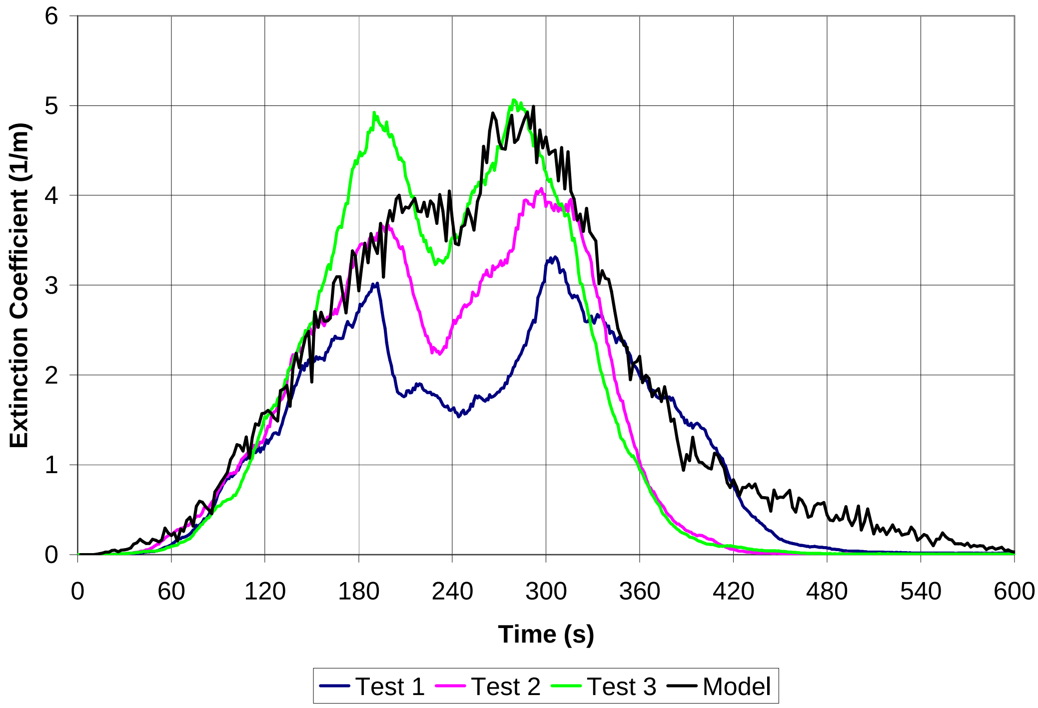

Figure 45 – Flaming PU foam with micro-fiber fabric extinction coefficient.

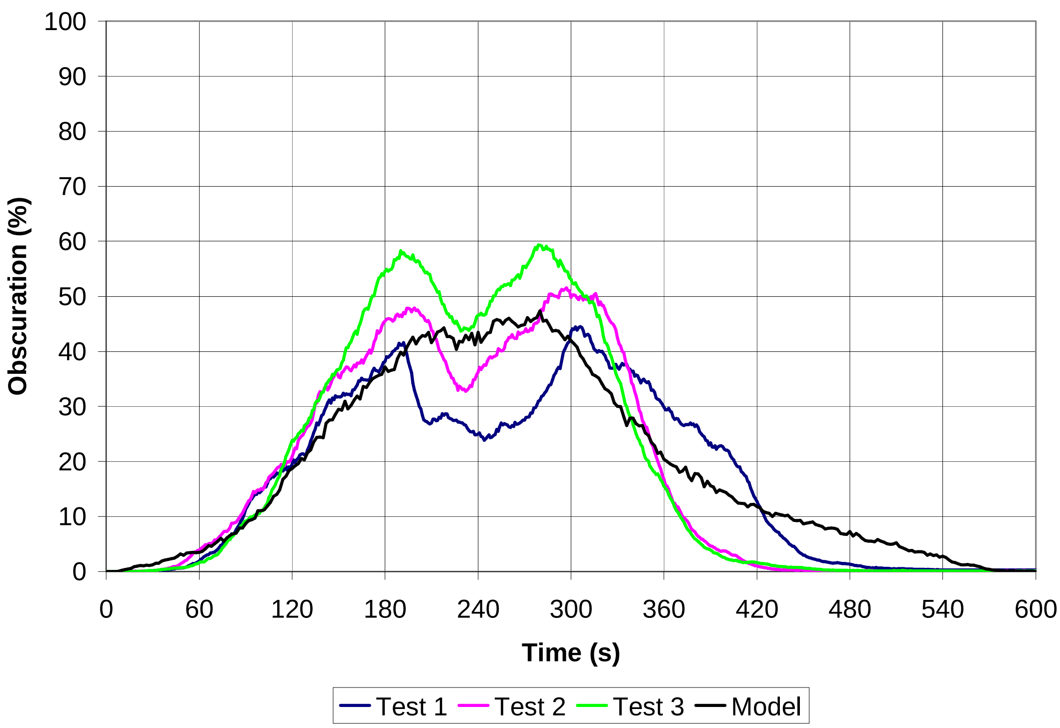

Figure 46 – Flaming PU foam with micro-fiber fabric obscuration.

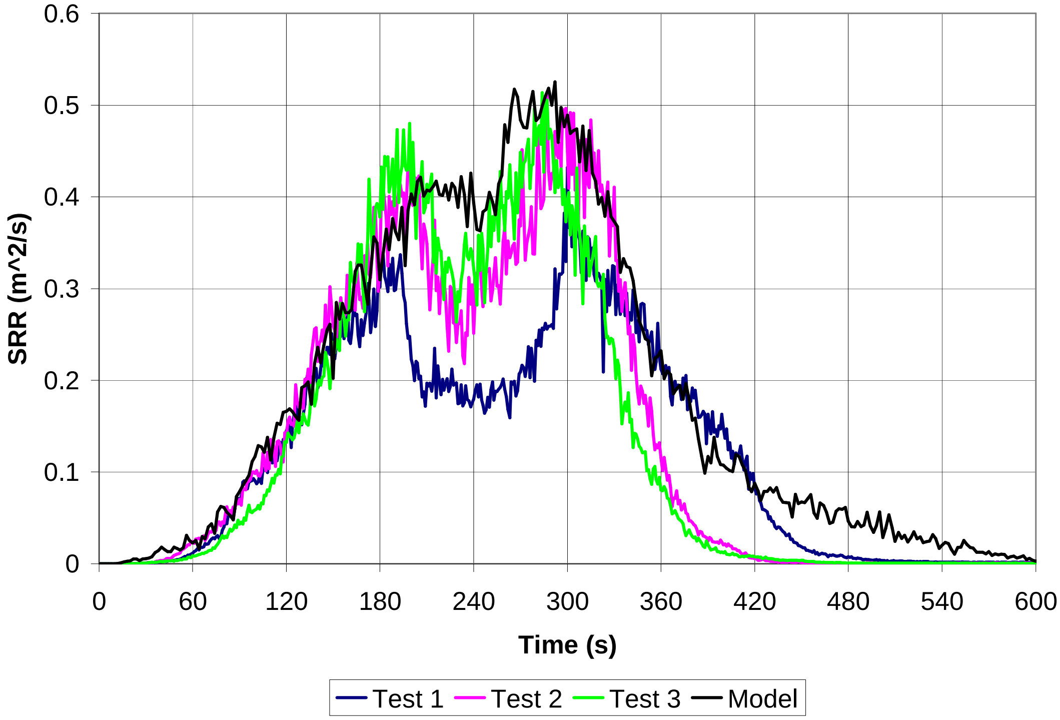

Figure 47 – Flaming PU foam with micro-fiber fabric smoke release rate.

The data displayed in these figures is derived from direct measurements made by FDS, with the exception of the smoke release rate, using the mixture fraction model. This is the only source that was successfully modeled using this procedure. The fuel source does not smolder at any point during the test and maintains a relatively dependable relationship between heat release rate and smoke release rate. This relationship is the foundation for smoke production in FDS as shown below. The smoke yield and heat of combustion are inputs into the mixture fraction model and the heat release rate is specified as a ramp function following Test 2 of the IMO tests.

$$\dot{S} = Y_s \frac{\dot{Q}}{\Delta H_c}$$

Where:

$\dot{S}$ = Smoke release rate (m^2/s)

Y_s = Smoke Yield (g_s/g_f)

$\dot{Q}$ = Heat Release Rate (kW)

ΔH_c = Heat of Combustion (kJ/g)

Figure 44 shows that the heat release rate output is similar to the model input. The output deviates near the end of the test but in a manner that is closer to the actual test than the model input.

Figure 45, Figure 46, and Figure 47 show the extinction coefficient, obscuration, and smoke release rate. These measurements remain similar to test two during the initial increase in smoke production, but then begin to differ. The extinction coefficient from the model peaks after the first peak and before the second peak from the IMO test. The maximum extinction coefficient produced from the model is approximately 20 % higher than Test 2. The decrease in extinction coefficient is also slower at the end of the simulation. These variations show the direct dependence of smoke production to the heat release rate. The extinction coefficient and smoke release rate in the model closely follow the specified profile of the heat release rate.

The model obscuration, Figure 46, is not as defined as the curve in Test 2. The peak obscuration is approximately 8 % lower than Test 2 and the slower decline near the end of the simulation agrees with the smoke dependency on heat release rate for the mixture fraction model.

Figure 47 shows that the smoke release rate calculated from the extinction coefficient measured in the simulation deviates after the first peak in Test 2. The total smoke produced in the model is 108.3 m^2, whereas Test 2 produces 84.2 m^2. The model produces 28.6 % more smoke than the actual test.

5.4.3 PU Foam with Micro-fiber Fabric (Flaming, Species ID Method)

Figures 48-53 show the results from the flaming PU foam with micro-fiber fabric model using the Species ID method in comparison to the data from the IMO tests. The source is modeled as a 20 by 15 by 10 cm tall volume with a 20 by 15 cm vent on top to provide the represented heat and smoke production.

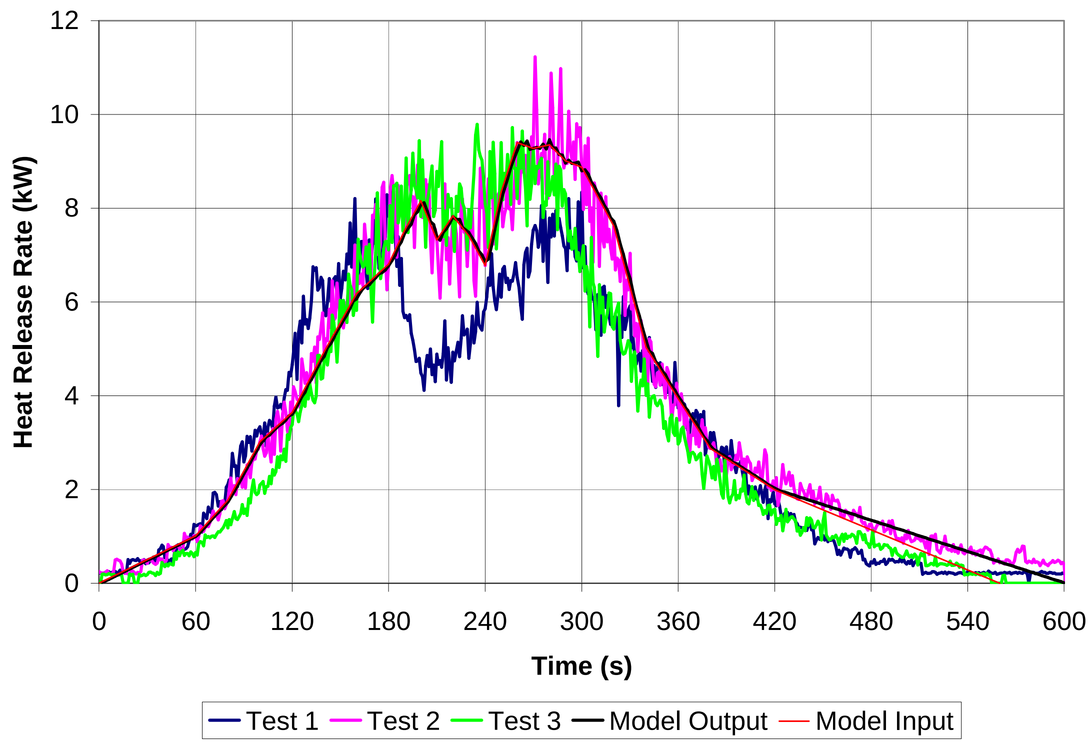

Figure 48 – Flaming PU foam w/ micro-fiber fab. heat release rate, SPEC ID.

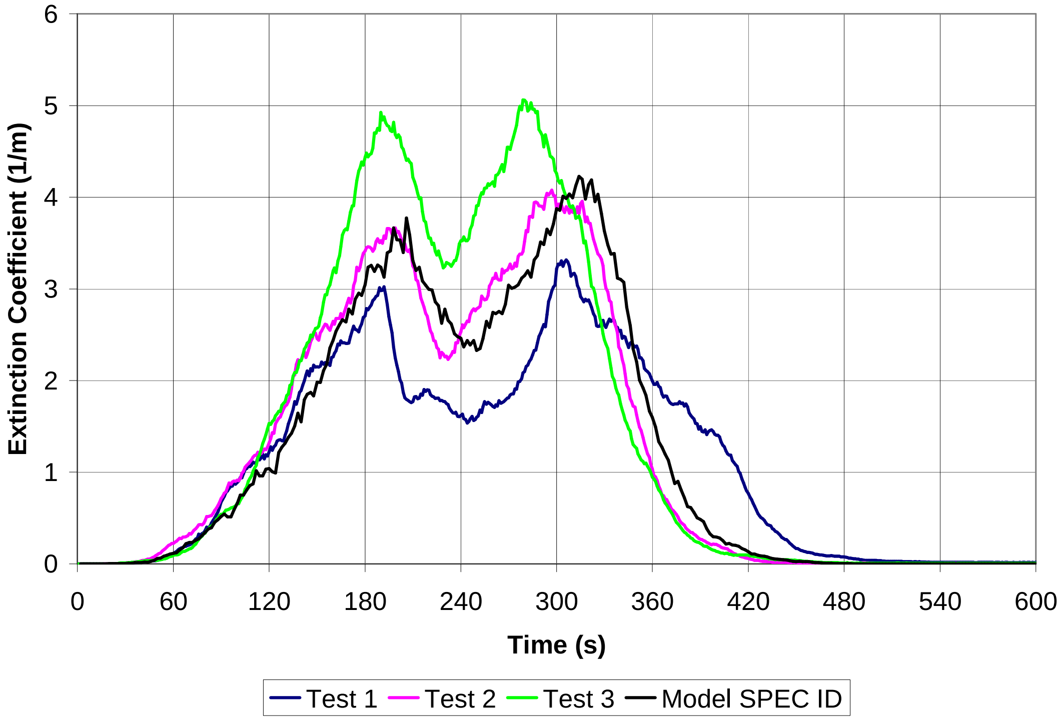

Figure 49 – Flaming PU foam w/ micro-fiber fab. ext. coefficient, SPEC ID.

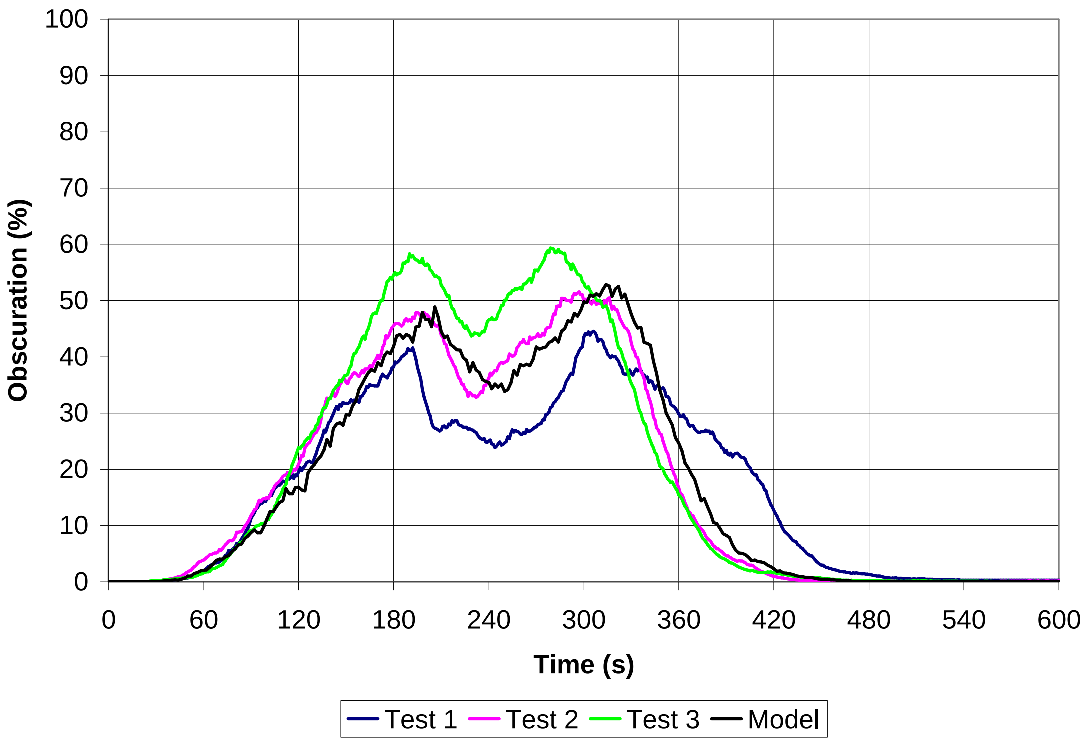

Figure 50 – Flaming PU foam w/ micro-fiber fab. obscuration, SPEC ID.

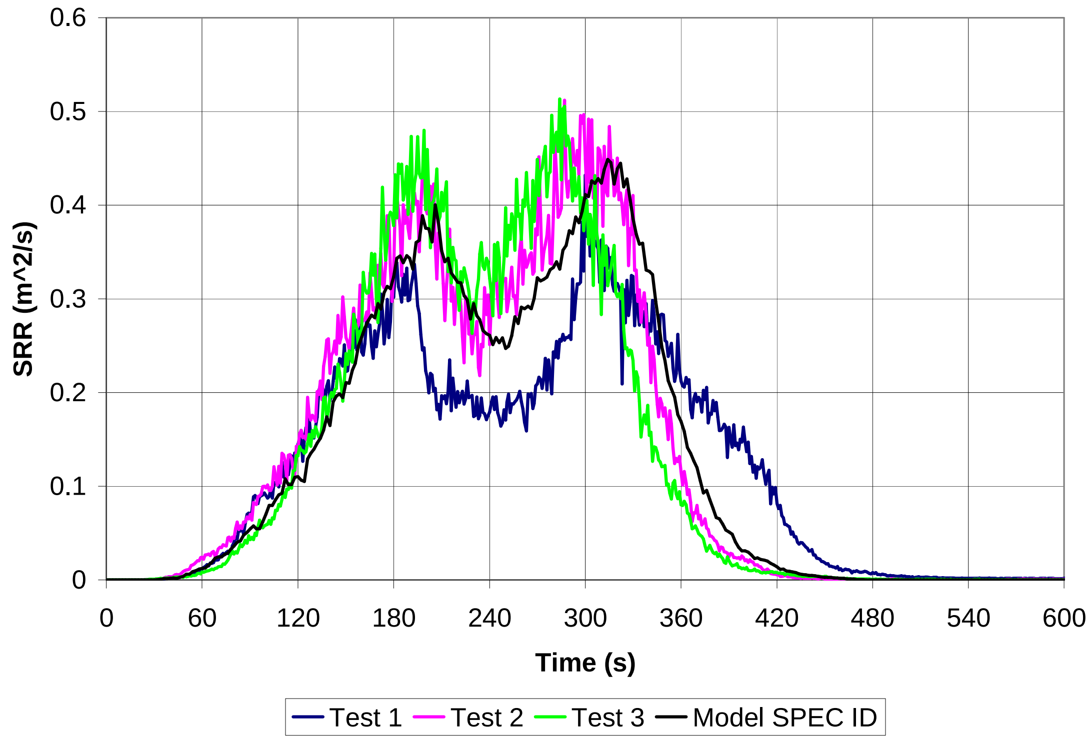

Figure 51 – Flaming PU foam w/ micro-fiber fab. smoke release rate, SPEC ID.

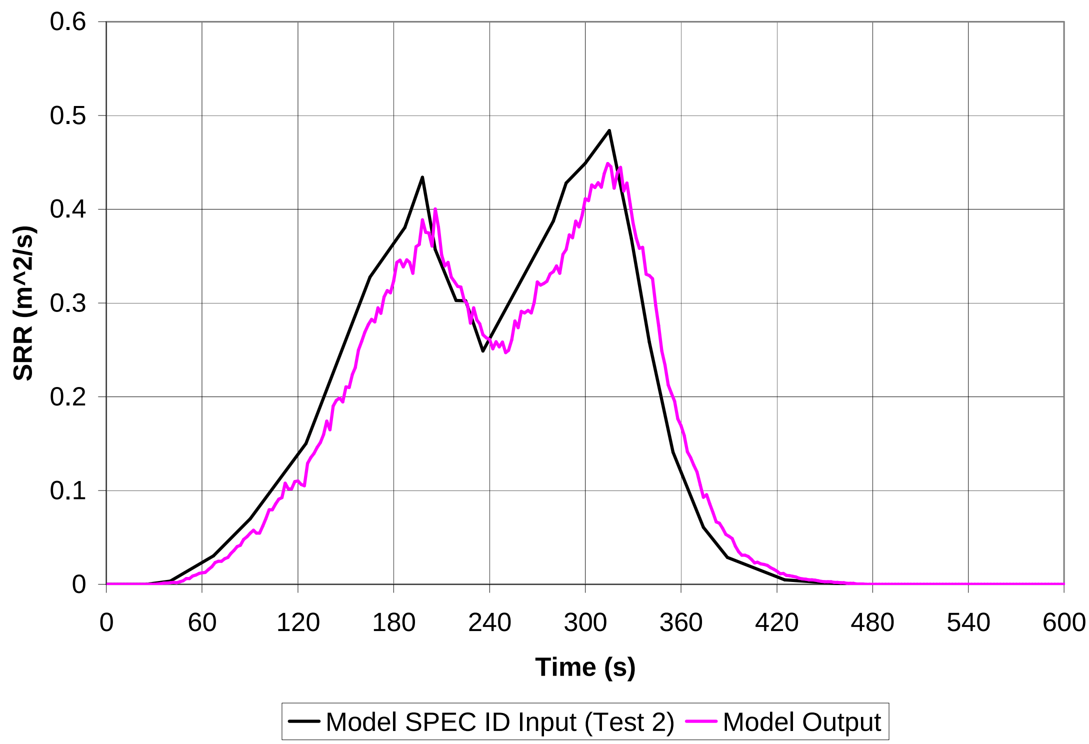

Figure 52 – Flaming PU Foam w/ micro-fiber fab. input/ output, SPEC ID.

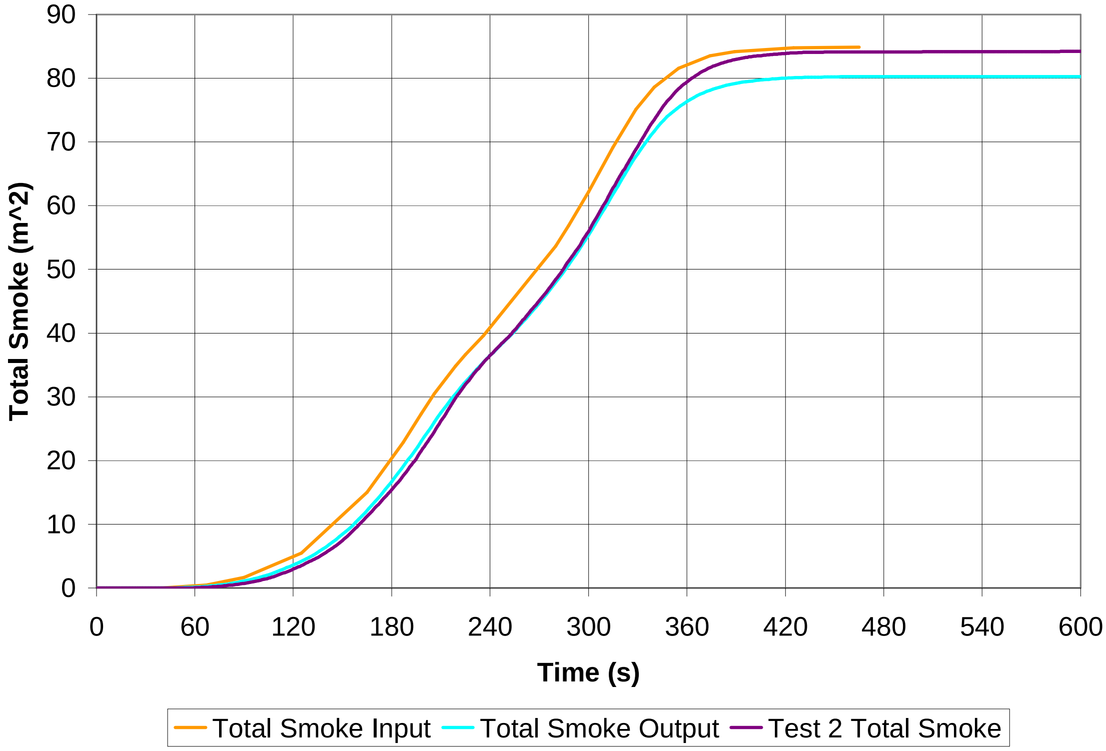

Figure 53 – Flaming PU Foam w/ micro-fiber fab. total smoke, SPEC ID.

The data displayed in these figures is produced using the Species ID method. Throughout these figures, a lag is evident between the model input and output. The input for this model is based on Test 2. This lag can be attributed to the uncorrected experimental data. The lag time between actual smoke output and measurement in the experimental part of this project has not been compensated. Therefore, the time at which the smoke characteristics develop at the vent in the model is the delayed measurement time in the experiment. The lag time in heat release rate, Figure 48, was automatically compensated for by the data acquisition system at UL.

Figure 48 shows that the heat release rate output is similar to the model input. The output deviates near the end of the test but in a manner that is closer to the actual test than the model input.

Figure 49, Figure 50, and Figure 51 show the extinction coefficient, obscuration, and smoke release rate. These measurements remain similar to test two throughout the simulation. The lag time and a slight inability to match the peak values can be noted as the significant deviations. The extinction coefficient from the model peaks slightly after the first peak and the second peak from the IMO test. The maximum extinction coefficient produced from the model is approximately 4.3 % higher than Test 2. This deviation is also representative of the obscuration difference between the model and the experimental data from Test 2. The smoke release rate curve produced by the model remains less than the maximum scatter of the Test 2 data.

Figure 52 shows that the smoke release rate output for the model is lower than the model input peaks. The initial increase in smoke is similar in rate of rise, but peak values and peak times differ. The peak time difference is caused by the uncorrected experimental data. Figure 53 shows the total smoke values produced from the model in comparison to the model input and Test 2. The total smoke produced in the model is 80.25 m^2, whereas Test 2 produces 84.24 m^2. The model produces 4.7 % less smoke than the actual test. The smoke release rate curve specified in the input file for this model produces a total smoke of 84.87 m^2. The output is 5.4 % less than the specified input. These small differences are caused by the simplification of the actual smoke release rate curve into an input curve, as well as the possible influences of the mixture fraction model due to the use of a heat release rate in the input file. Using a heat release rate automatically invokes the mixture fraction model which inputs standard combustion gases into the domain. This addition of gases may have an affect on the smoke species being injected into the domain.

5.4.4 Printed Circuit Board

Figures 54-59 show the results from the printed circuit board model in comparison to the data from the IMO tests. The source is modeled as a 2.5 by 7.5 by 7.5 cm tall volume with a 2.5 by 7.5 cm vent on top to provide the represented heat and smoke production.

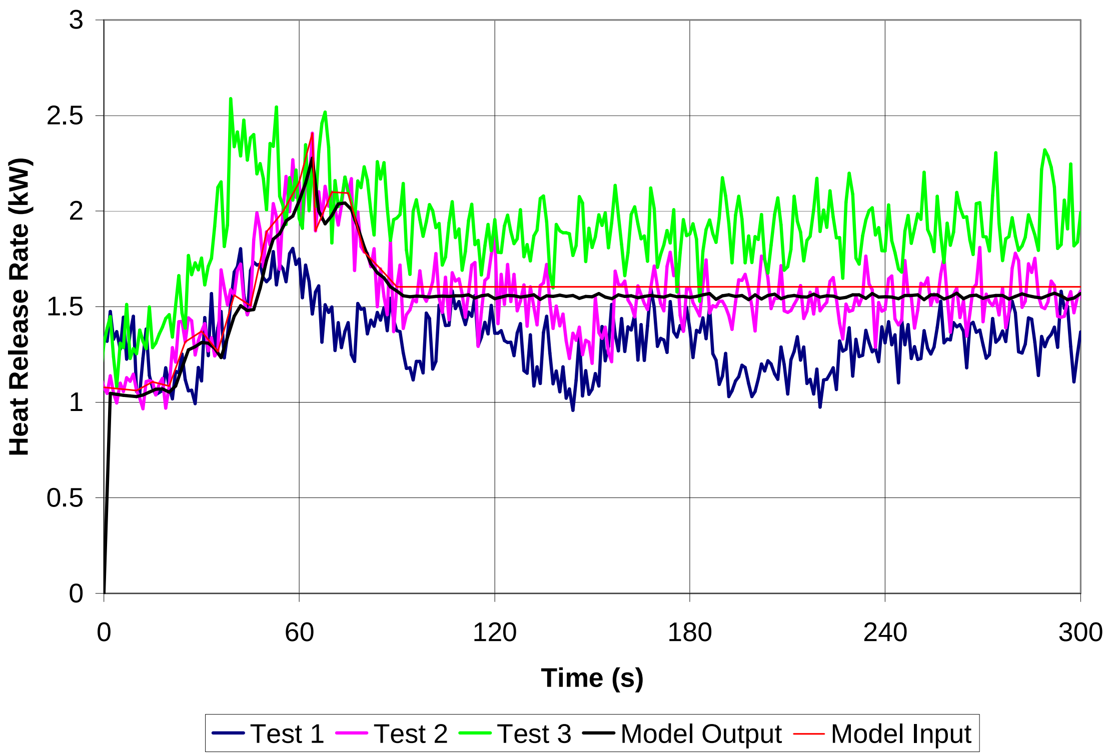

Figure 54 – Printed circuit board heat release rate.

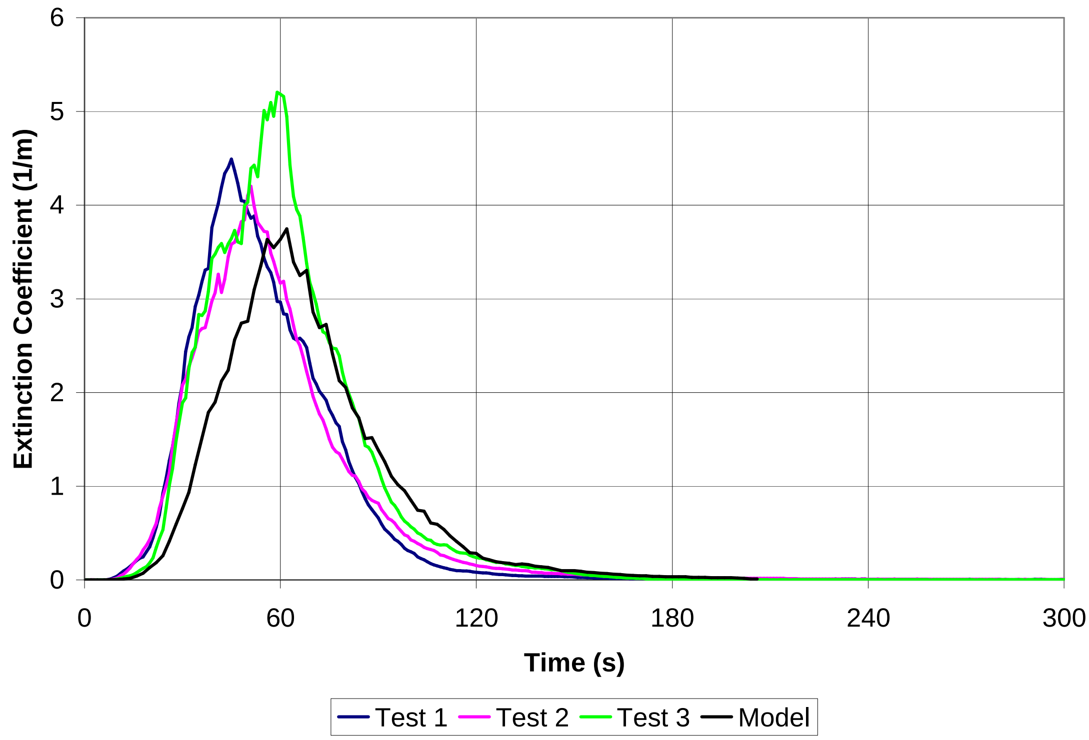

Figure 55 – Printed circuit board extinction coefficient.

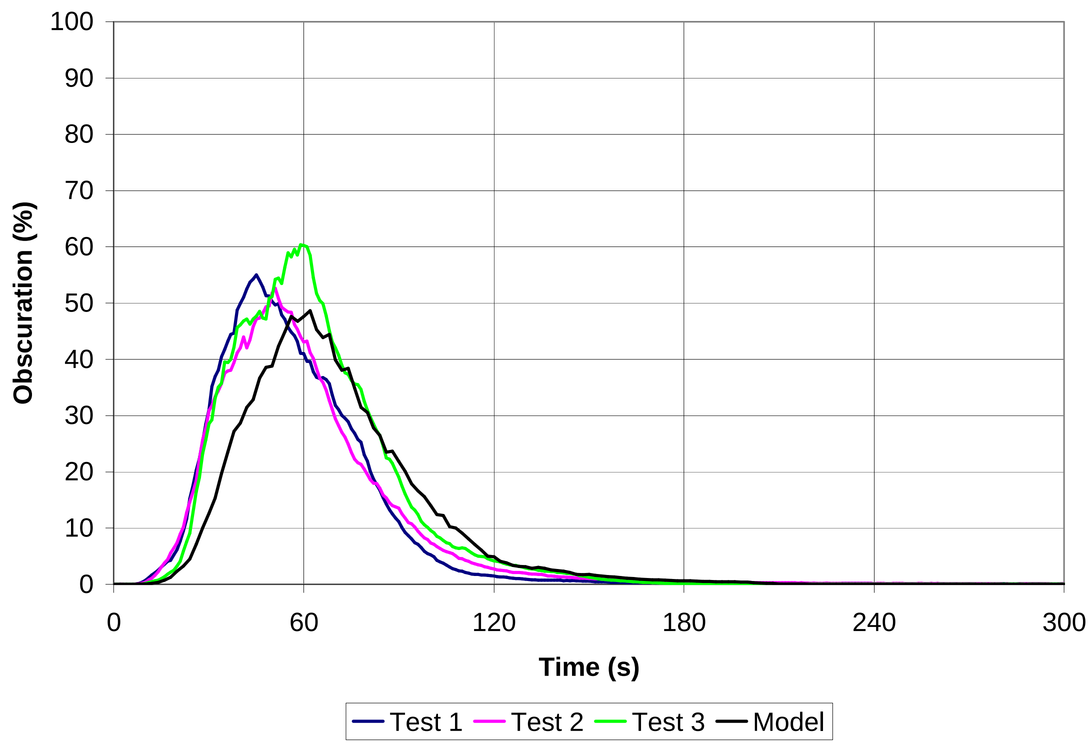

Figure 56 – Printed circuit board obscuration.

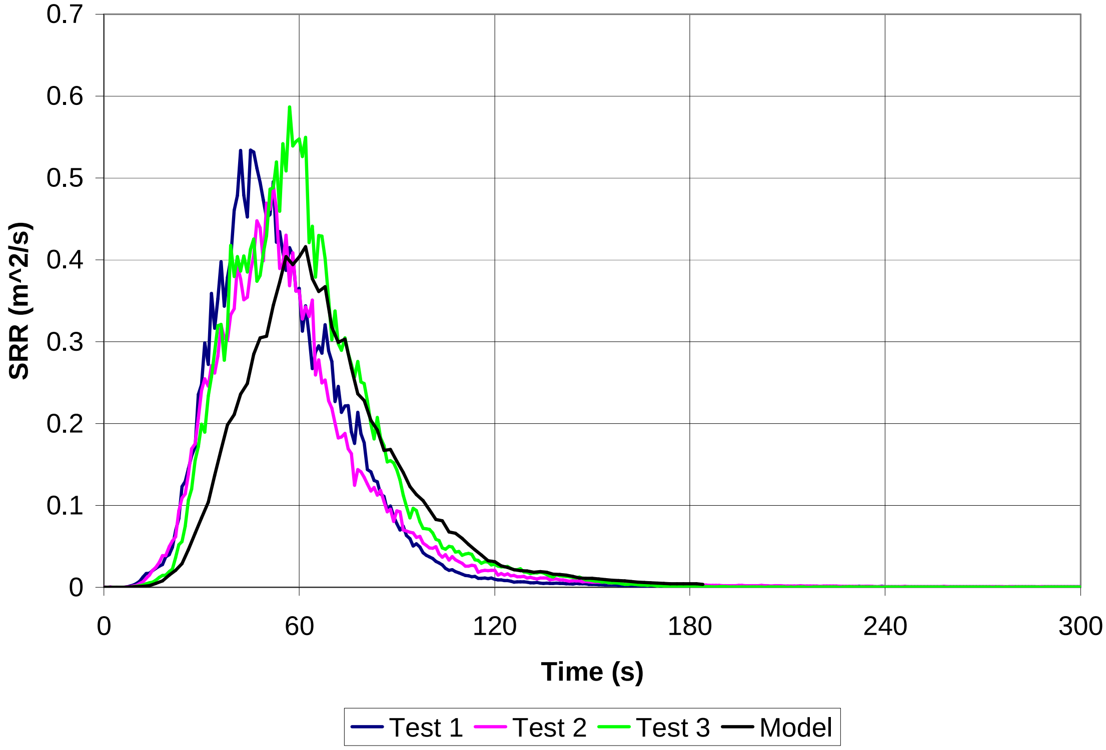

Figure 57 – Printed circuit board smoke release rate.

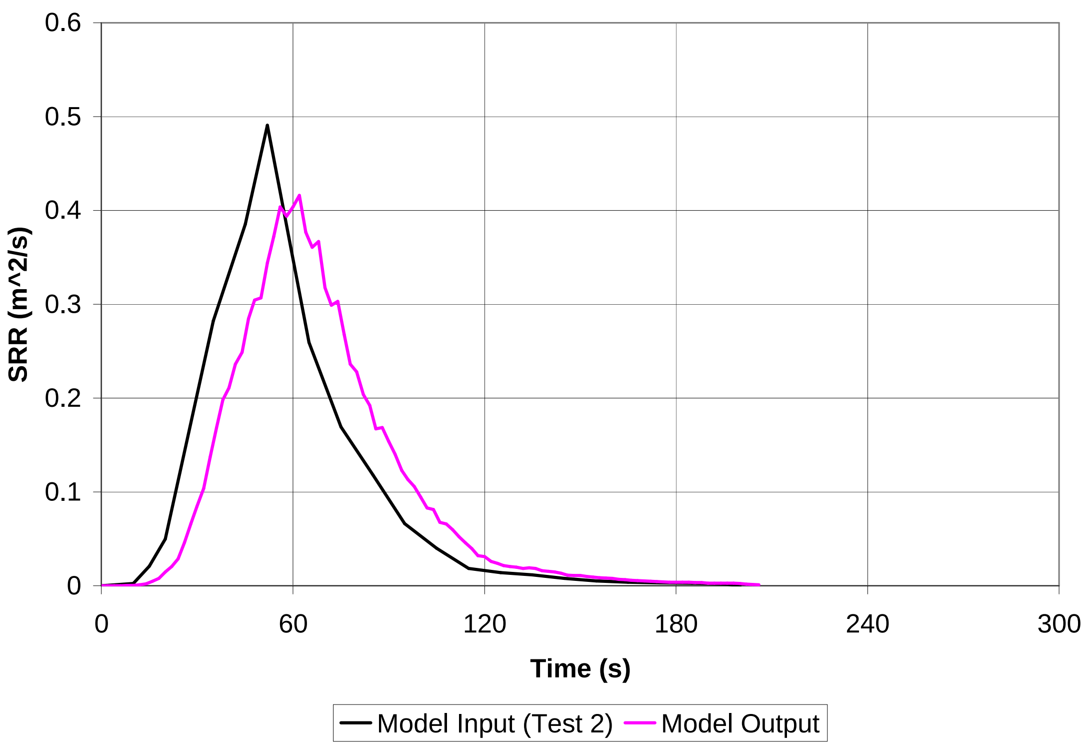

Figure 58 – Printed circuit board model input and output.

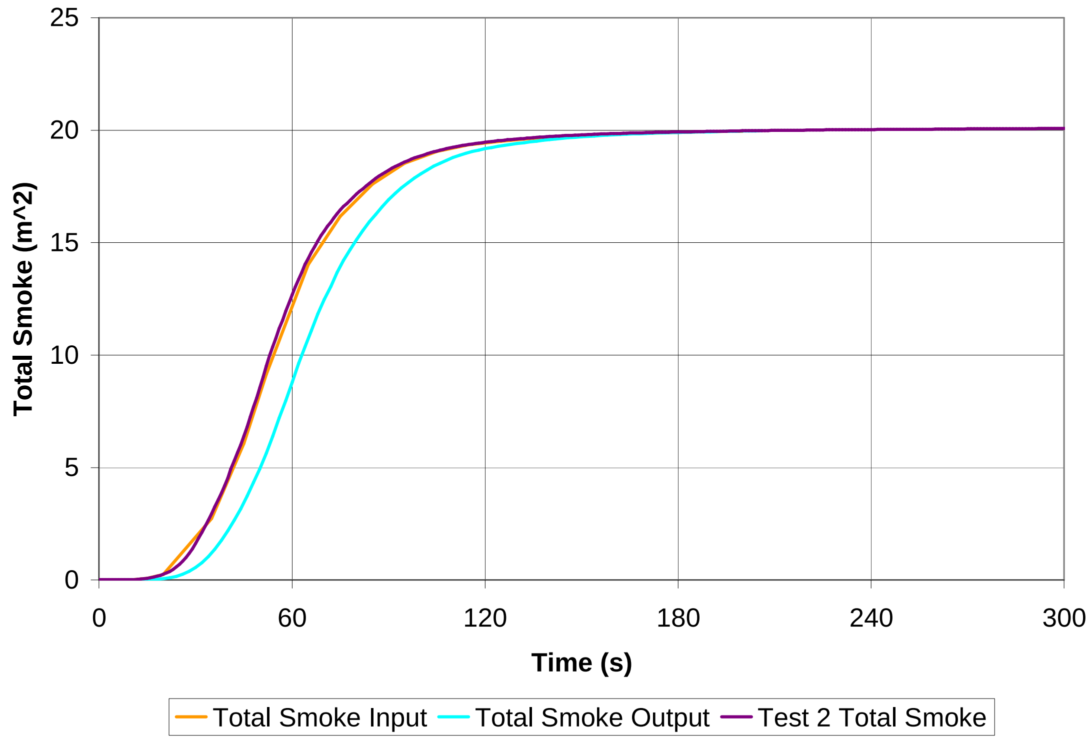

Figure 59 – Printed circuit board total smoke.

The data displayed in these figures is produced using the Species ID method. The lag between the input (Test 2) and the output (Model) for measurements related to the species is caused by the uncorrected lag time associated with the experimental data acquisition. Figure 54 shows that the heat release rate does not follow this trend and the input and output for the model is similar. The heat release rate curve from the experimental data shows a continuous influence from the line burner. This is reflected in the input for the simulation to match buoyancy effects.

Figure 55, Figure 56, and Figure 57 are all derived from the simulated measurement of obscuration within the modeled exhaust duct. The lag and difference in peak values between the input and the output of the model is shown in these three figures.

The model output is up to approximately 12 seconds behind the input and this is translated through each of the figures. Figure 57 shows that the peak smoke release rate output in the model is approximately 15 % lower than the specified value in Test 2. Figure 58 clearly shows the lag between input and output of the model associated with the transport lag from the source to the measurement from the uncorrected experimental data. The difference in peak value can also be noted here.

Figure 59 shows the total smoke produced in the model as well as Test 2. The total smoke produced in the model is 19.97 m^2, whereas Test 2 produces 20.3 m^2. The model produces 1.6 % less smoke than the actual test. The smoke release rate curve specified in the input file for this model produces a total smoke of 19.95 m^2. The output is 0.1 % more than the specified input.

5.4.5 Computer Case ABS Plastic

Figures 60-65 show the results from the computer case ABS plastic model in comparison to the data from the IMO tests. The source is modeled as a 2.5 by 2.5 by 12.5 cm tall volume with a 2.5 by 2.5 cm vent on top to provide the represented heat and smoke production.

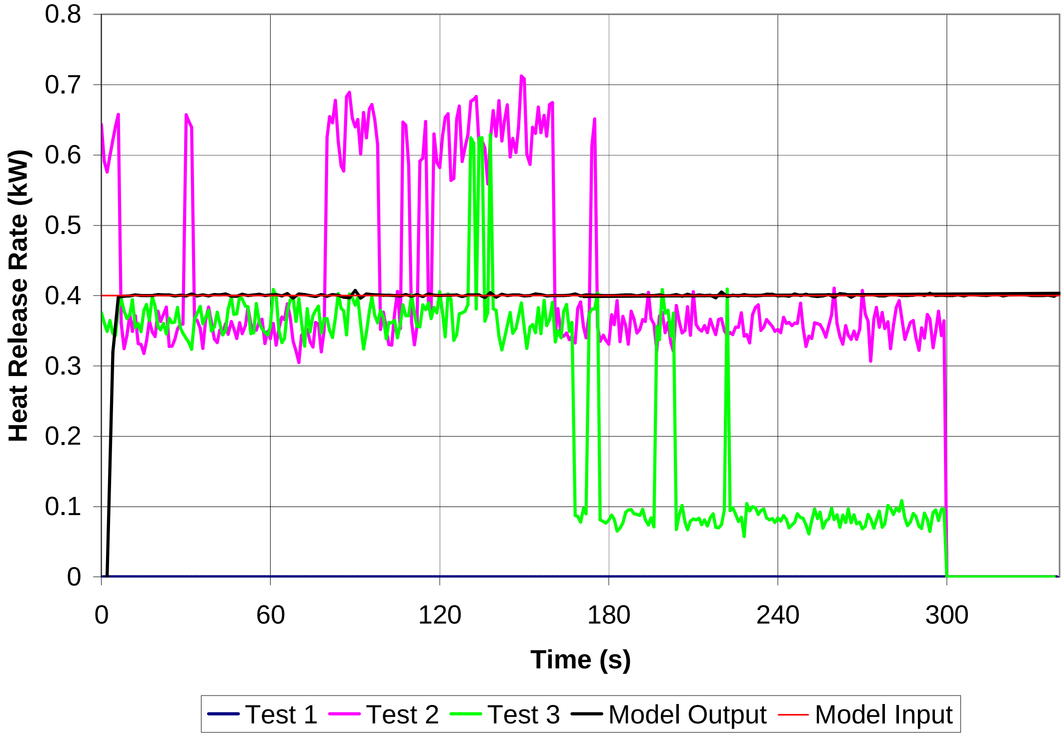

Figure 60 – Computer case ABS plastic heat release rate.

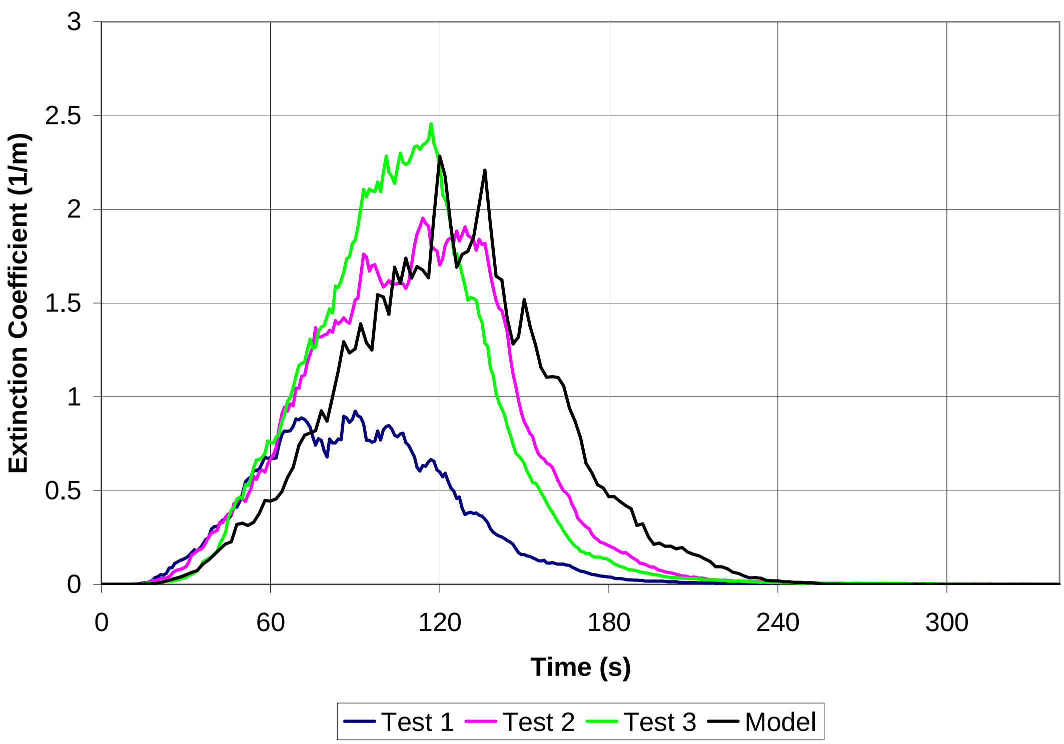

Figure 61 – Computer case ABS plastic extinction coefficient.

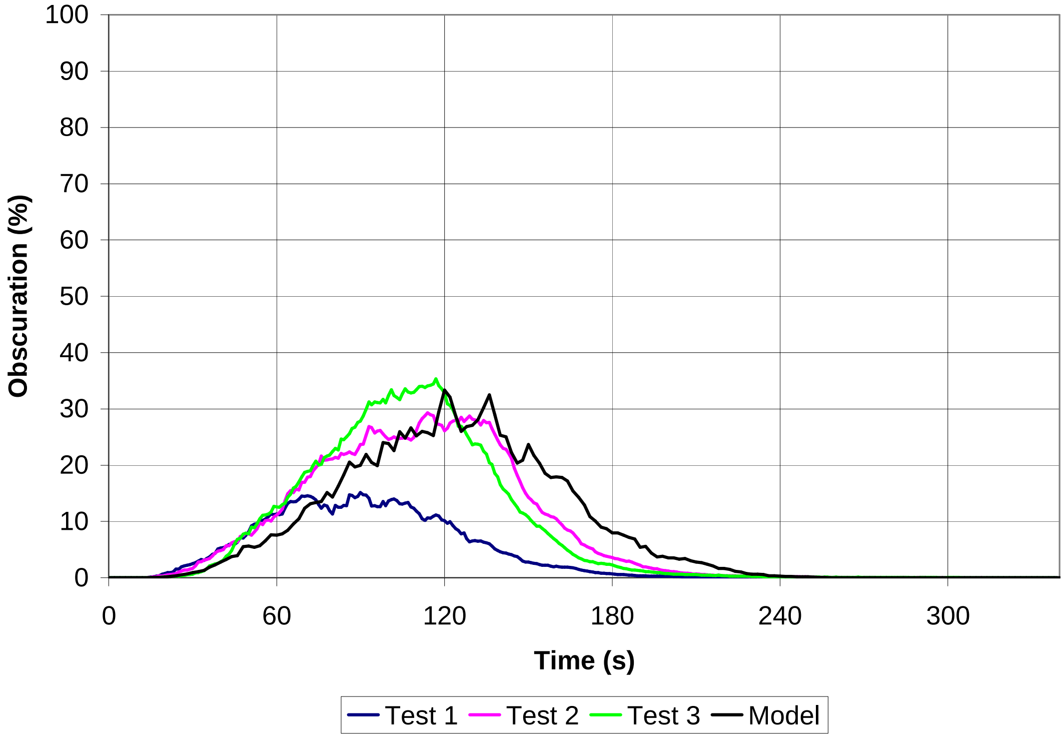

Figure 62 – Computer case ABS plastic obscuration.

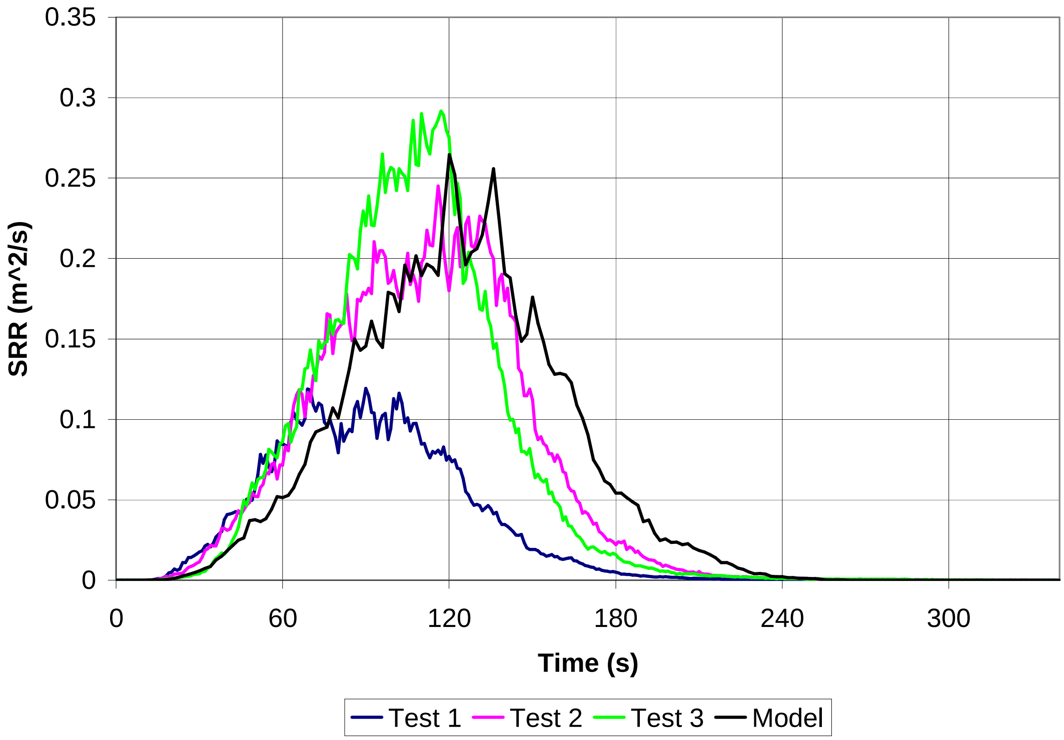

Figure 63 – Computer case ABS plastic smoke release rate.

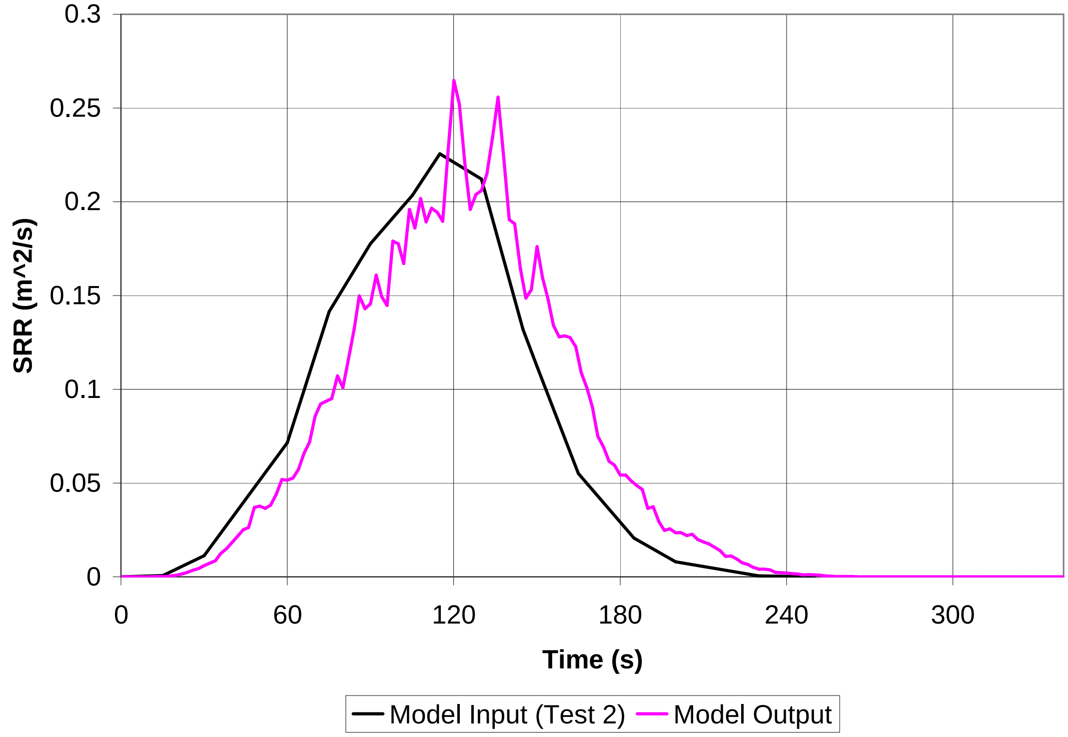

Figure 64 – Computer case model input and output.

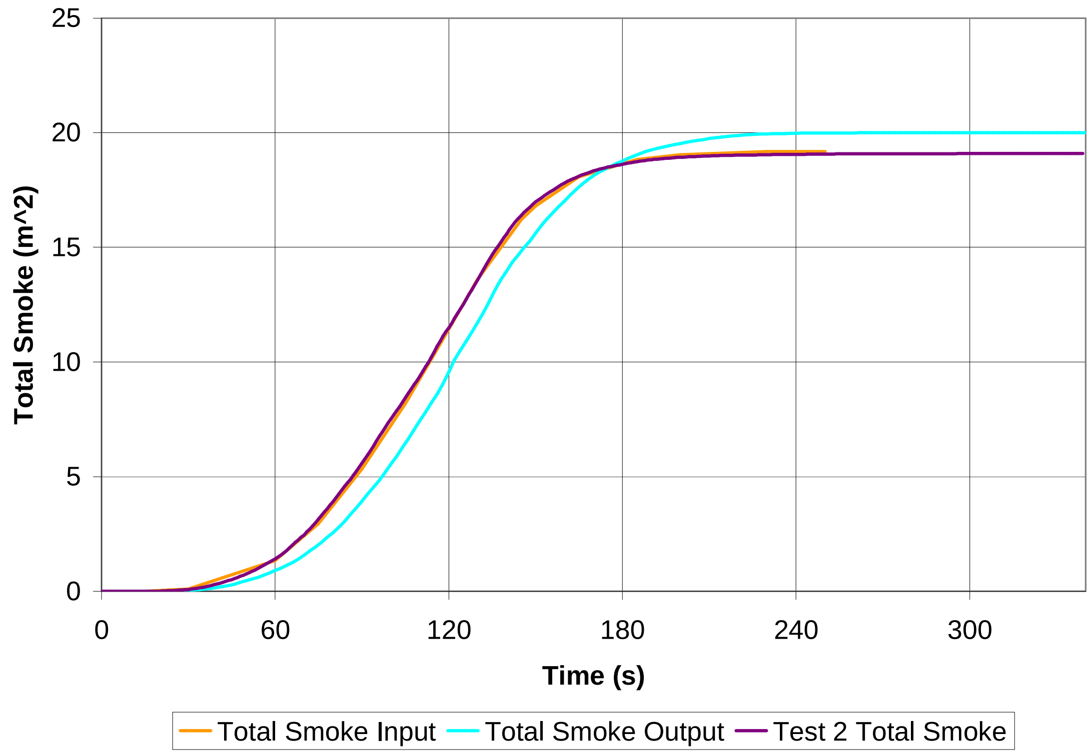

Figure 65 – Computer case total smoke.

The Species ID method is used for this simulation. The lag associated with the uncorrected experimental data can again be noted. There is also a difference in peak values as well. The peak values produced in the model are slightly higher than the model input and the experimental data.

Figure 60 shows that the heat release rate output from the simulation is identical to the input. The heat release rate from this source was lower than the accuracy of the IMO intermediate-scale hood, so 0.4 kW is specified to create buoyancy.

Figure 61, Figure 62, and Figure 63 are all derived from the simulated measurement of obscuration within the modeled exhaust duct. The lag and difference in peak values that has been noted in each model is shown in these three figures. The model output is up to 18 seconds behind the input and this is translated through each of the figures. Figure 63 shows that the peak smoke release rate output in the model is approximately 8 % higher than the specified value in Test 2. Figure 64 shows the relationship between the model input and output. The lag can be noted, as well as the higher peak output values

Figure 65 shows the total smoke produced in the model as well as Test 2. The total smoke produced in the model is 20.0 m^2, whereas Test 2 produces 19.1 m^2. The model produces 4.7 % more smoke than the actual test. The smoke release rate curve specified in the input file for this model produces a total smoke of 19.17 m^2. The output is 4.3 % more than the specified input.

5.4.6 PU Foam with Micro-fiber Fabric (Smoldering)

Figures 66-70 show the results from the smoldering PU foam with micro-fiber fabric model in comparison to the data from the IMO tests. The source is modeled as a 20 by 15 by 10 cm tall volume with a 20 by 15 cm vent on top to provide the represented smoke production using the Species ID method. The heat is provided by a 30 by 30 cm hotplate surface, modeled as a vent, below the source.

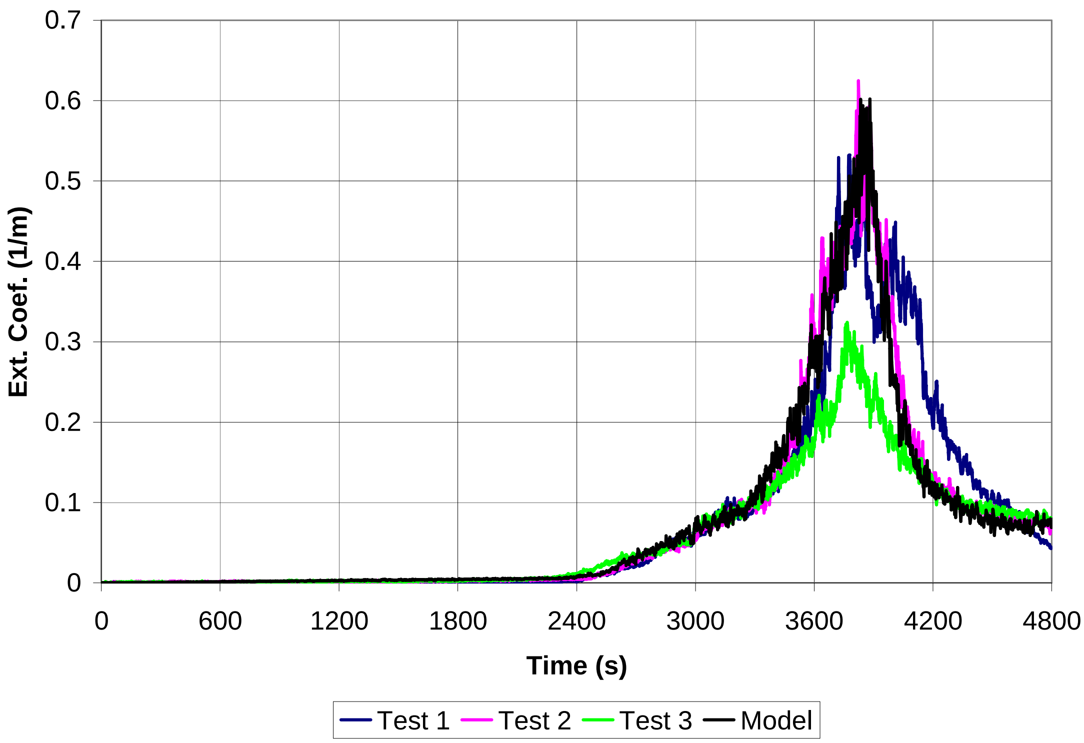

Figure 66 – Smoldering PU foam w/ micro-fiber fabric extinction coefficient.

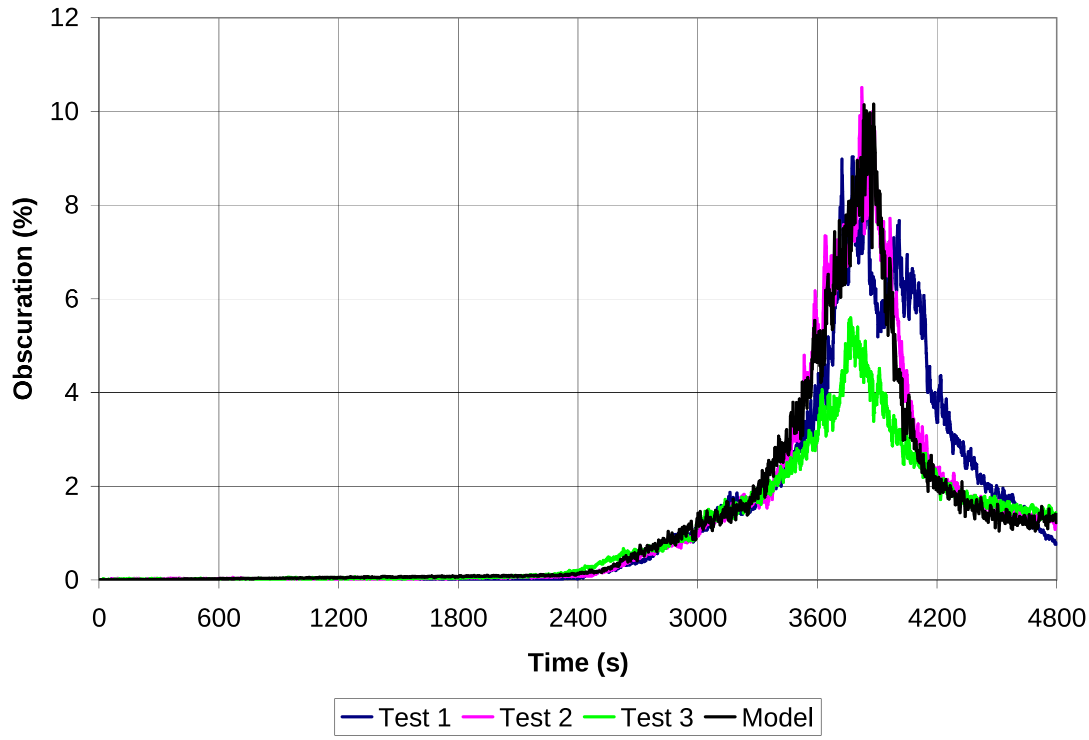

Figure 67 – Smoldering PU foam w/ micro-fiber fabric obscuration.

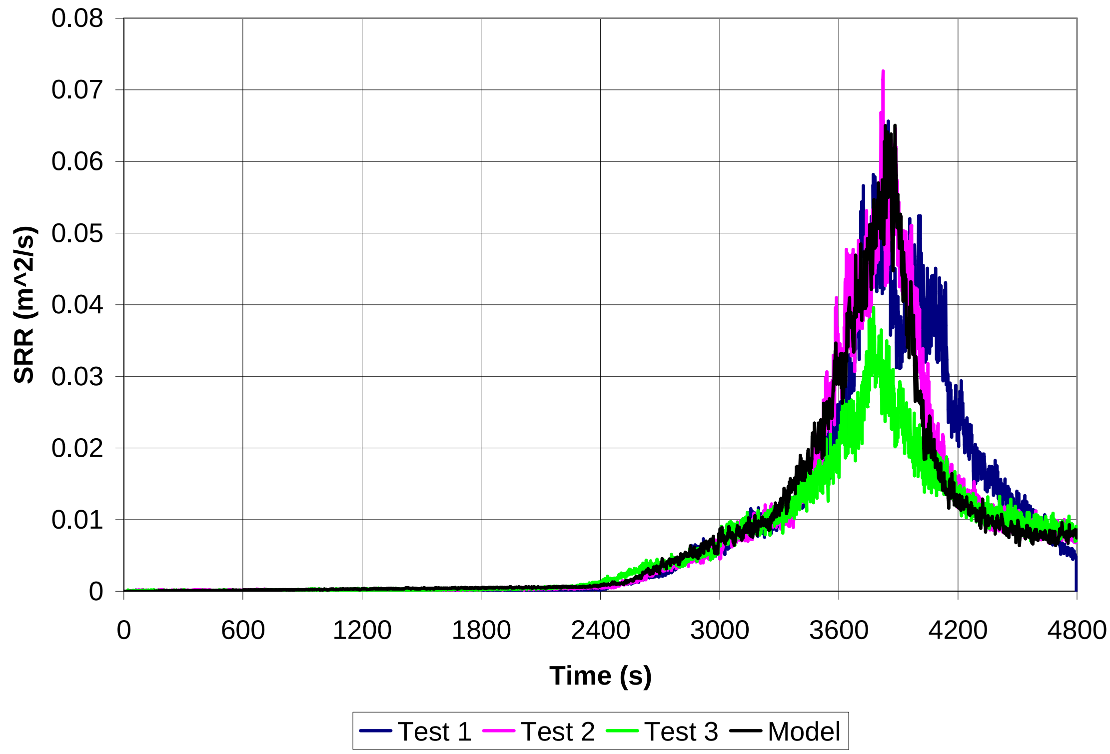

Figure 68 – Smoldering PU foam w/ micro-fiber fabric smoke release rate.

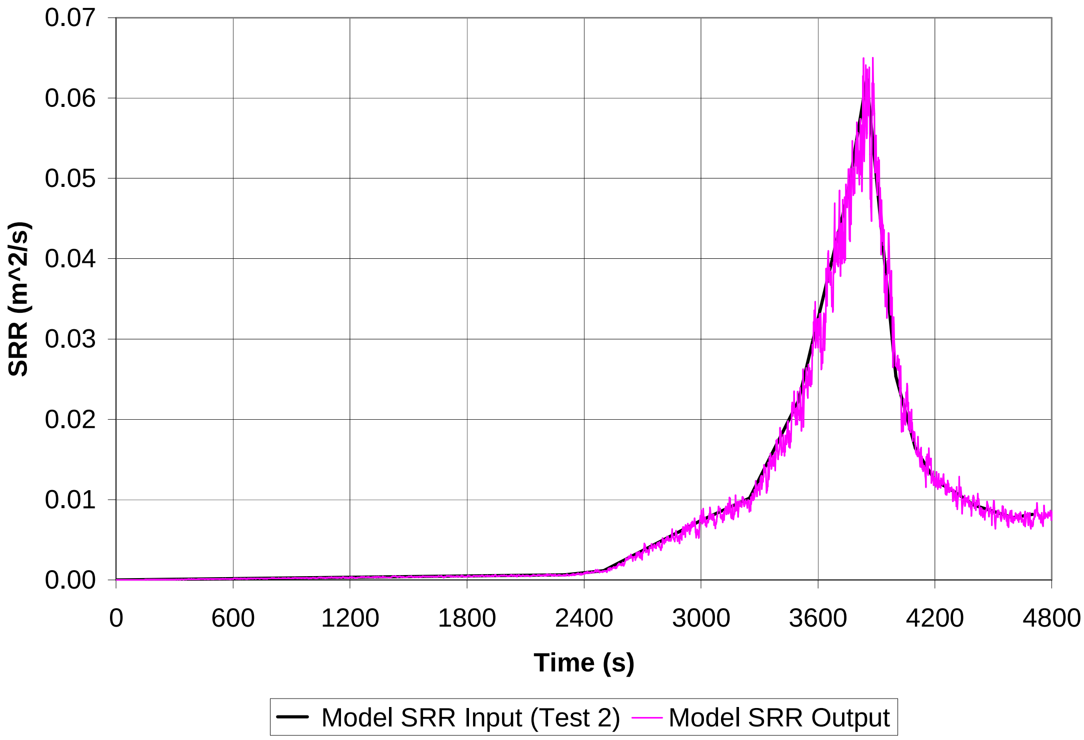

Figure 69 – Smoldering PU foam w/ micro-fiber fabric model input and output.

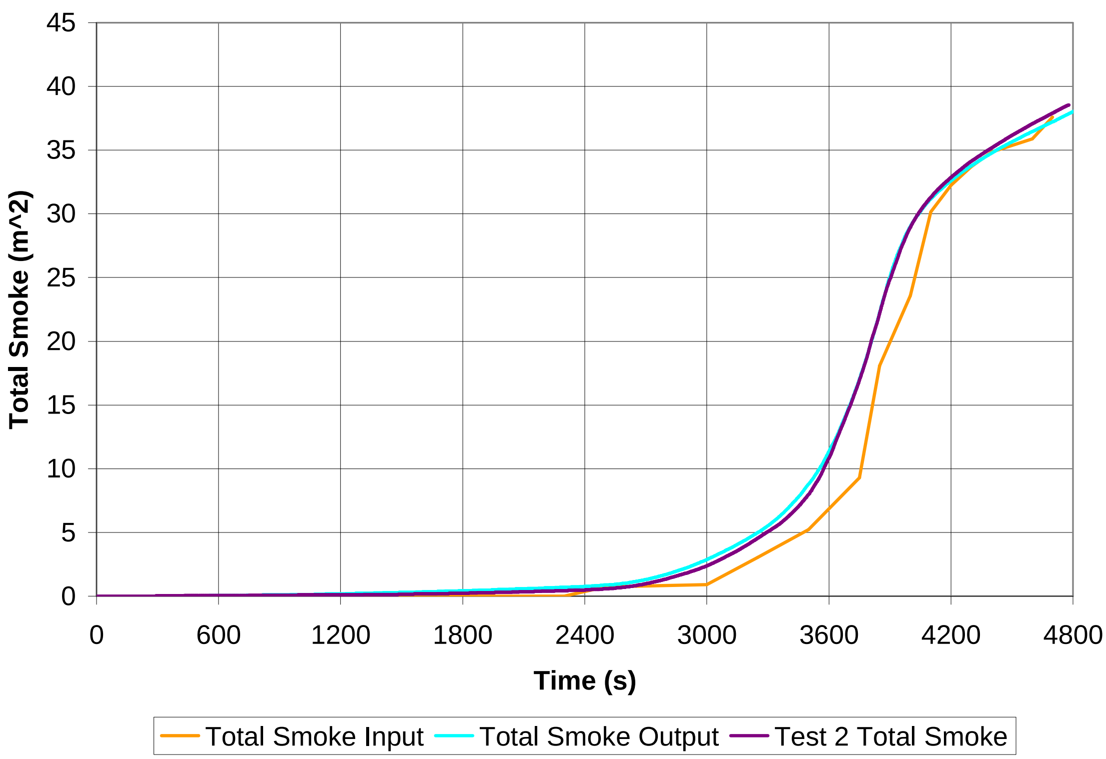

Figure 70 – Smoldering PU foam w/ micro-fiber fabric total smoke.

The smoldering PU foam with micro-fiber fabric source produces repeatable trends. It is complicated to model smoldering sources in general due, in part, to the length of time required to run the simulation. The lag from the uncorrected experimental data is not as noticeable when based in a time scale as long as this one.

Figure 66, Figure 67, and Figure 68 extinction coefficient, obscuration, and smoke release rate, respectively, show the smoke characteristics from this simulation compared to the IMO tests. The extinction coefficient and smoke release rate are calculated from the simulated measurement of the obscuration in the model. The profiles for each of the model calculations are similar to the input (Test 2). The model tends to slightly lag Test 2 prior to the peak and then begins to lead the experimental data for a brief moment. This is shown in Figure 68. The rate of increase, peak, and rate of decay of the smoke release rate is nearly identical, on this scale, to the experimental data and the model input seen in Figure 69. The peak smoke release rate in the model is approximately 9 % higher than Test 2. The resolution of the smoke release rate curve is well resolved in the output data from the simulation. Figure 69 shows the comparison between the model smoke release rate input and output. The output shown in this graph generally lags the input slightly, which is consistent with the uncorrected lag from the experimental data.

Figure 70 shows the total smoke. The total smoke produced in the model is 39.59 m^2, whereas Test 2 produces 40.19 m^2 near the end of the test at 5000 seconds. The model produces 1.5 % less smoke than the actual test. The smoke release rate curve specified up to 4700 seconds for this model produces a total smoke of 38.39 m^2. The model output at 4700 seconds is up to 37.21, which is 3.1% less than the specified input.

5.4.7 Ponderosa Pine Wood

Figures 71-75 show the results from the ponderosa pine model in comparison to the data from the IMO tests. The source is modeled as a 15 by 10 by 2.5 cm tall volume with a 15 by 10 cm vent on top to provide the represented smoke production using the Species ID method. The heat is provided by a 30 by 30 cm hotplate surface, modeled as a vent, below the source.

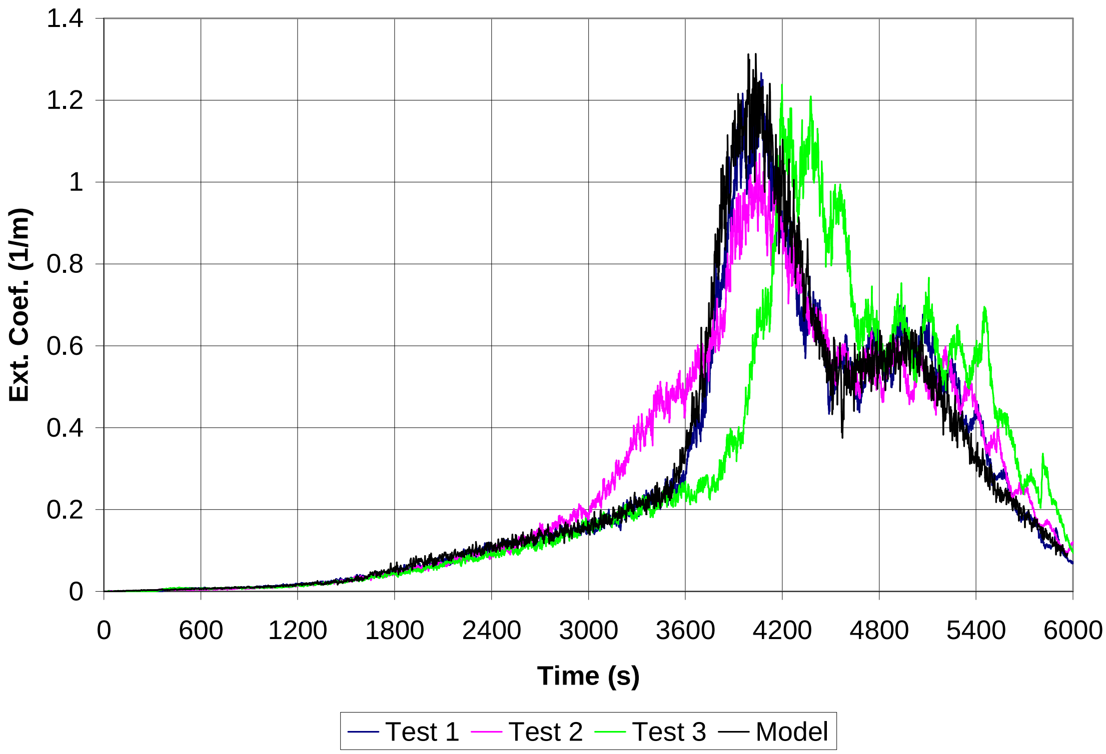

Figure 71 – Ponderosa pine extinction coefficient.

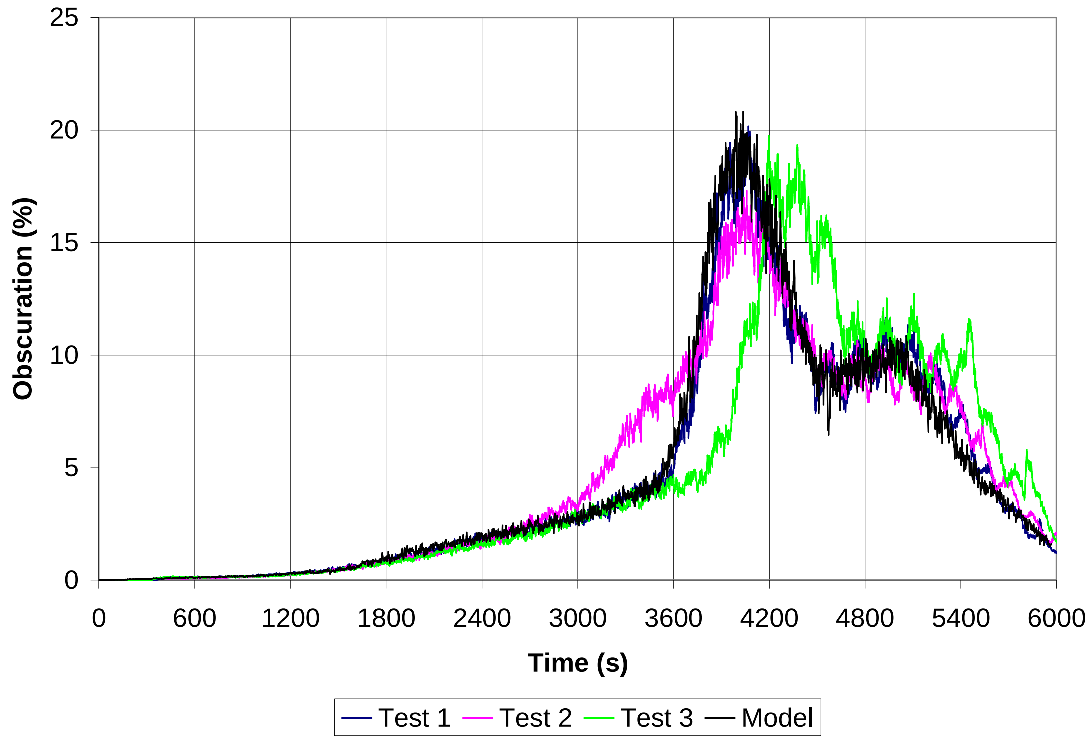

Figure 72 – Ponderosa pine obscuration.

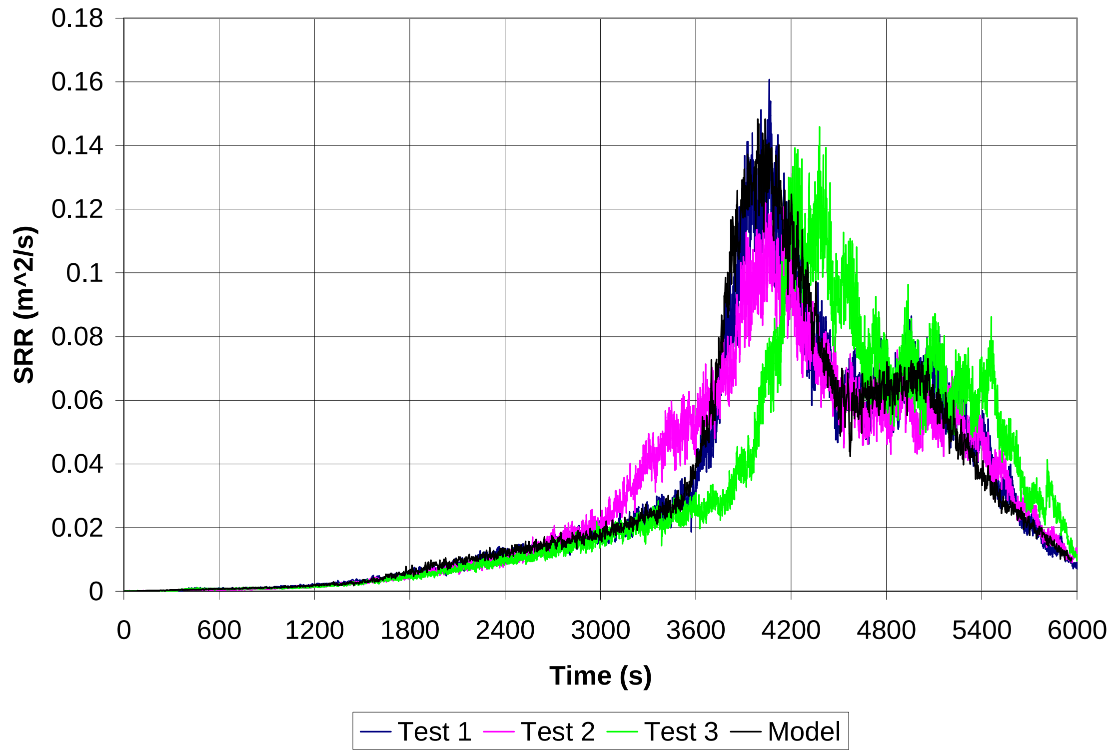

Figure 73 – Ponderosa pine smoke release rate.

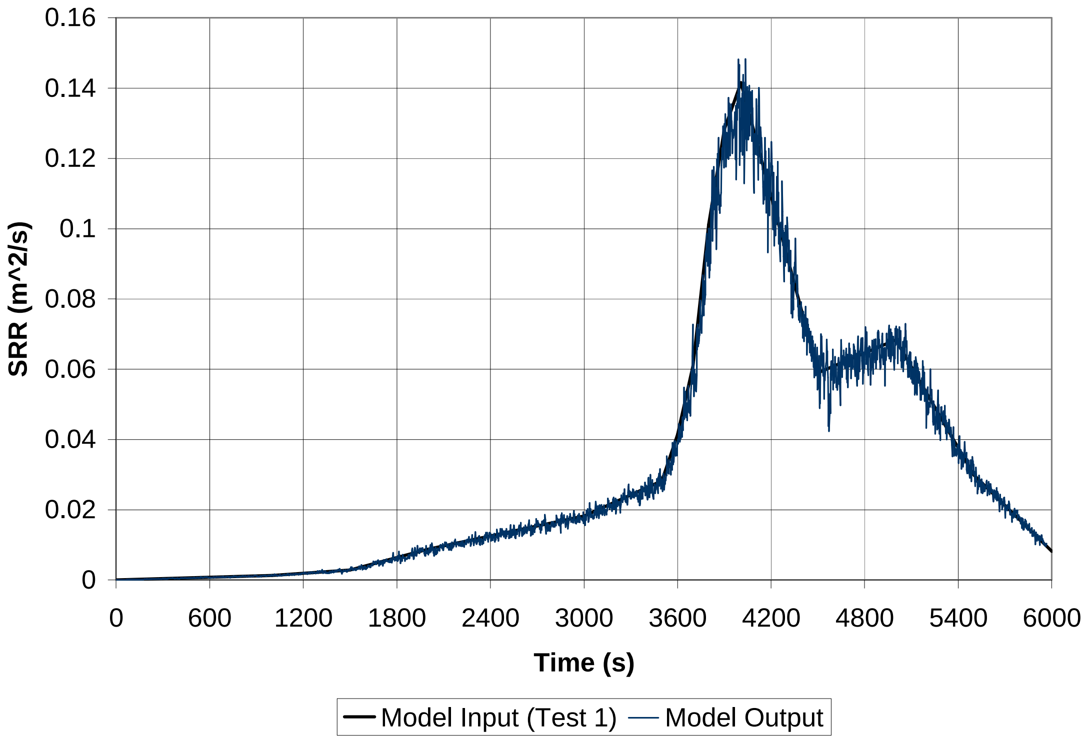

Figure 74 – Ponderosa pine model input and output.

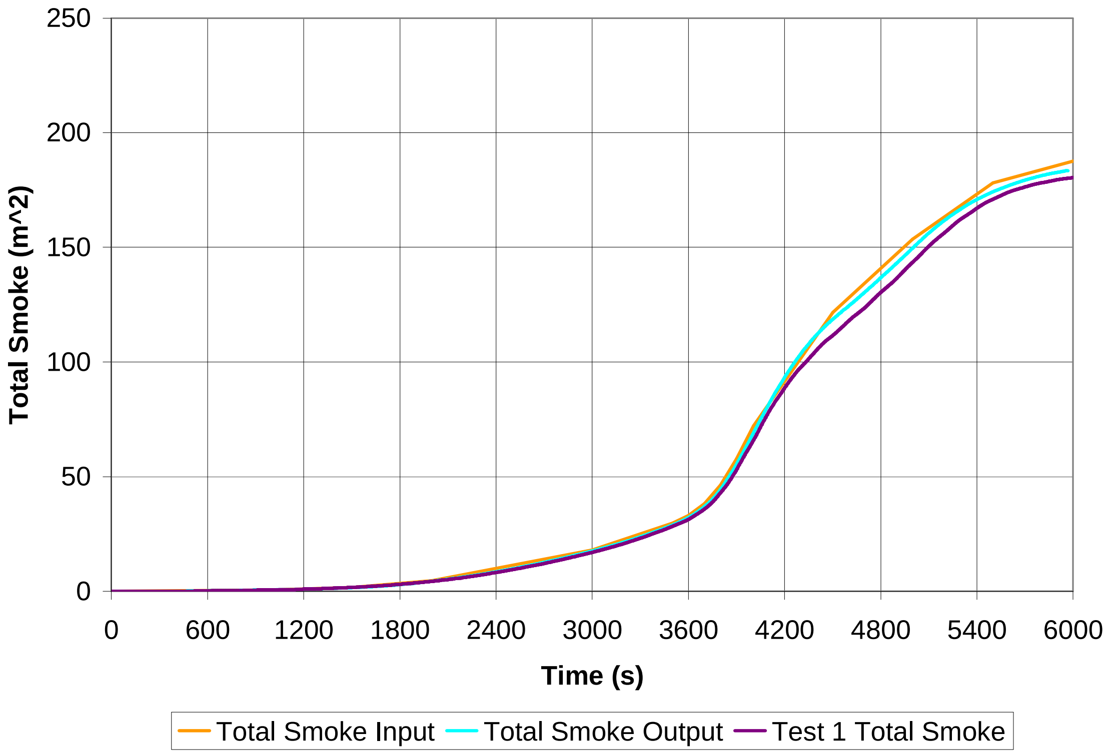

Figure 75 – Ponderosa pine total smoke.

The ponderosa pine test requires a simulation run time of approximately 6000 seconds to capture the phenomenon. This test was highly repeatable in the experimental phase of this project.

Figure 71, Figure 72, and Figure 73 show the smoke characteristics produced in the simulation. The relationship between the model output and input is similar throughout each of these figures. The model input is configured to represent Test 1 of the experimental data. The input rate of increase and decay is recreated well by the simulated measurement in FDS. Generally, the output lags the input, which is caused by the uncorrected lag time in the experimental data. This is shown in Figure 74. The peak value in the smoke release rate output is slightly lower than the specified input. The smoke release rate output, when compared to the data from Test 1 is approximately 8 % less than the absolute maximum rate from the experimental data. The model output peaks at 0.148 m^2/s, whereas Test 1 peaks at 0.161 m^2/s.

The total smoke produced in the model is 183.5 m^2, whereas Test 1 produces 180.15 m^2 at the time that the model ended. The model produces 1.9 % more smoke than the actual test. The smoke release rate curve specified for this model produces a total smoke of 186.51 m^2 at the time that the model ended. The output is 1.6 % less than the specified input. The total smoke curves are provided in Figure 75.

5.4.8 Cotton Linen Fabric

Figures 76-80 show the results from the cotton linen fabric model in comparison to the data from the IMO tests. The source is modeled as a 30 by 30 cm vent to provide the represented smoke production using the Species ID method. The fuel source and hotplate surface have been modeled as the same object due to the low thickness of the cotton linen fabric source.

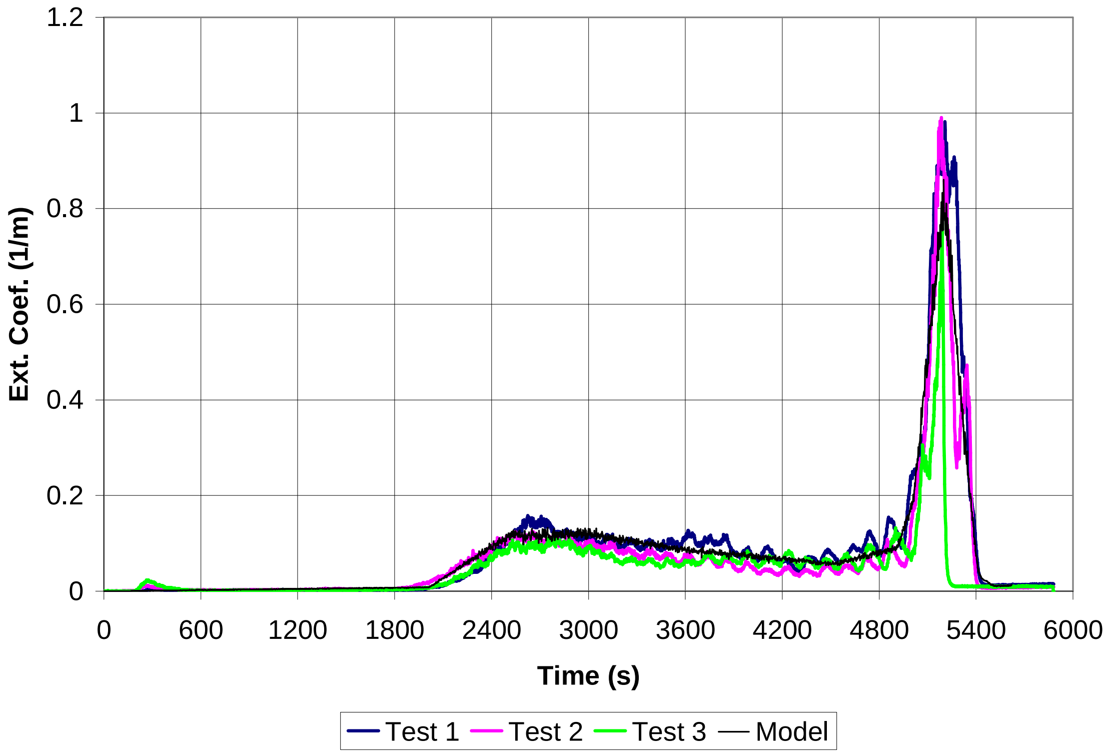

Figure 76 – Cotton linen fabric extinction coefficient.

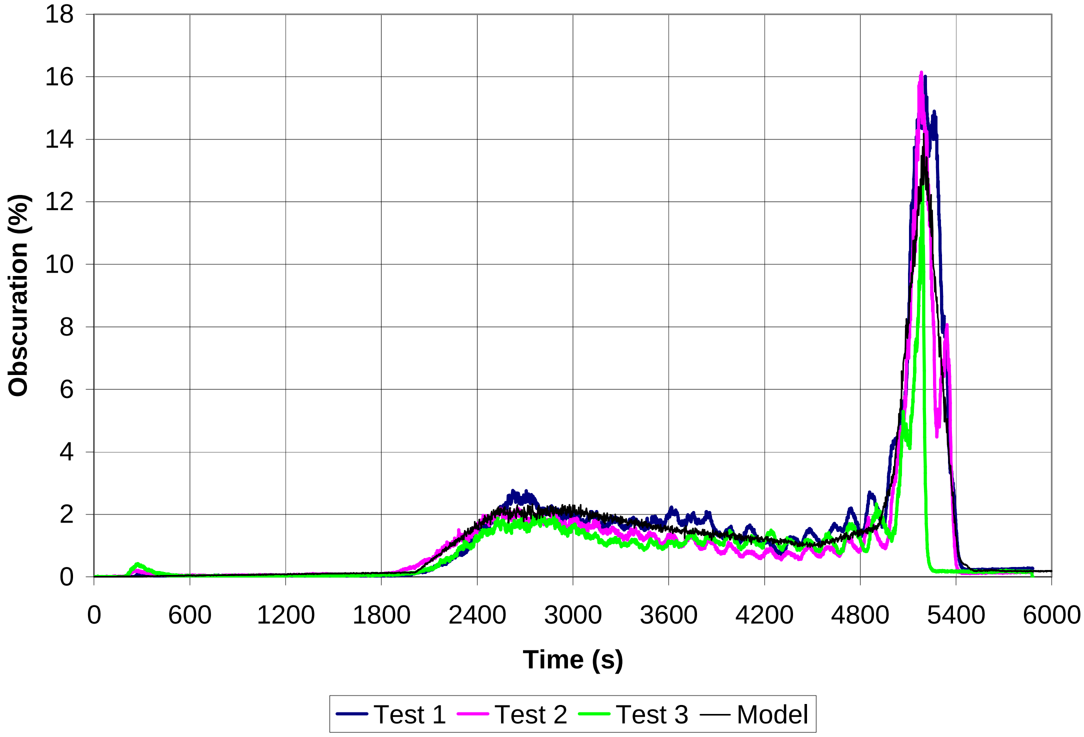

Figure 77 – Cotton linen fabric obscuration.

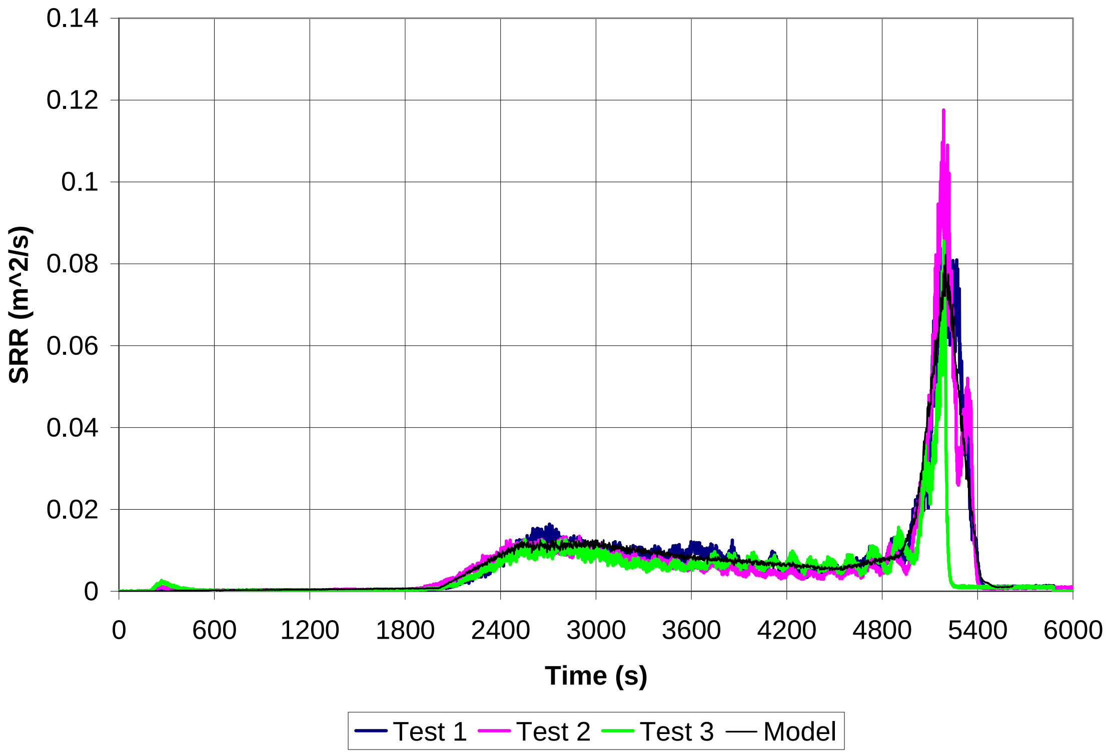

Figure 78 – Cotton linen fabric smoke release rate.

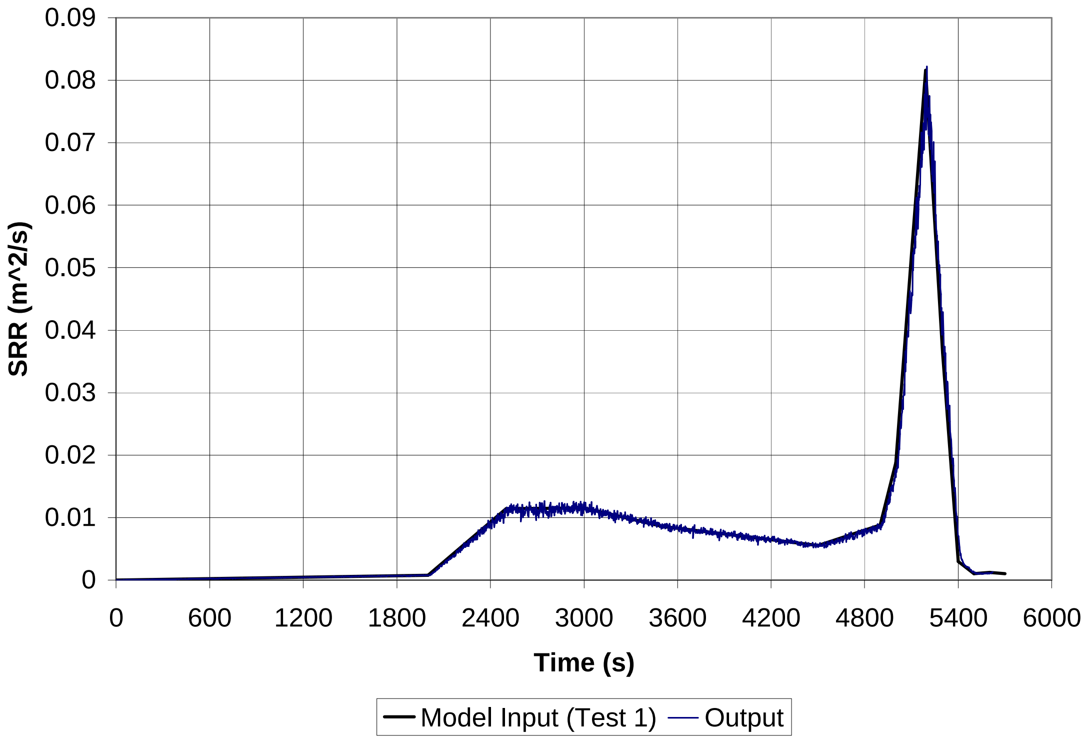

Figure 79 – Cotton linen fabric model input and output.

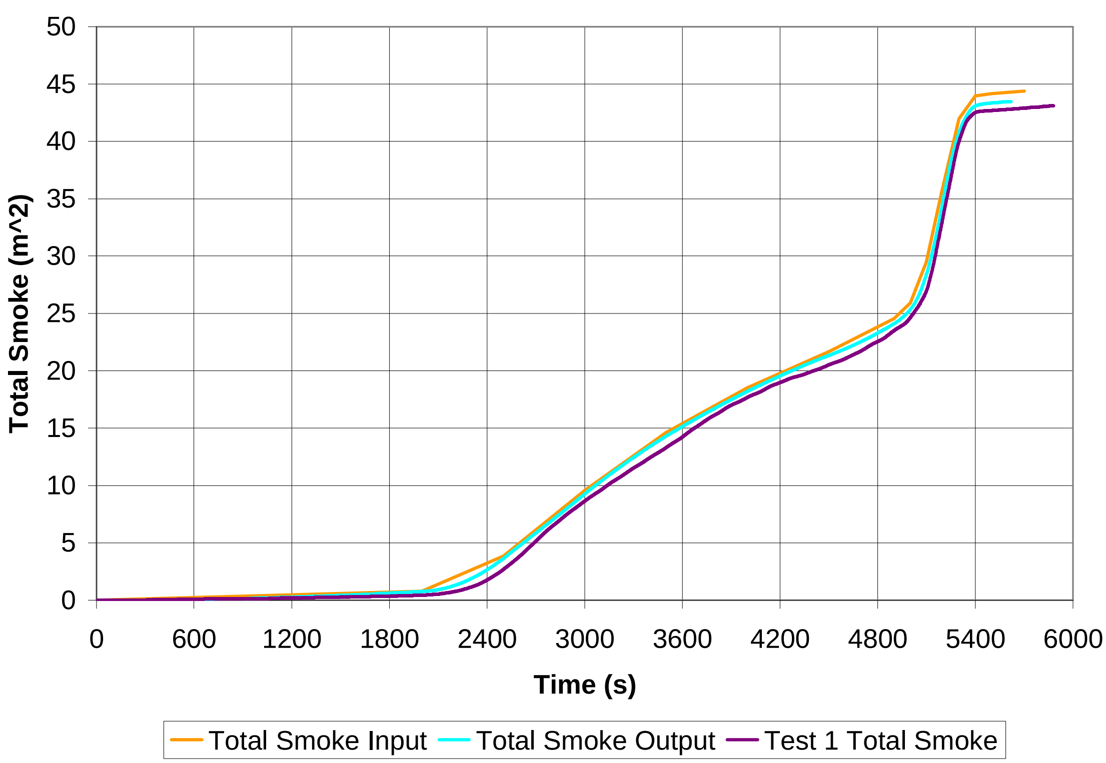

Figure 80 – Cotton linen fabric total smoke.

The cotton linen fabric test requires a minimum simulation run time of 5700 seconds to capture the phenomenon. The rates of rise and decay are similar throughout the graphs with some discrepancies in peak values.

Figure 76, Figure 77, and Figure 78 show the smoke characteristics produced in the simulation. The extinction coefficient and obscuration peak values are less than the value produced in Test 1 by approximately 12 %. This relationship is not carried over to the smoke release rate data. The maximum smoke release rate from Test 1 is 0.0839 m^2/s and 0.0822 m^2/s from the model output. The model peak value is only 2.03 % less than Test 1. The resolution of the smoke release rate from input to output can be clearly seen in Figure 79. The model recreates the specified input curve throughout the simulation.

The total smoke produced in the model is 43.48 m^2, whereas Test 1 produces 42.83 m^2 at the end of the simulation run time. The model produces 1.3 % more smoke than the actual test. The smoke release rate curve specified for this model produces a total smoke of 43.76 m^2. The output is 0.87 % less than the specified input. The total smoke curves are displayed in Figure 80.

5.4.9 PVC Insulated Wire

Figures 81-85 show the results from the PVC insulated wire model in comparison to the data from the IMO tests. The source is modeled as a 2.5 by 2.5 by 100 cm long volume, placed in a square shape with the top surface specified as a vent to provide the represented smoke production using the Species ID method.

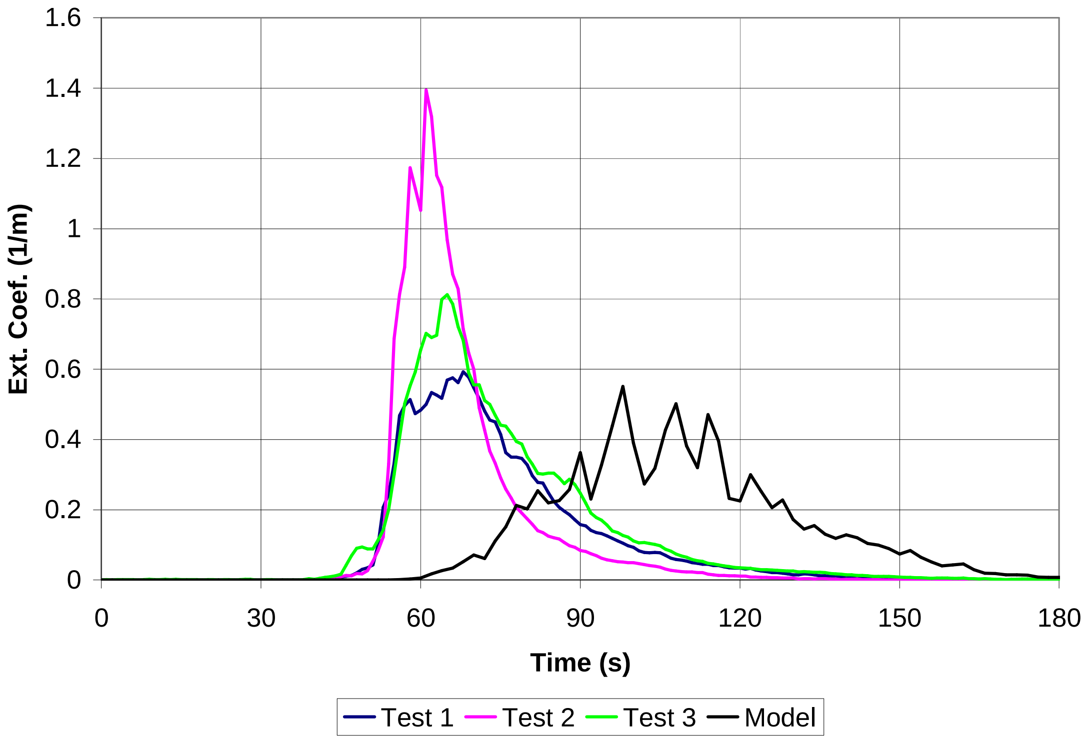

Figure 81 – PVC insulated wire extinction coefficient.

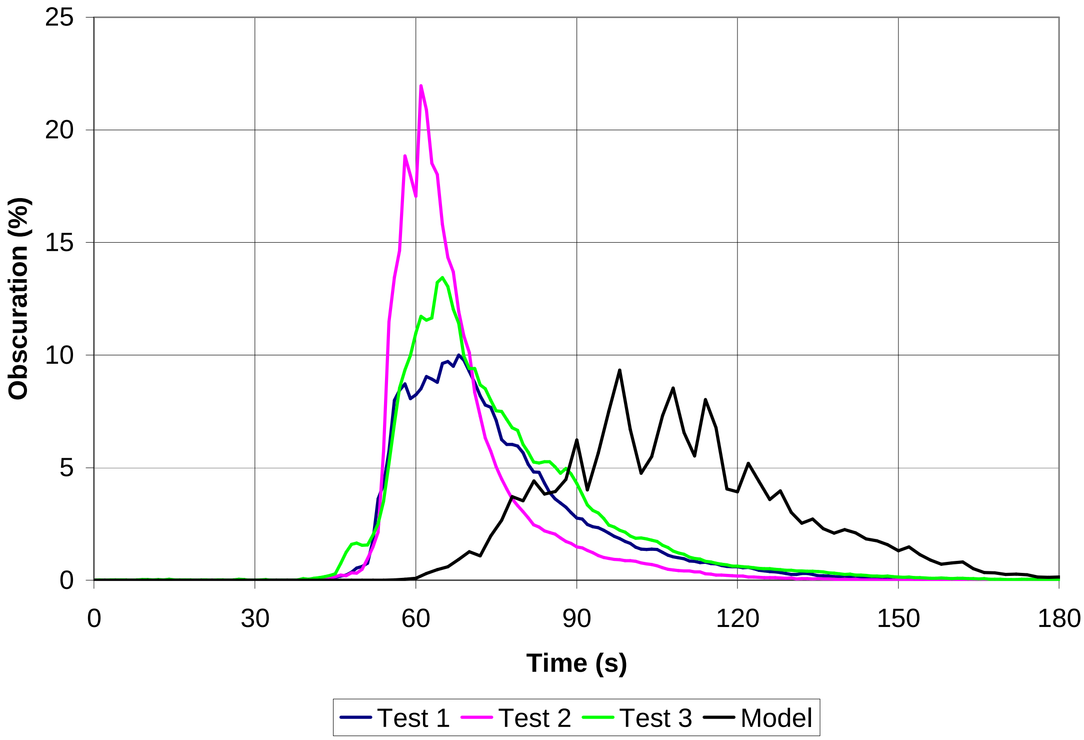

Figure 82 – PVC insulated wire obscuration.

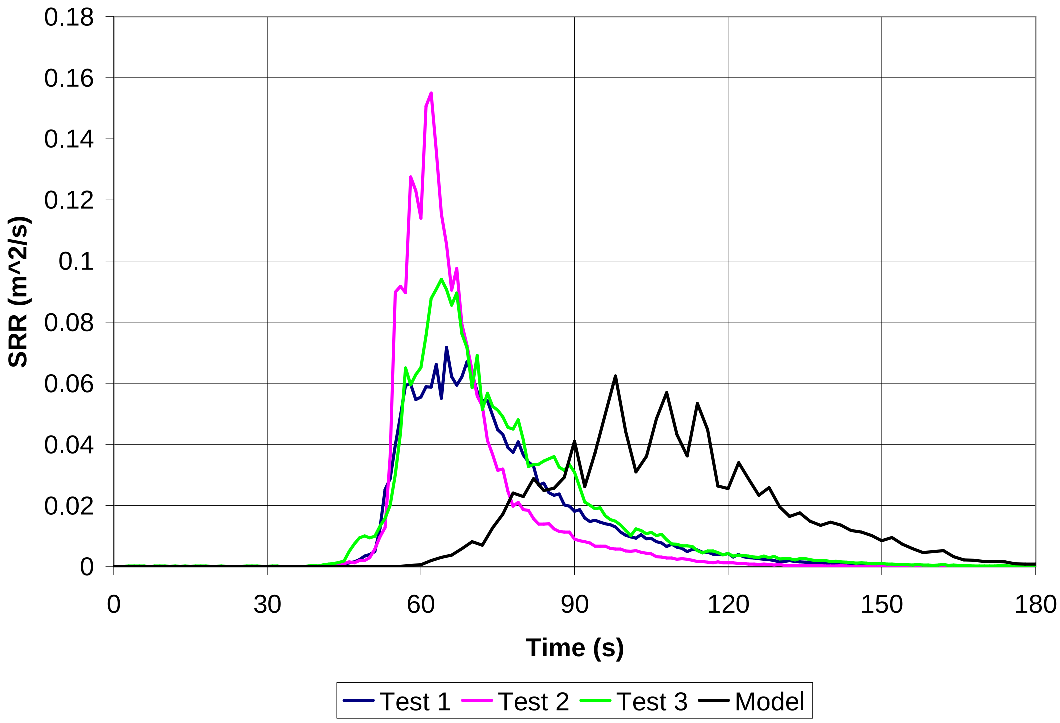

Figure 83 – PVC insulated wire smoke release rate.

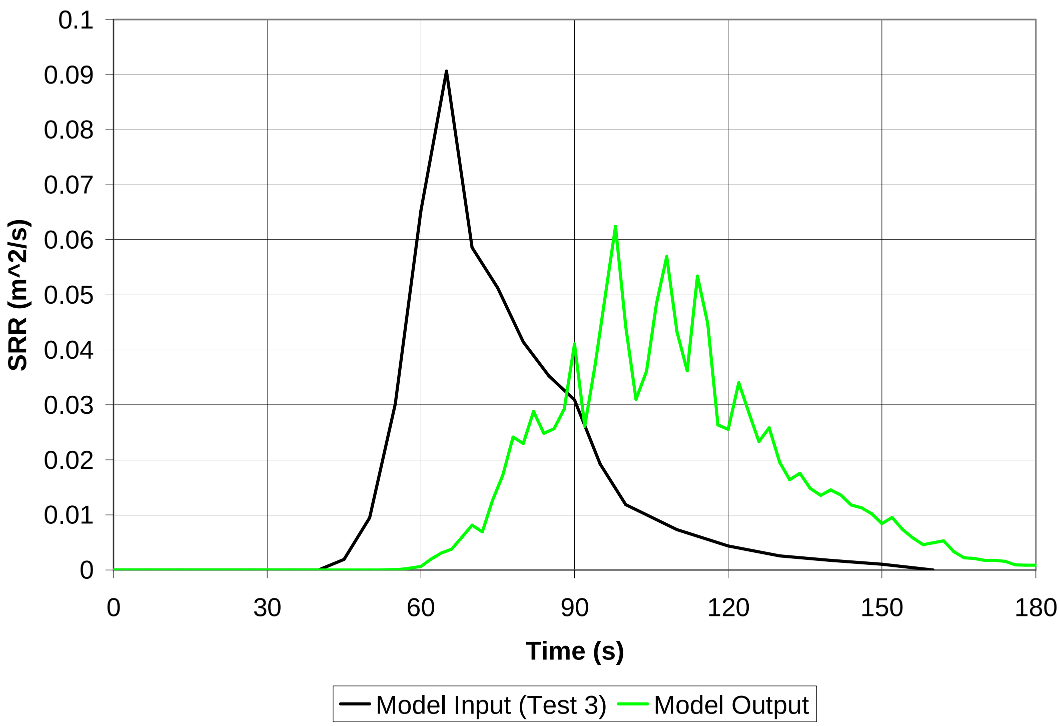

Figure 84 - PVC insulated wire model input and output.

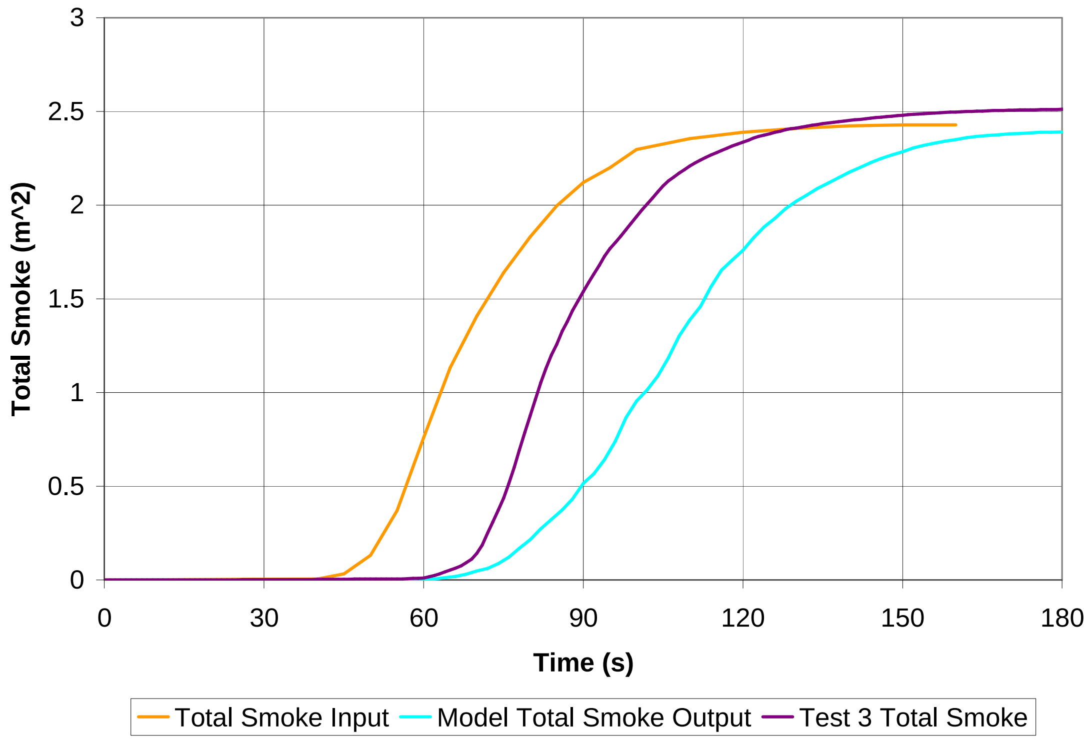

Figure 85 – PVC insulated wire total smoke.

The PVC insulated wire is a unique smoldering source because it does not use a hotplate and has little heat generation of its own. The heat generation of this specimen produces very little buoyancy in the smoke plume. The amount of smoke produced during the IMO tests is small compared to the other sources and the overall time this test is performed is short. The lack of buoyancy causes issues with smoke travel up to the measurement point in the exhaust duct. The smoke tends to mix more in the hood prior to traveling up into the exhaust shaft. This causes the lag time from the uncorrected data to be magnified and the overall smoke characteristic values are lower due to mixing.

Figure 81, Figure 82, and Figure 83 show these characteristics. The smoke species within the model is based on the Test 3 smoke release rate curve. The profile of this test is not recreated in the model due to the lack of buoyancy. The profiles from the model lag behind and do not reach the appropriate peaks. Figure 84 shows that the model peak time is 33 seconds later than the input curve when no natural buoyancy is present and the smoke release rate value is approximately 31 % less than Test 3. If buoyancy is introduced into the simulation similar to the smoldering sources that use a hotplate, the recreation of the input curve and Test 3 is significantly more accurate. The lag time from the uncorrected experimental time remains, but the profiles from the experimental data are matched in the model output data. The introduction of buoyancy into this model improves the accuracy, but does not represent the phenomena of the experimental tests.

Figure 85 shows the total smoke produced in the model without induced buoyancy is 2.39 m^2, whereas Test 3 produces 2.52 m^2 at 180 seconds. The model produces 5.2 % less smoke than the actual test. The smoke release rate curve specified for this model produces a total smoke of 2.43 m^2. The output from the model is 1.6 % less than the specified input. This indicates that all of the smoke is being collected by the exhaust duct, and that the total smoke calculated is within the realm of accuracy that the other specimen models produced.

5.5 Discussion of Results

5.5.1 Smoke Characteristics Range of Accuracy

The smoke characteristics produced in FDS can be controlled by the user by specifying a species injection with a SPEC ID line to represent the smoke, or they can be calculated independently of the user by enabling the mixture fraction model and specifying a heat of combustion and a smoke yield. The Species ID method has been used for all of the fuel sources in this project because the smoke production for these incipient and smoldering sources does not correlate well with the heat release rate. This correlation is the foundation of the mixture fraction model in FDS. A summary of the input and output values of the smoke production are shown in the Tables below.

Table 2 – Total Smoke Variance

Fuel Source	Model Output to Input	Model Output to Test
Flaming		
Shredded Office Paper	-0.8%	4.8%
PU Foam with Micro-fiber Fabric	-5.4%	-4.7%
Printed Circuit Board	0.1%	-1.6%
Computer Case ABS Plastic	4.3%	4.7%
Smoldering		
PU Foam with Micro-fiber Fabric	-3.1%	-1.5%
Ponderosa Pine	-1.6%	1.9%
Cotton Linen Fabric	-0.9%	1.3%
PVC Insulated Wire	-1.6%	-5.2%

Table 3 – Peak Smoke Release Rate Model Input v. Model Output

Fuel Source	Peak Value			Peak Time		
	Input (m^2/s)	Output (m^2/s)	Difference (%)	Input (s)	Output (s)	Difference (s)
Flaming						
Shredded Office Paper	0.990	0.846	-14.5	84	100	16
PU Foam with Micro-fiber Fabric	0.484	0.449	-7.2	315	326	11
Printed Circuit Board	0.491	0.416	-15.3	52	56	4
Computer Case ABS Plastic	0.226	0.265	17.3	115	134	19
Smoldering						
PU Foam with Micro-fiber Fabric	0.062	0.065	4.8	3850	3834	-16
Ponderosa Pine	0.142	0.148	4.2	4006	4036	30
Cotton Linen Fabric	0.081	0.082	1.2	5220	5198	-22
PVC Insulated Wire	0.091	0.064	-29.7	65	98	33

Table 2 shows the total smoke variations between the model output and the model input and represented test. The values shown for flaming PU foam with micro-fiber fabric are for the species ID method only. The mixture fraction simulation for this source is not shown. The total smoke values remain within approximately 5 % of the experimental values and the specified input values. The smoke release rate curve is accurately reproduced in FDS to create the same levels of smoke from the experimental data. The total smoke input is derived by integrating the specified smoke release rate curve that is used in the input file for each simulation. The total smoke output is based on the measurement of the species obscuration within the exhaust duct by integrating the smoke release rate curve calculated from this measurement. The simulated measurement is not directly associated with the specified input; it is calculated after the species has moved through the domain, which clearly shows the capabilities of FDS to reproduce the specified smoke volume in these simulations.

Table 3 displays the peak smoke release rate values for the model input and model output, as well as the peak times for each. The difference between model input and output values is in percent and the time difference is in seconds. The peak smoke release rate values are more scattered due to variations in mixing and dilution between the model and the experimental tests. The lag time associated with the uncorrected experimental data is shown on the right side of Table 3. The longest lag time is found in the PVC insulated wire simulation, which is attributed to the lack of buoyancy and slow smoke retrieval of the exhaust duct. The smoke diluted significantly in the hood, causing a delay in the transport to the exhaust duct and the simulated obscuration measurement. The ponderosa pine simulation shows a peak time difference of 30 seconds. This is relatively insignificant when compared to the total time scale of the simulation. In general, the peak value comparison between the model input and the output is more accurate for the smoldering tests. The PVC insulated wire simulation values are affected by the low buoyancy characteristics of the fuel and do not share this level of accuracy with the other smoldering sources.

Chapter 6: Summary and Conclusions

6.1 Summary of Research

The purpose of this research is to provide guidance on methods to characterize incipient fuel sources to be used in simulations using Fire Dynamics Simulator (FDS) and evaluate the capability of FDS to recreate the appropriate phenomena. The experimental phase of this research has been performed at Underwriter's Laboratories Inc. in Northbrook, Illinois within the Fire Protection Department. Computer modeling has been performed at the University of Maryland, College Park, within the Department of Fire Protection Engineering in the A. James Clark School of Engineering using the UL Fire Modeling Lab.

A process was developed to characterize both flaming and smoldering fuel sources for input into FDS. Subsequently, FDS modeling of this process is studied to reveal the ability of the program to accurately reproduce the appropriate phenomena. Finally, the variations between the models and the initial characterization are quantified to determine the attainable range of accuracy.

6.1.1 Phase 1 – Fuel Source Characterization

During the experimental phase of this project, eight sources were characterized under UL's IMO intermediate-scale calorimeter. The process by which each of these materials was characterized and the data collected from each test has been presented in this thesis.

The data collected from these tests includes mass loss (for flaming sources), heat release rate (for flaming sources), smoke release rate, smoke particle size and count, and gas effluents. The fuel packages have been designed to share similar physical characteristics to how they would be used in manufactured goods. The flaming sources were ignited using predefined ignition sources from various codes and standards. In addition to fuel source measurements, ambient room conditions and exhaust duct conditions were also monitored to ensure similarity between the model and the true physical parameters.

6.1.2 Phase 2 – Model Development and Analysis

Upon completion of Phase 1, a model of UL's IMO intermediate-scale calorimeter was created using FDS and each of the fuel package experiments was simulated. A grid resolution study was performed, revealing that a 2.5 cm grid would be adequate. The information calculated from FDS was then compared to the original experimental data as well as the input parameters for FDS.

The Species ID method is used for these simulations. This method defines the source gas production as a species injection for the smoke so that the smoke generation in the model can follow the profile generated in the experiments. This method allows the user to directly specify the smoke release rate ramp in the model using a mass flux with the species. The benefit to this is that the smoke generation in the model is now independent of the heat release rate, allowing for more a more accurate representation of any smoldering phenomena, which is shown in the comparison between the mixture fraction method and the Species ID method used for the flaming polyurethane foam with micro-fiber fabric fuel source modeling.

The mixture fraction model requires the heat release rate, smoke yield, and heat of combustion as inputs into the reaction. This method bases smoke production on a calculation from the three previously mentioned parameters. The smoke production is not a direct user input, but is calculated by FDS. Smoldering phenomena cannot be captured using this method. This method was used for comparative purposes only.

6.2 Conclusions

FDS has provided a range of accuracy near 5 % of the input values for smoke characteristics. The lag times associated with the output data can be attributed to the uncorrected experimental data. The time scaled inputs for FDS are based on the time that the instrumentation within the exhaust duct detected the smoke release from the material and the transport time required to move the smoke from the specimen to the instrumentation is not compensated for. The Species ID method is an accurate method to represent incipient fire sources.

Appendix A: Summary of Test Results

Sample Description	Mode	Ignition Source	Ignition Fuel	Flame Height	Ignition Source Contact Time	Average Air Velocity	Initial Wt. of Sample	Total Wt. loss	HOC	Peak HRR	Peak SRR	Dilution		Peak CO	Peak CO2	Smoke Yield	Spec. Ext. Area	Total SR	Total HR
												FTIR	WPS						
				(mm)	(sec)	(m/sec)	(g)	(g)	(kJ/g)	(kW)	(m^2/s)	(SCFH)		(ppm)	(ppm)	(g/g)	(m^2/g)	(m^2)	(MJ)
Shredded Paper-1	Flaming	TB 604	Propane	35	5	4.28	75.0	58.76	6.6	7.76	1.350	0:10	20:2	428.4	5021.6	0.094	0.810	110.5	0.388
Shredded Paper-2	Flaming	TB 604	Propane	35	5	4.37	75.0	63.19	9.7	8.91	0.990	0:10	20:2	410.6	4879.9	0.083	0.710	105.8	0.612
Shredded Paper-3	Flaming	TB 604	Propane	35	5	4.44	75.0	60.71	9.7	12.49	2.000	0:10	20:2	564.2	5907.3	0.097	0.830	117.4	0.589
PU Foam/Microfiber-1	Flaming	TB 604	Propane	35	20	4.30	118.0	90.37	21.0	8.54	0.432	0:10	20:2	145.7	4576.3	0.094	0.821	74.2	1.896
PU Foam/Microfiber-2	Flaming	TB 604	Propane	35	20	4.28	119.7	100.9	22.2	11.23	0.512	0:10	20:2	162.4	5558.2	0.096	0.835	84.2	2.240
PU Foam/Microfiber-3	Flaming	TB 604	Propane	35	20	3.54	117.2	97.33	20.3	9.79	0.513	0:10	20:2	214	6034.4	0.095	0.828	80.6	1.974
Circuit Board-1	Flaming	ATIS T1.319	Methane	65	Duration of test	4.65	68.8	11.74	4.4	1.90	0.534	0:10	20:2	209.8	638	0.215	1.871	22.0	0.826
Circuit Board-2	Flaming	ATIS T1.319	Methane	65	Duration of test	4.47	66.5	10.55	14.2	2.41	0.491	0:10	20:2	220.8	891.5	0.221	1.922	20.3	0.924
Circuit Board-3	Flaming	ATIS T1.319	Methane	65	Duration of test	4.59	65.5	8.9	38.9	2.59	0.587	0:10	20:2	242.1	891.4	0.319	2.777	24.7	1.120
Computer Case-1	Flaming	UL 94 50 W	Methane	20	Duration of test	4.96	10.5	1.6	N/A	0.00	0.119	0:10	20:2	22.3	58.4	0.785	5.721	9.2	0.000
Computer Case-2	Flaming	UL 94 50 W	Methane	20	Duration of test	4.67	10.2	1.9	N/A	0.73	0.245	0:10	20:2	7.2	59.0	0.967	10.053	19.1	0.129
Computer Case-3	Flaming	UL 94 50 W	Methane	20	Duration of test	4.68	10.1	2.1	37.0	0.63	0.292	0:10	20:2	19.7	109.1	0.878	9.316	19.6	0.078
PU Foam/Microfiber-1	Smoldering	UL 217	N/A	N/A	N/A	4.33	118.4	53.9	N/A	N/A	0.066	0:10	20:2	127.4	113.7	0.085	0.740	39.9	N/A
PU Foam/Microfiber-2	Smoldering	UL 217	N/A	N/A	N/A	4.35	118.0	56.5	N/A	N/A	0.073	0:10	20:2	123.9	100.8	0.089	0.774	43.8	N/A
PU Foam/Microfiber-3	Smoldering	UL 217	N/A	N/A	N/A	4.35	119.0	56.9	N/A	N/A	0.040	0:10	20:2	100.3	42.9	0.073	0.636	36.2	N/A
Ponderosa Pine-1	Smoldering	UL 217	N/A	N/A	N/A	4.55	158.9	149.2	N/A	N/A	0.161	0:10	10:2	253.0	303.8	0.141	1.224	182.7	N/A
Ponderosa Pine-2	Smoldering	UL 217	N/A	N/A	N/A	4.32	160.1	147.6	N/A	N/A	0.122	0:10	10:2	255.9	229.3	0.142	1.235	182.3	N/A
Ponderosa Pine-3	Smoldering	UL 217	N/A	N/A	N/A	4.38	152.0	148.6	N/A	N/A	0.146	0:10	10:2	265.4	207.4	0.140	1.231	183.0	N/A
Cotton Linen Fabric-1	Smoldering	UL 217	N/A	N/A	N/A	3.85	19.5	19.5	N/A	N/A	0.084	0:10	10:2	241.3	46.9	0.254	2.211	43.1	N/A
Cotton Linen Fabric-2	Smoldering	UL 217	N/A	N/A	N/A	3.90	19.6	19.6	N/A	N/A	0.118	0:10	10:2	217.5	45.3	0.240	2.088	40.9	N/A
Cotton Linen Fabric-3	Smoldering	UL 217	N/A	N/A	N/A	4.26	20.4	20.4	N/A	N/A	0.086	0:10	10:2	252.6	944.7	0.168	1.465	29.9	N/A
PVC Insulated Wire-1	Smoldering	NFPA 76	N/A	N/A	N/A	4.59	7.40	1.00	N/A	N/A	0.072	0:20	10:2	1.1	25.7	0.237	2.061	2.1	N/A
PVC Insulated Wire-2	Smoldering	NFPA 76	N/A	N/A	N/A	4.48	7.43	1.06	N/A	N/A	0.155	0:20	10:2	2.3	20.4	0.258	2.246	2.4	N/A
PVC Insulated Wire-3	Smoldering	NFPA 76	N/A	N/A	N/A	4.57	7.43	1.13	N/A	N/A	0.094	0:20	10:2	1.2	11.9	0.256	2.231	2.5	N/A

Appendix B: Additional Experimental Data

This section includes all of the additional data that from the experimental phase. This includes particle count density, mean particle diameter, and carbon monoxide and carbon dioxide concentrations.

B.1 Shredded Office Paper

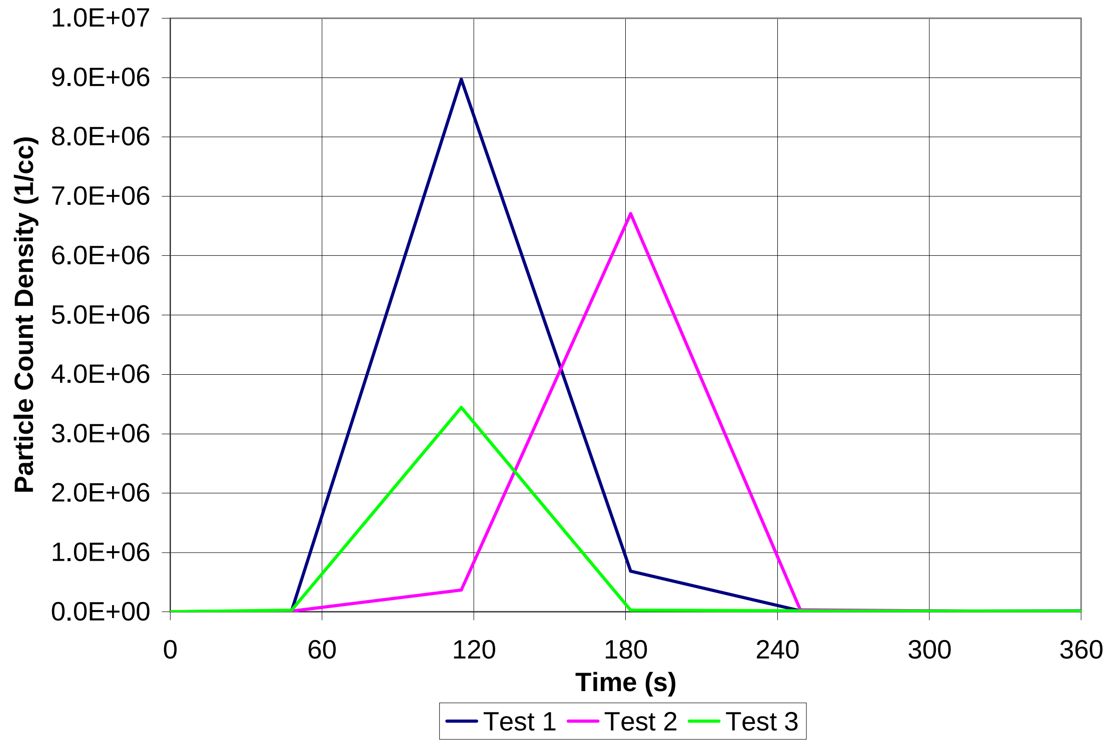

Figure B 1 - Shredded office paper particle count density

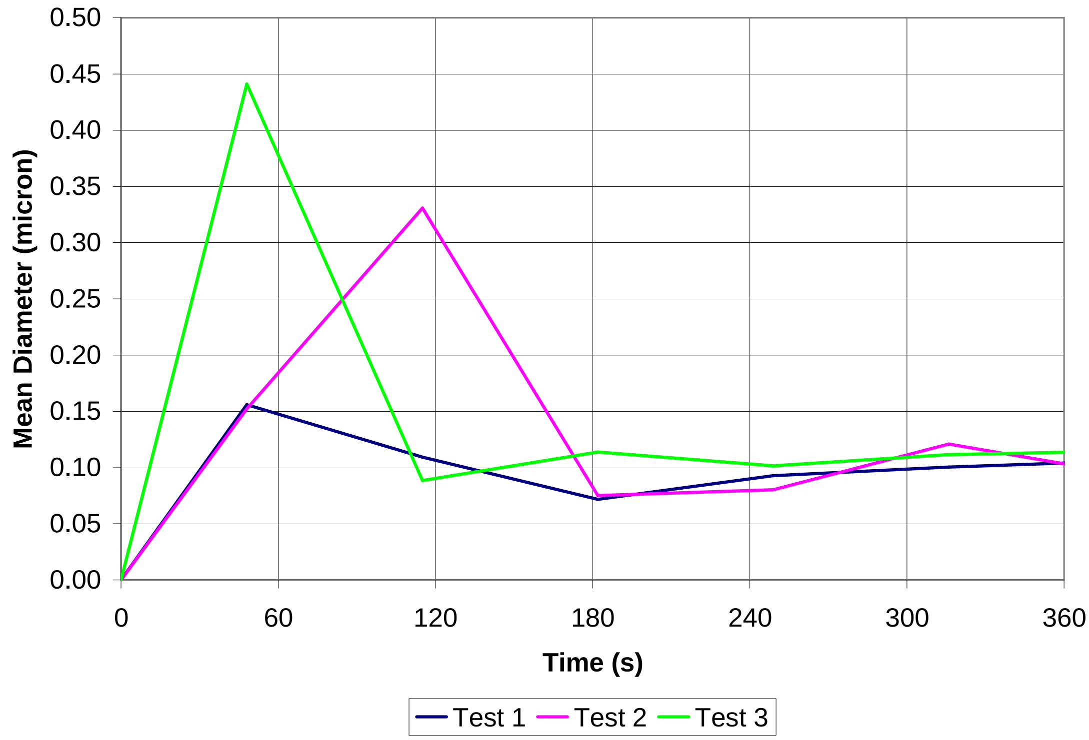

Figure B 2 - Shredded office paper mean particle diameter.

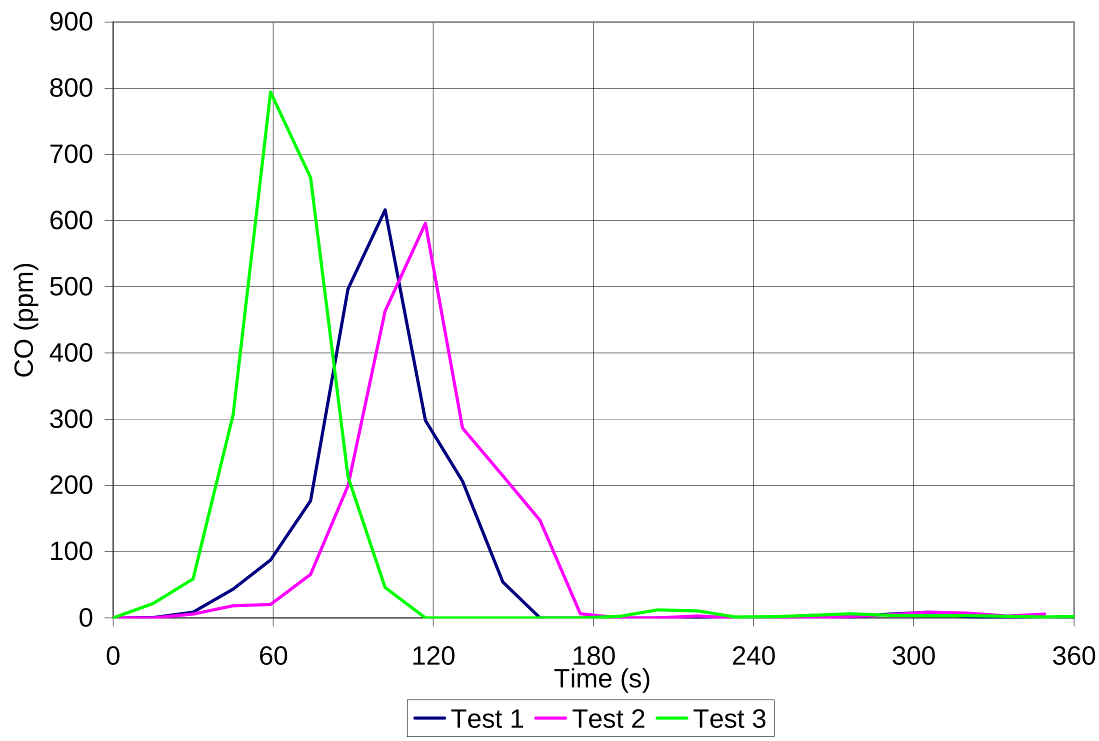

Figure B 3 - Shredded office paper carbon monoxide output.

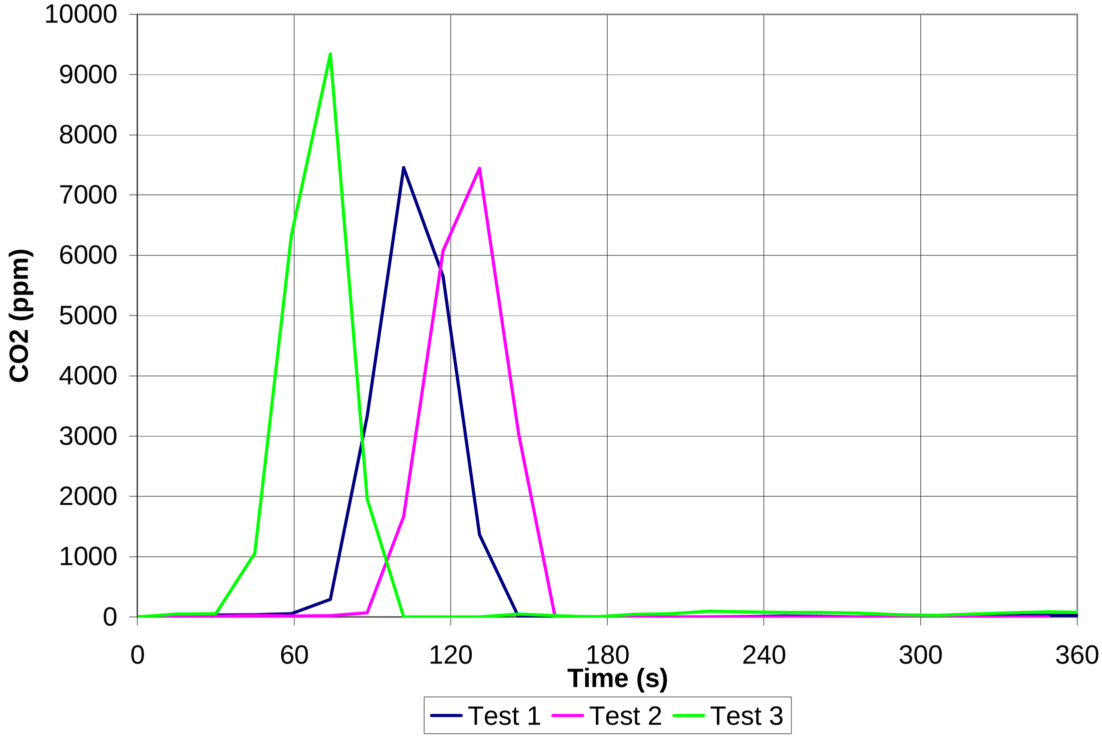

Figure B 4 - Shredded office paper carbon dioxide output.

B.2 Polyurethane Foam with Micro-fiber Fabric (Flaming)

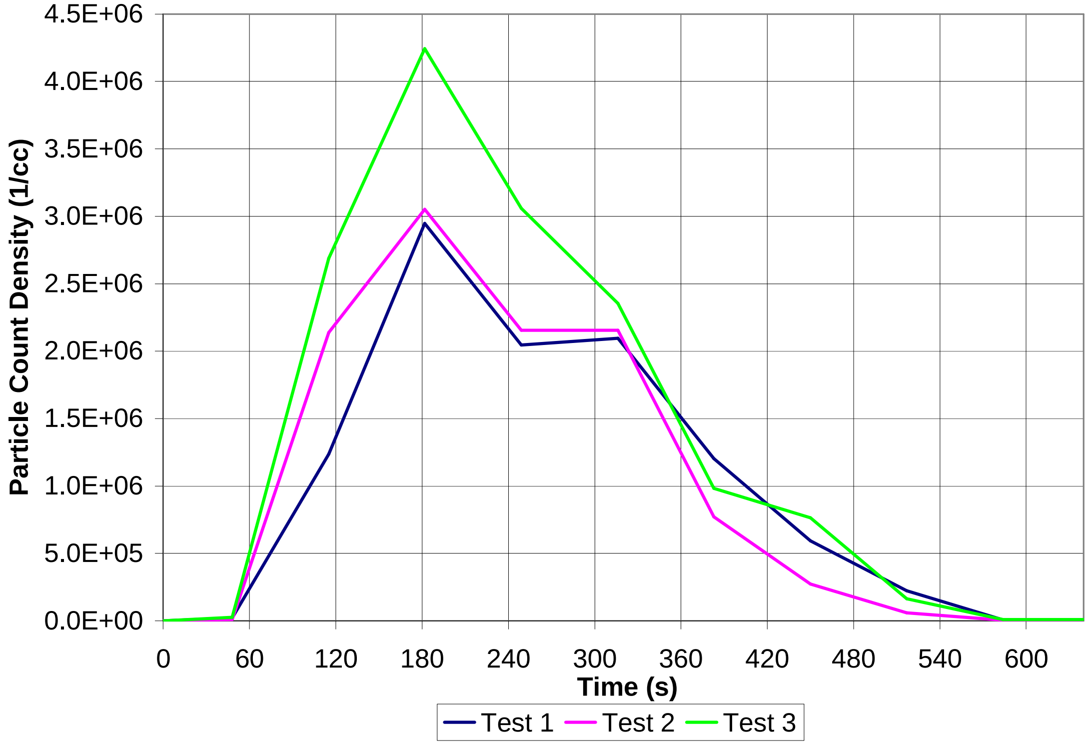

Figure B 5 - Flaming PU foam with micro-fiber fabric particle count density.

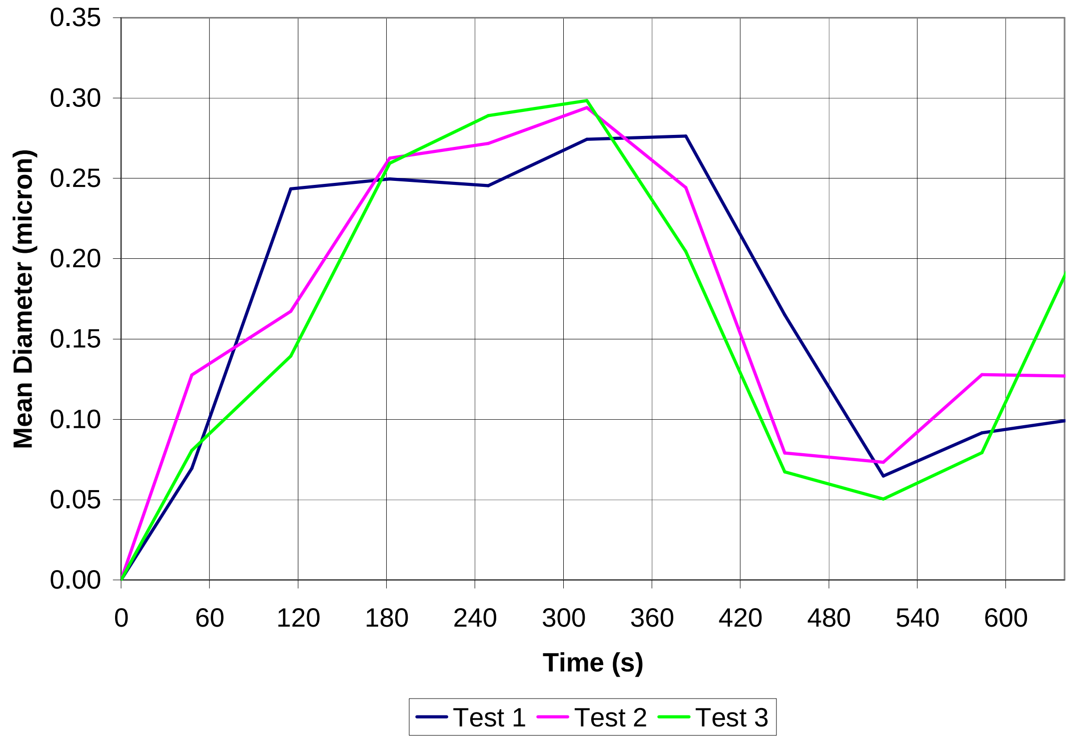

Figure B 6 - Flaming PU foam with micro-fiber fabric mean particle diameter.

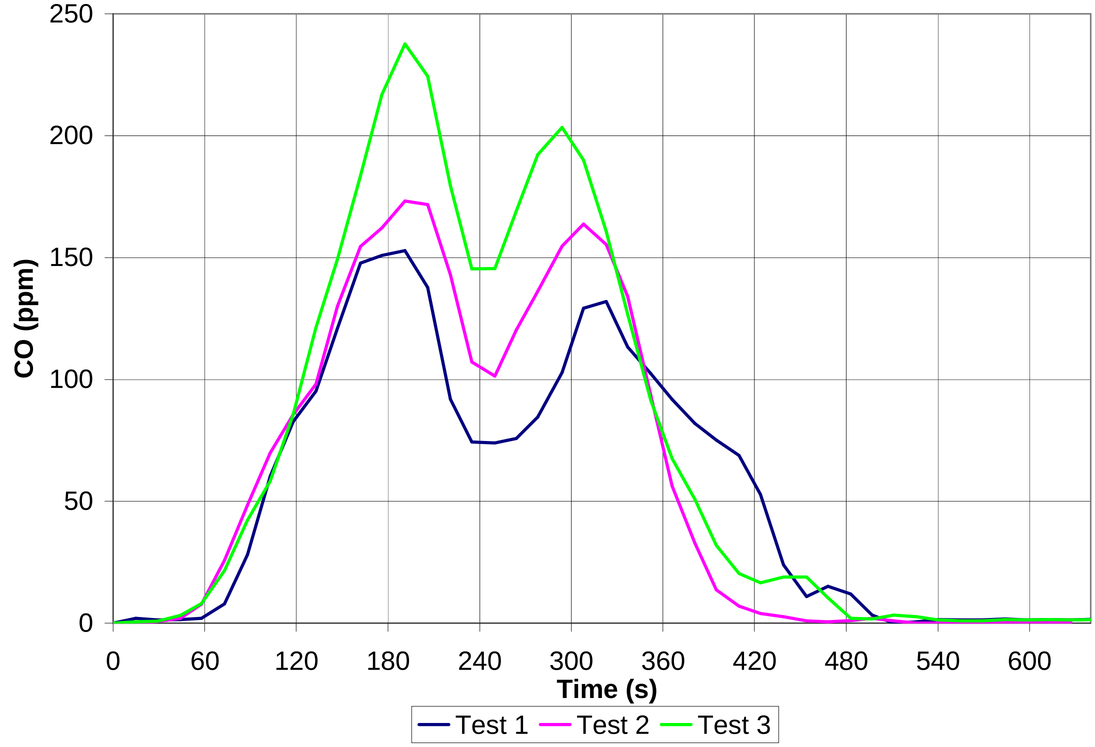

Figure B 7 - Flaming PU foam with micro-fiber fabric carbon monoxide output.

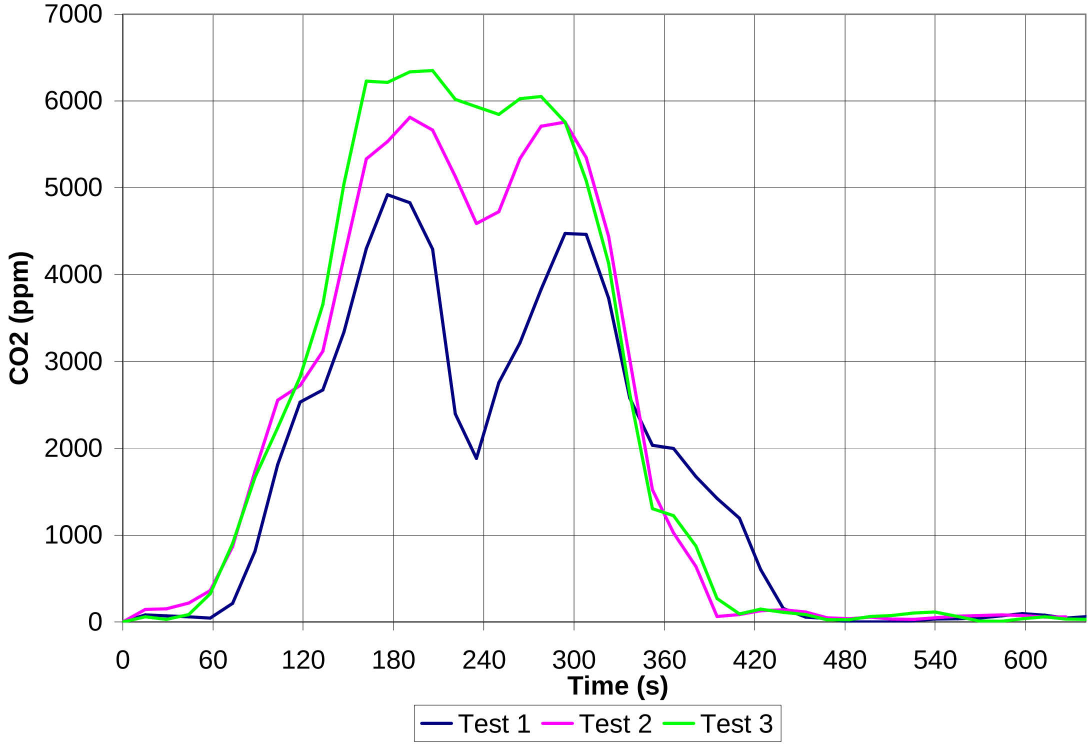

Figure B 8 - Flaming PU foam with micro-fiber fabric carbon dioxide output.

B.3 Printed Circuit Board

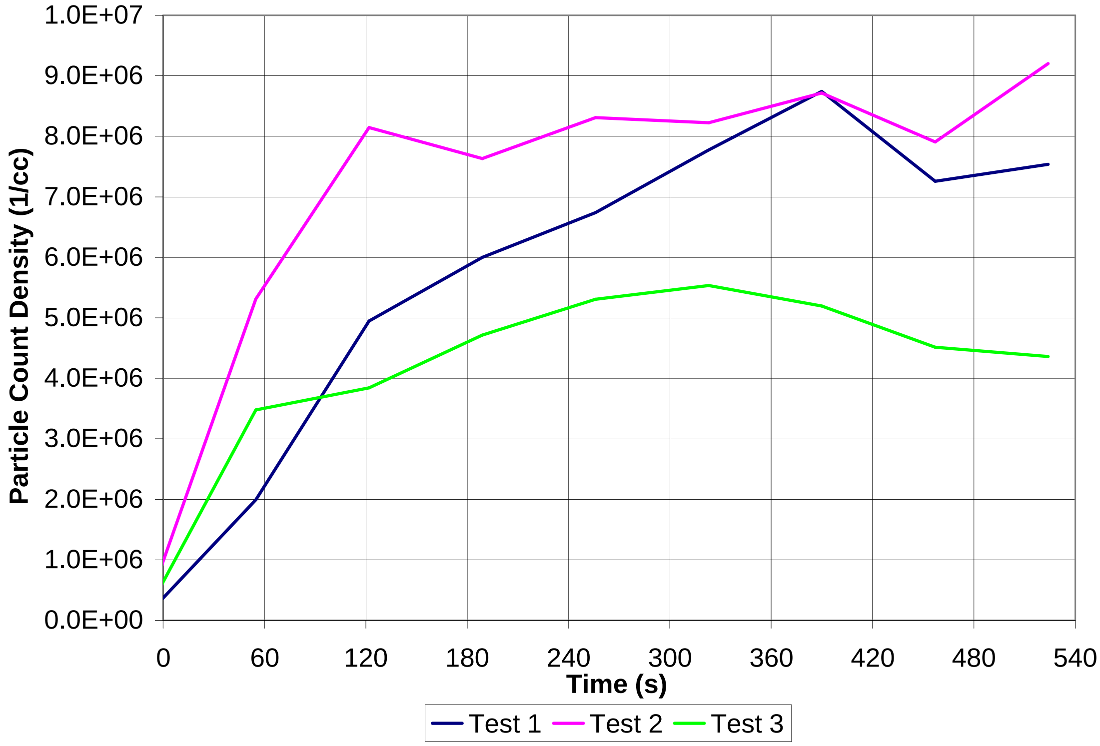

Figure B 9 - Printed circuit board particle count density.

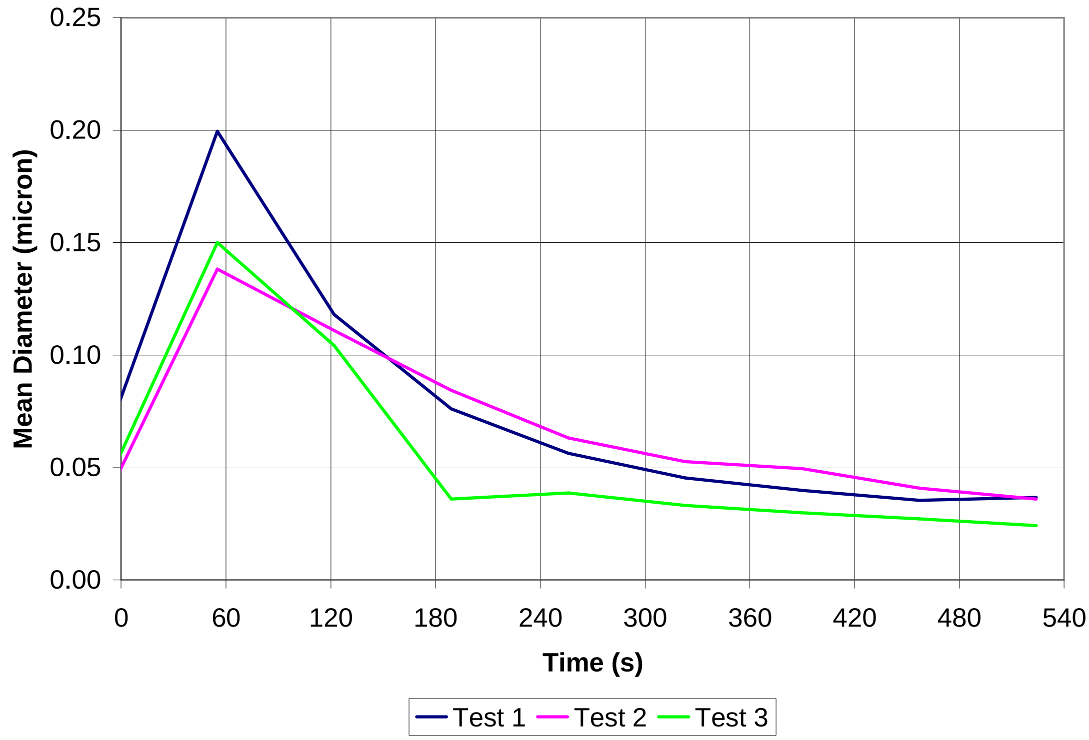

Figure B 10 - Printed circuit board mean particle diameter.

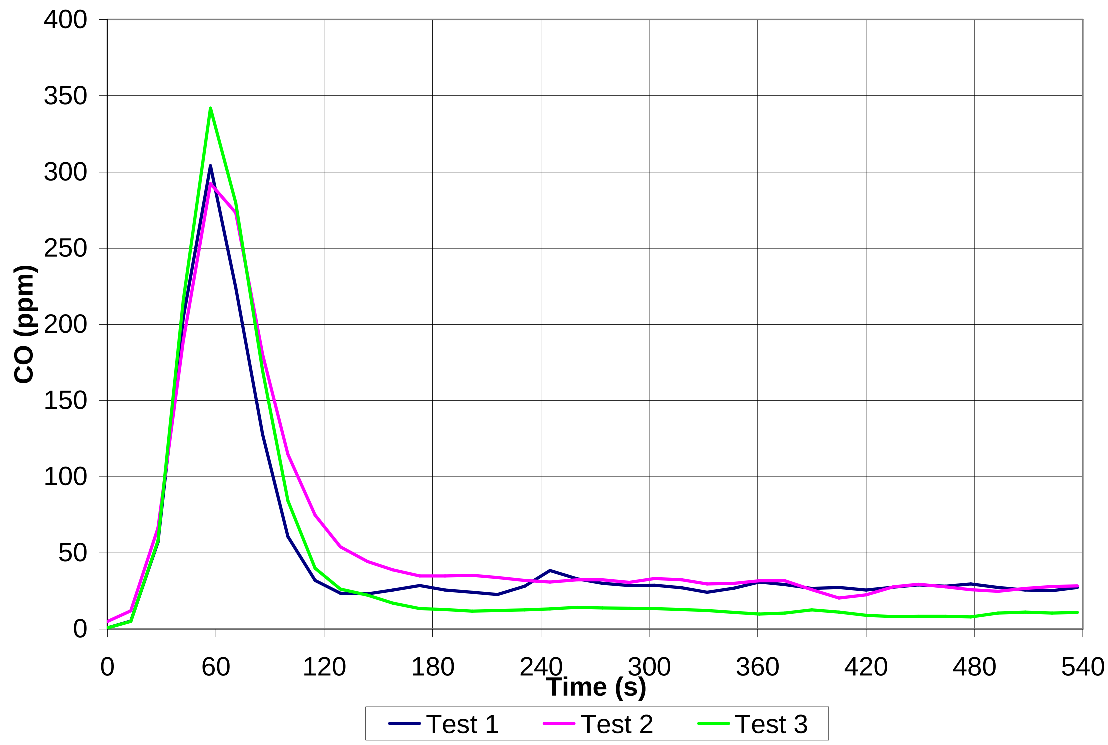

Figure B 11 - Printed circuit board carbon monoxide output.

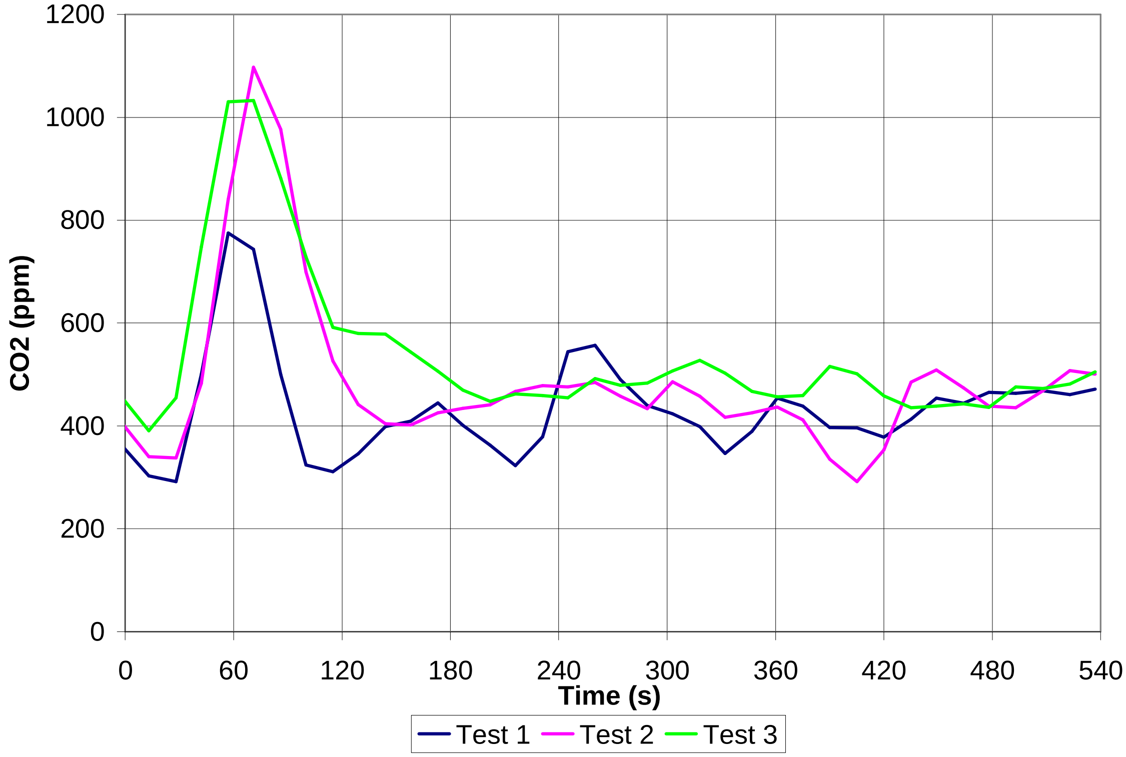

Figure B 12 - Printed circuit board carbon dioxide output.

B.4 Computer Case ABS Plastic

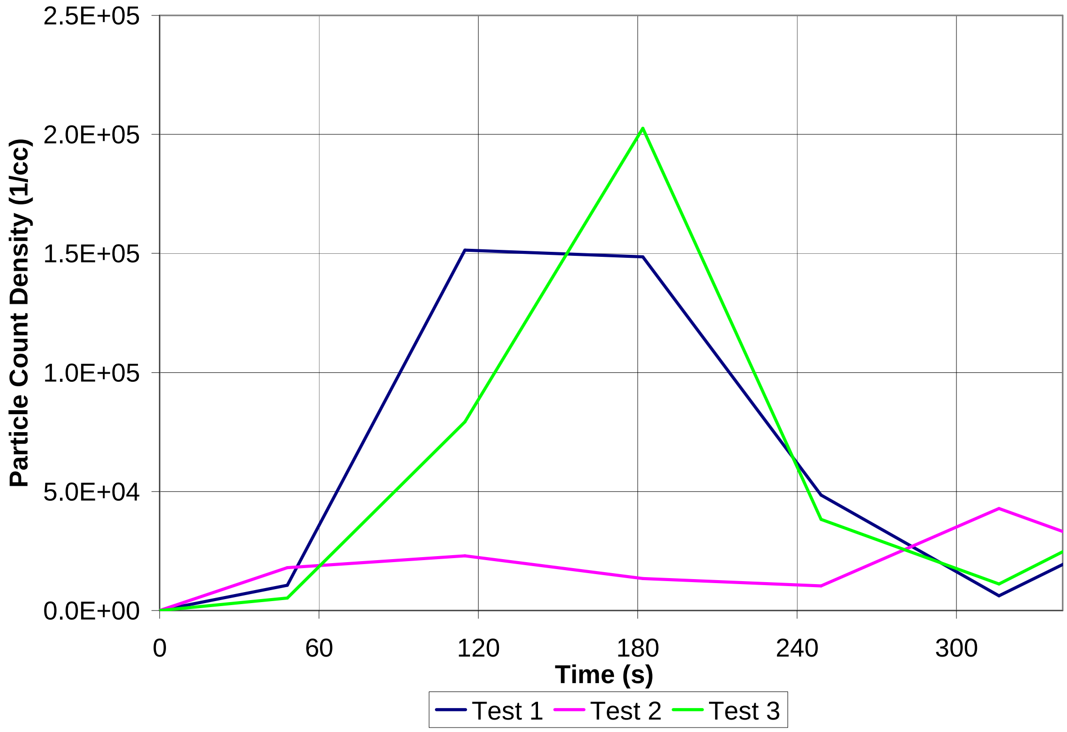

Figure B 13 - Computer case ABS plastic particle count density.

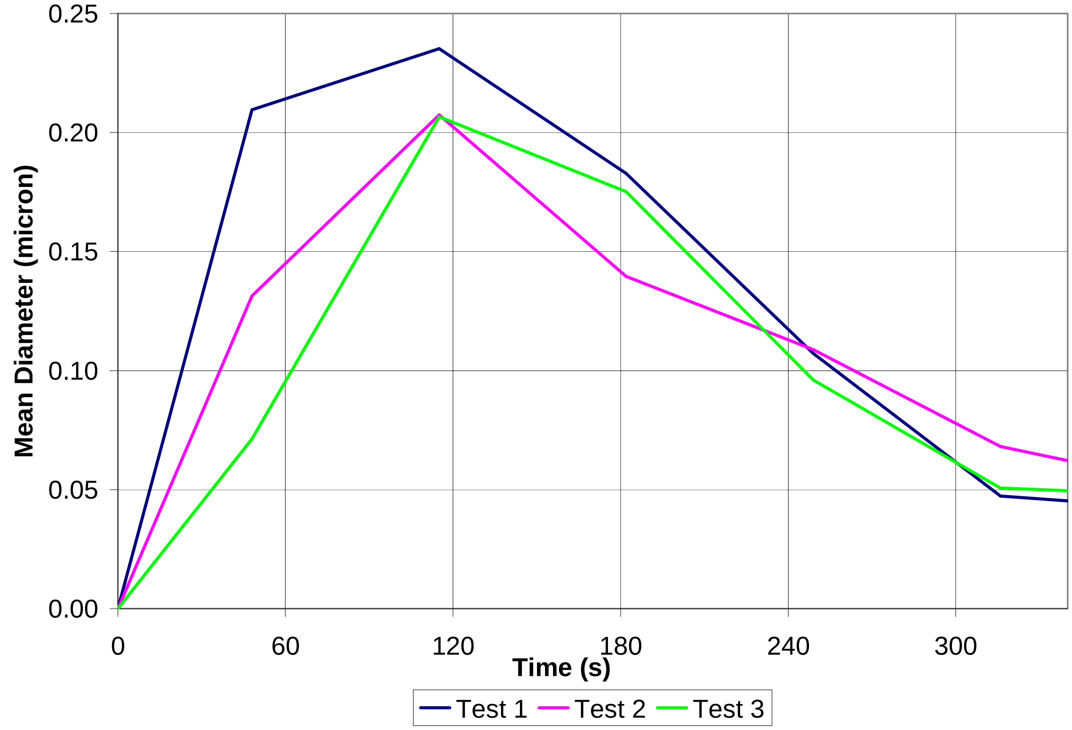

Figure B 14 - Computer case ABS plastic mean particle diameter.

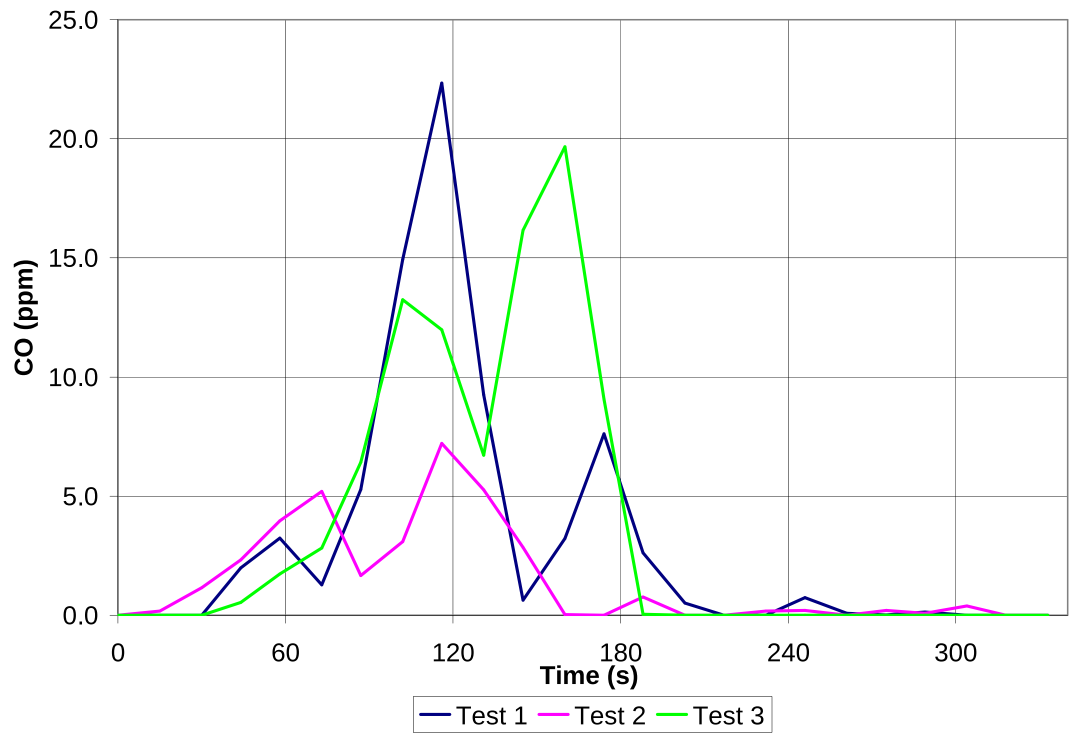

Figure B 15 - Computer case ABS plastic carbon monoxide output.

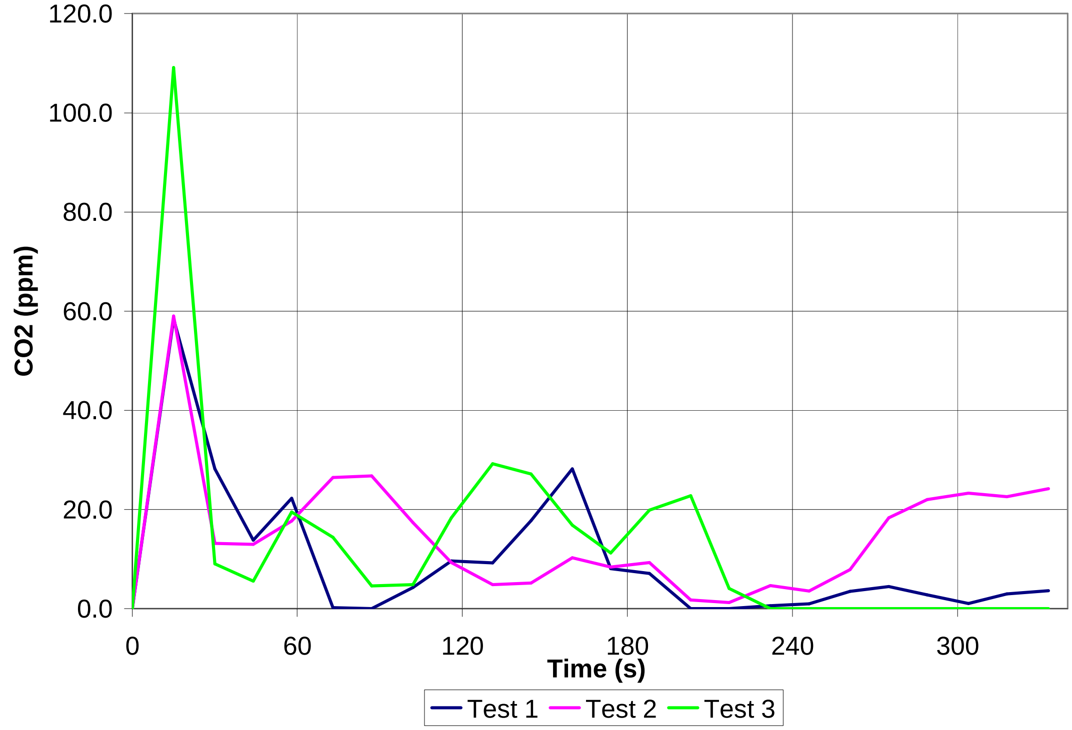

Figure B 16 - Computer case ABS plastic carbon dioxide output.

B.5 Polyurethane Foam with Micro-fiber Fabric (Smoldering)

During Tests 2 and 3, the FTIR spectrometer malfunctioned and failed to produce data after approximately 1000 seconds.

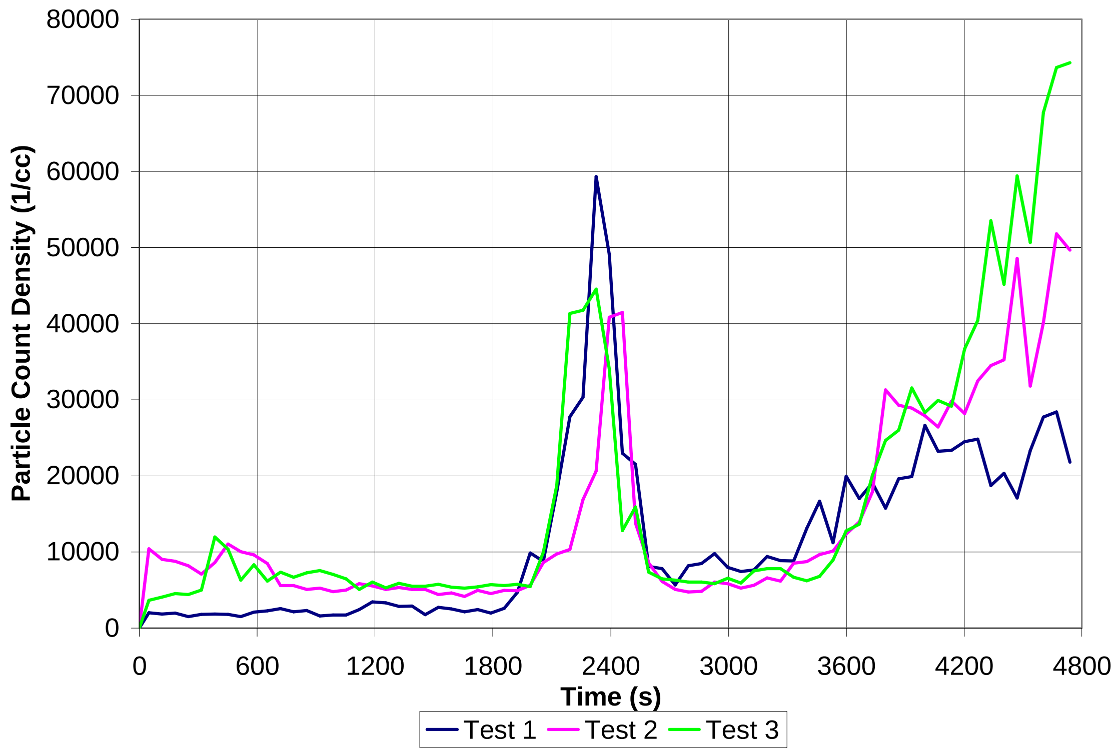

Figure B 17 - Smoldering PU foam w/ micro-fiber fabric particle count density.

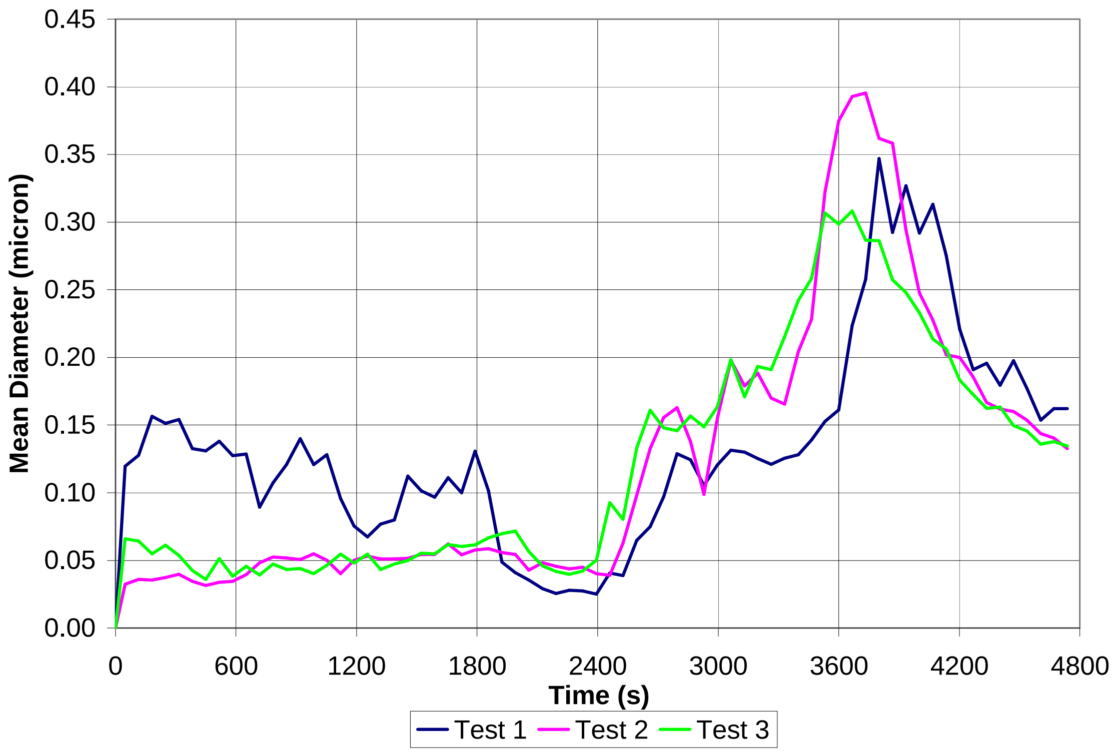

Figure B 18 - Smoldering PU foam w/ micro-fiber fabric mean particle diameter.

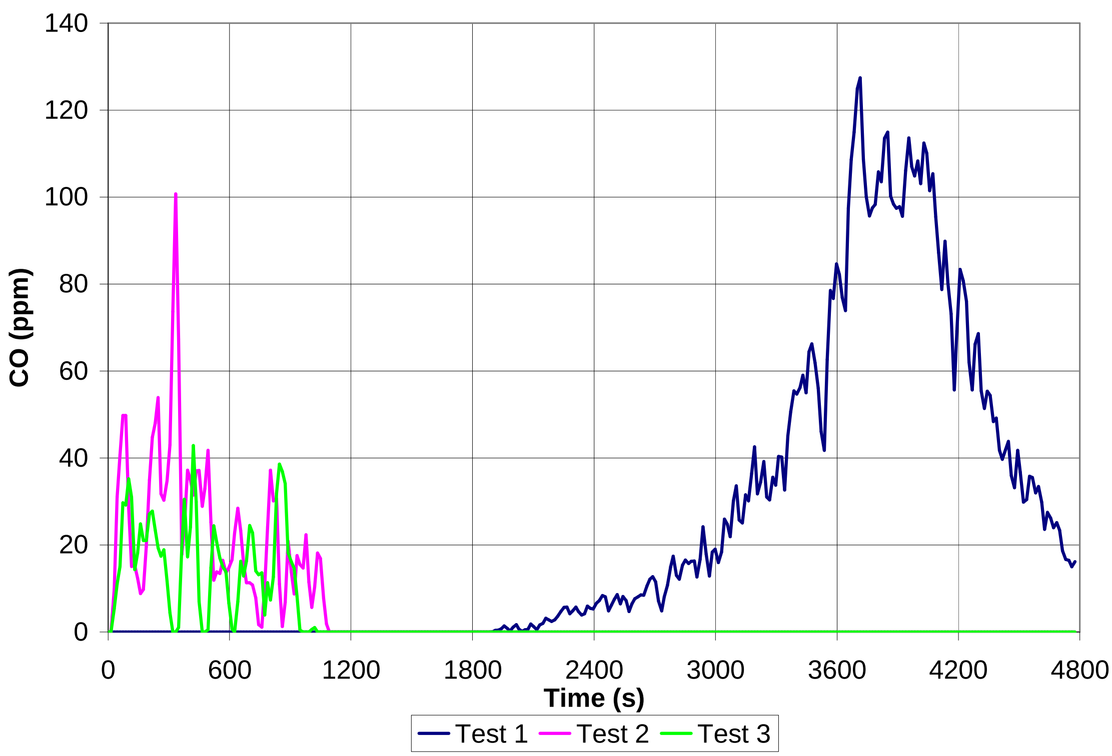

Figure B 19 - Smoldering PU foam w/ micro-fiber fabric CO output.

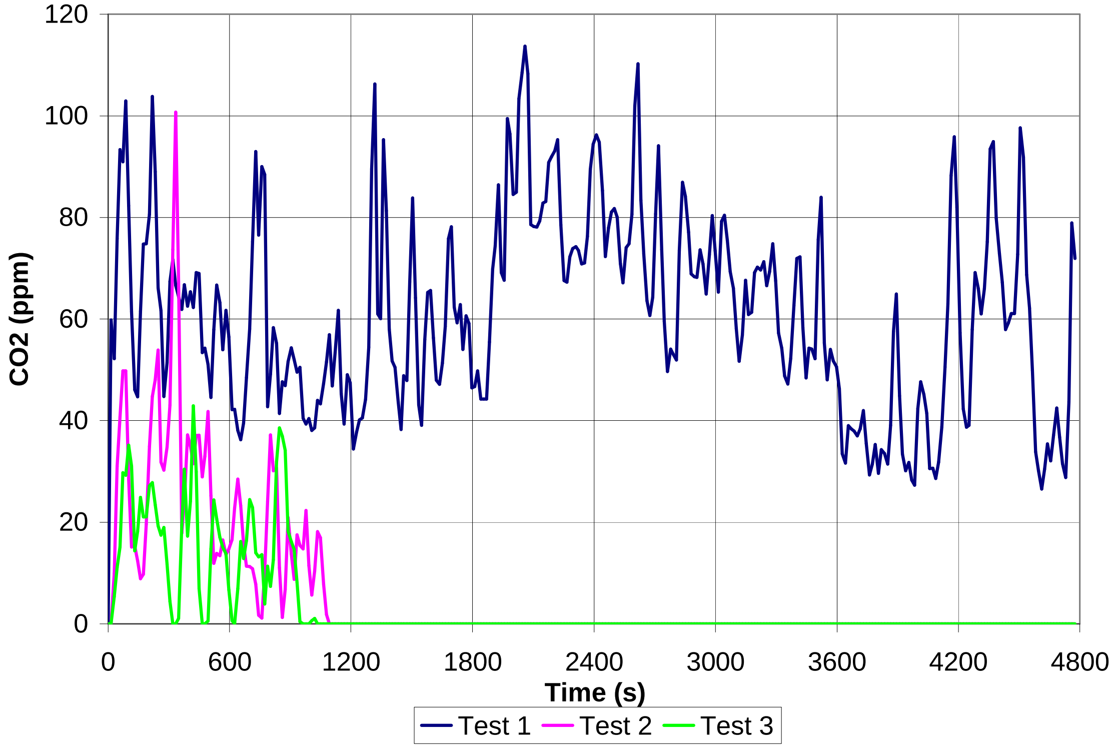

Figure B 20 - Smoldering PU foam w/ micro-fiber fabric carbon dioxide output.

B.6 Ponderosa Pine

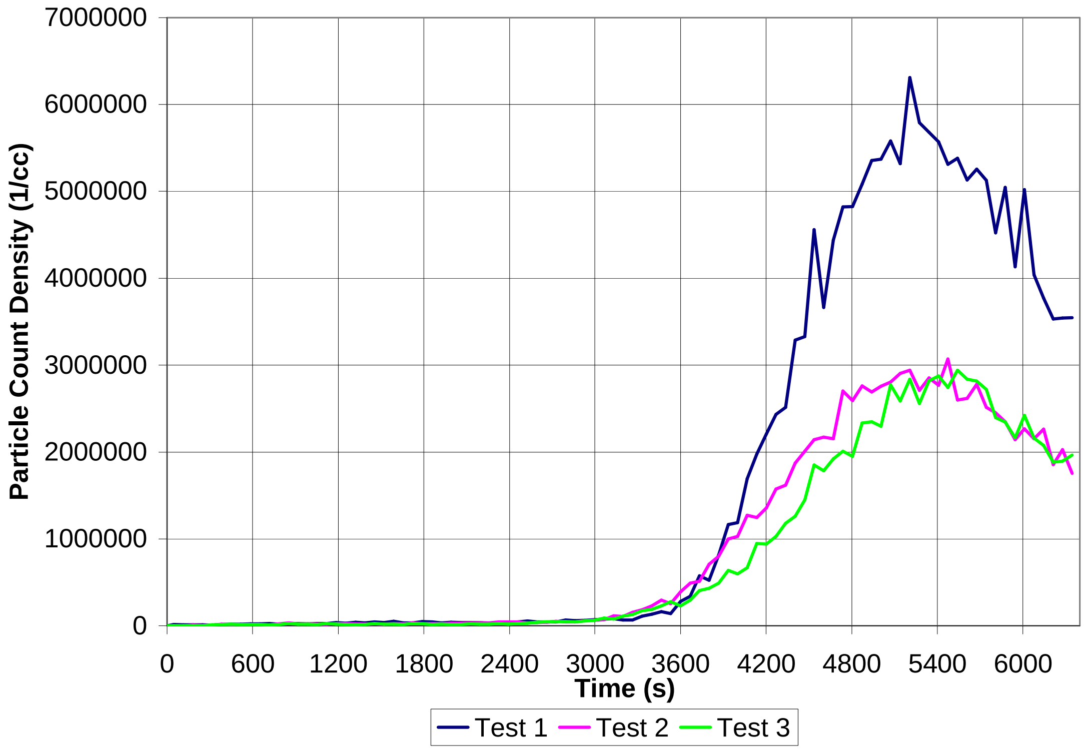

Figure B 21 - Ponderosa pine particle count density.

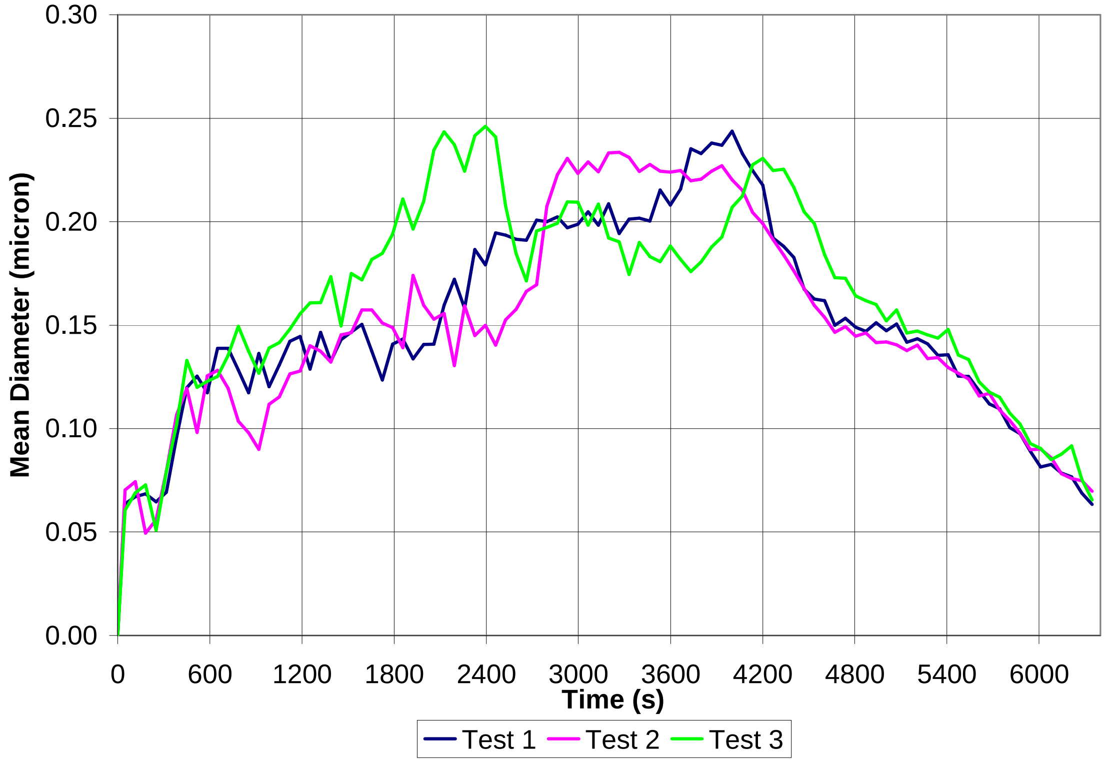

Figure B 22 - Ponderosa pine mean particle diameter.

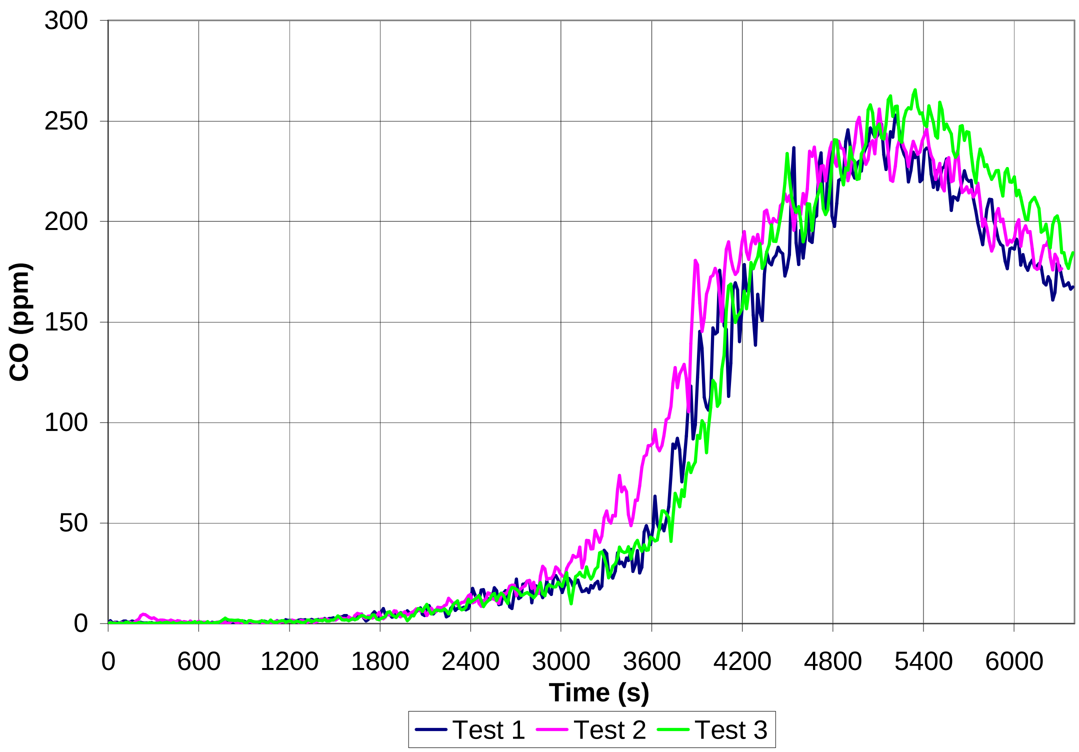

Figure B 23 - Ponderosa pine carbon monoxide output.

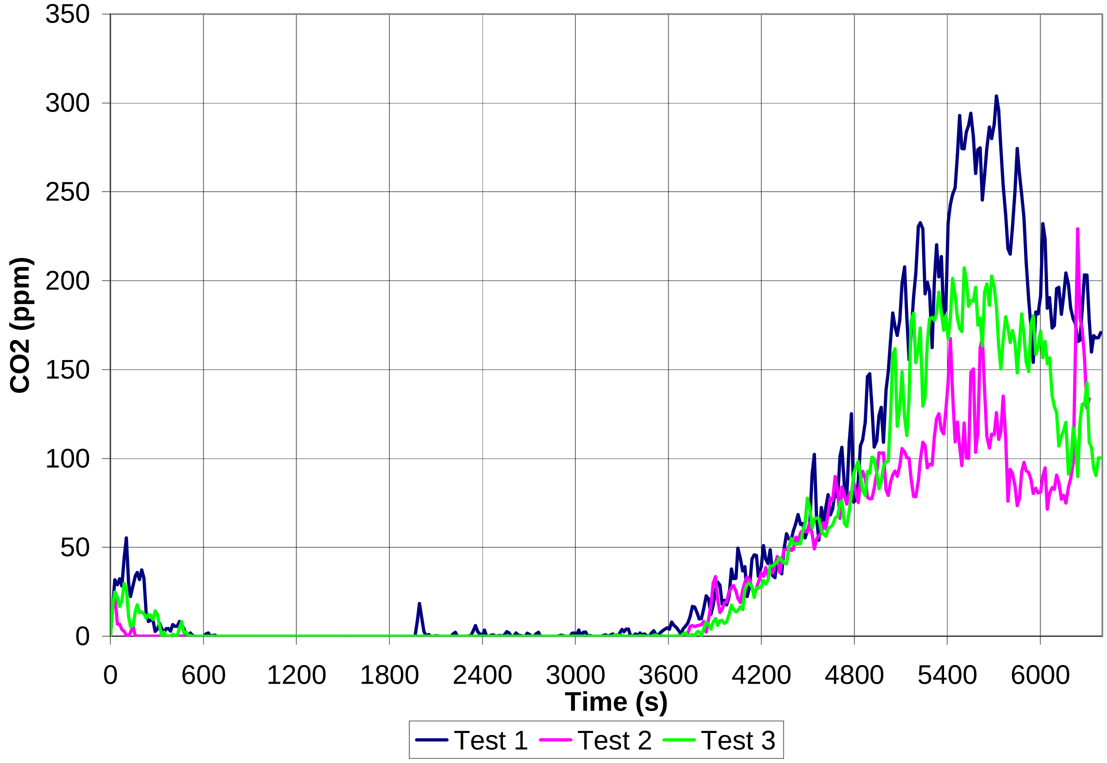

Figure B 24 - Ponderosa pine carbon dioxide output.

B.7 Cotton Linen Fabric

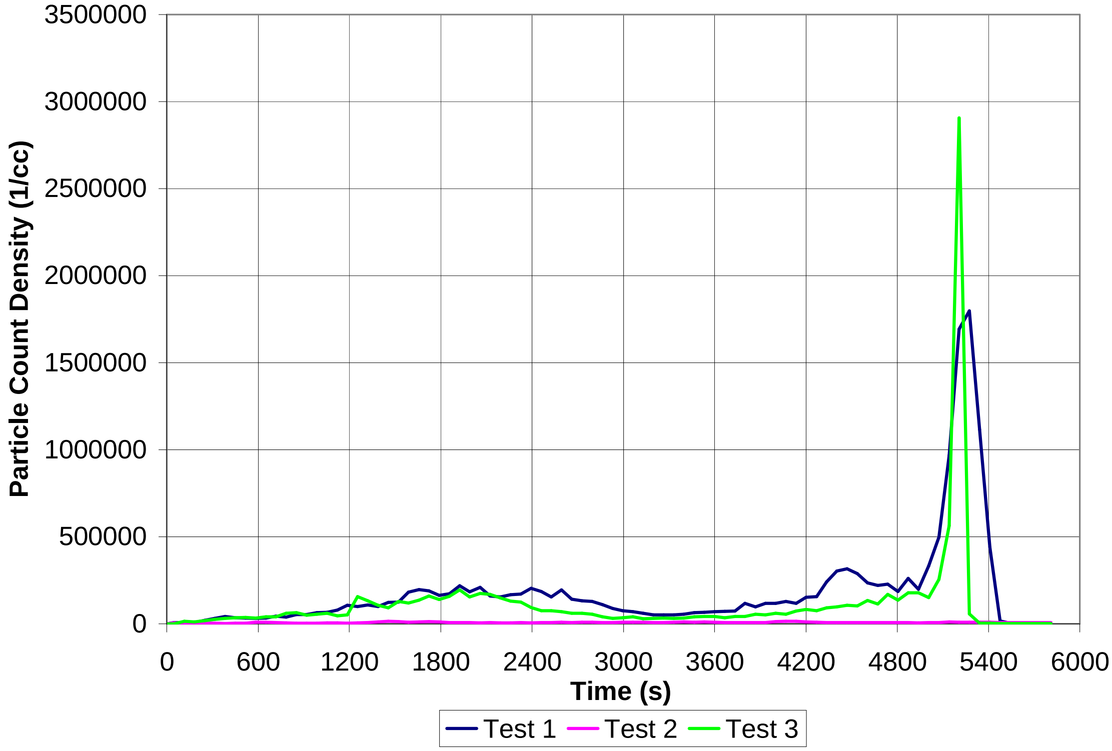

Figure B 25 - Cotton linen fabric particle count density.

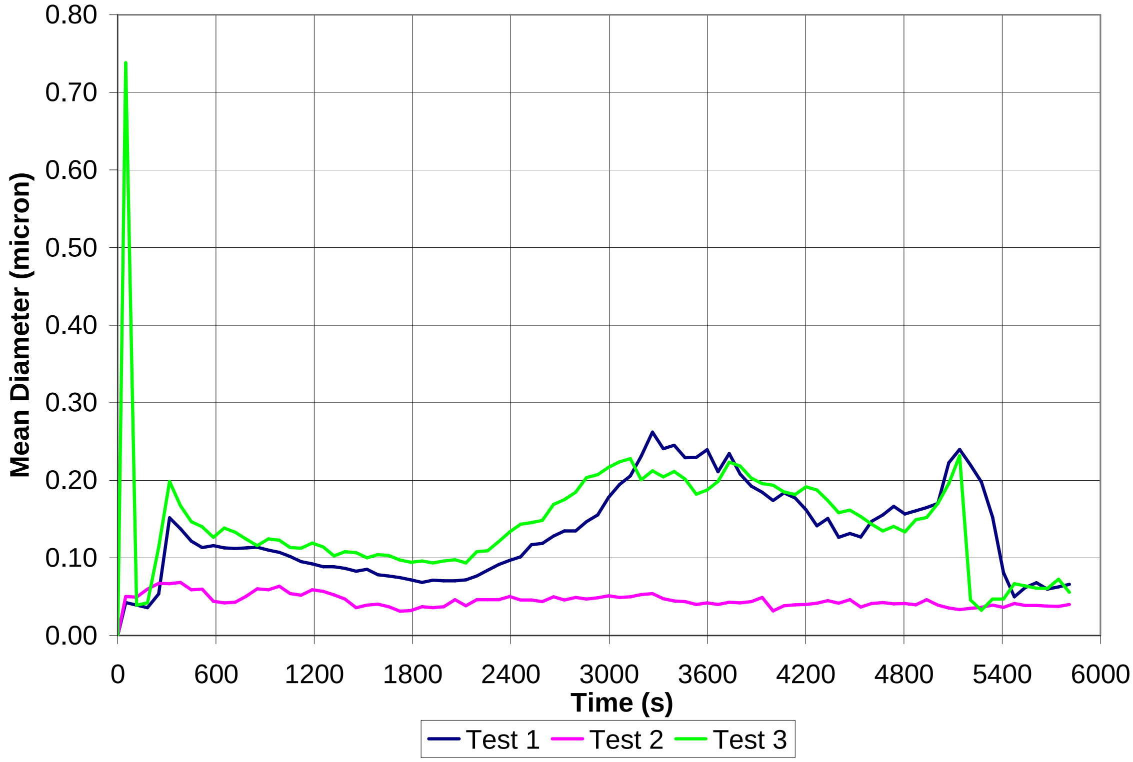

Figure B 26 - Cotton linen fabric mean particle diameter.

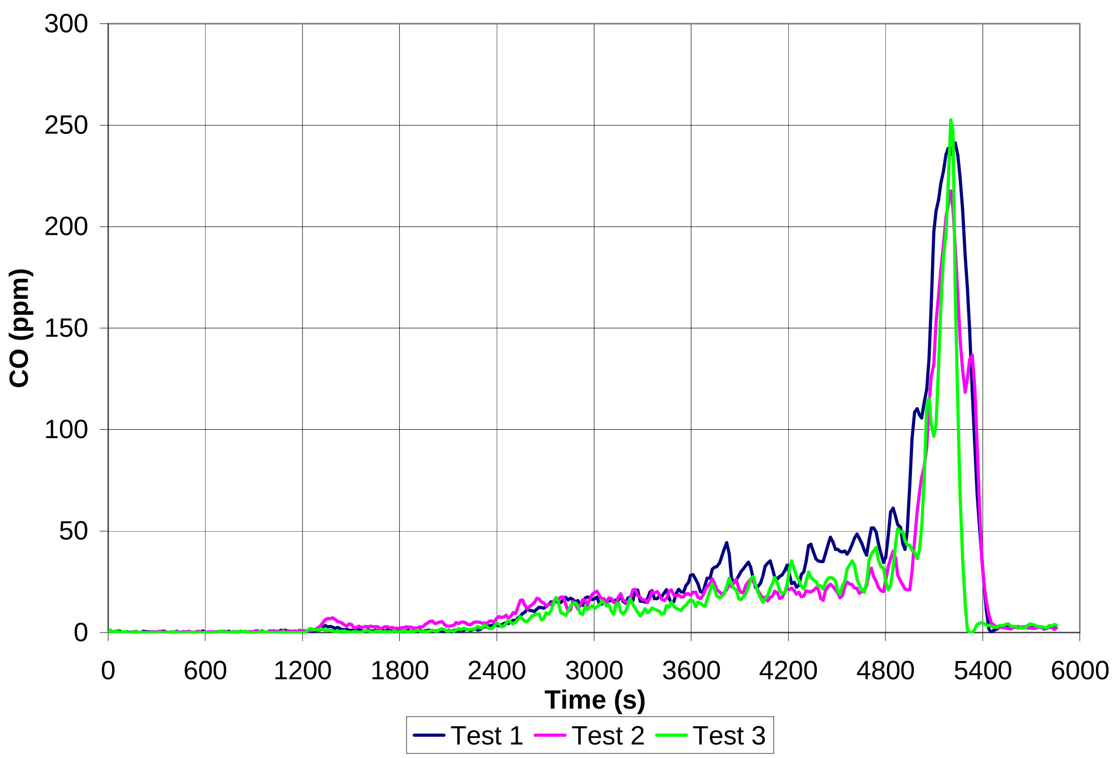

Figure B 27 - Cotton linen fabric carbon monoxide output.

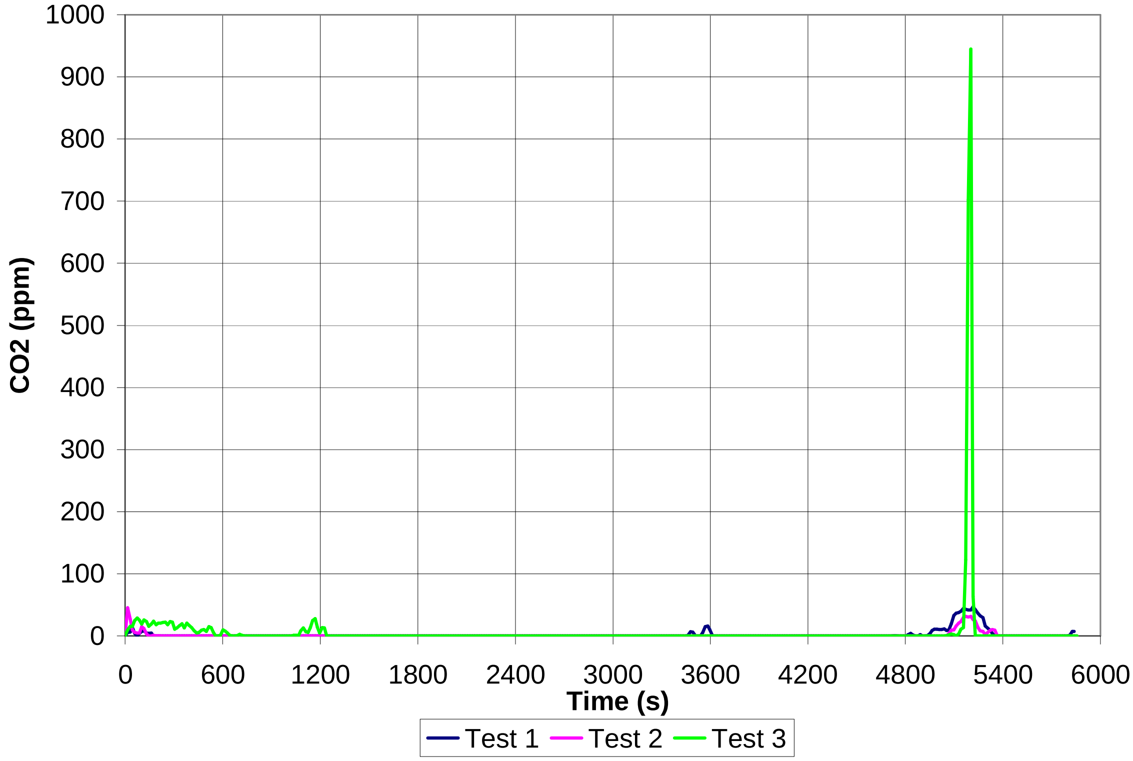

Figure B 28 - Cotton linen fabric carbon dioxide output.

B.8 PVC Insulated Wire

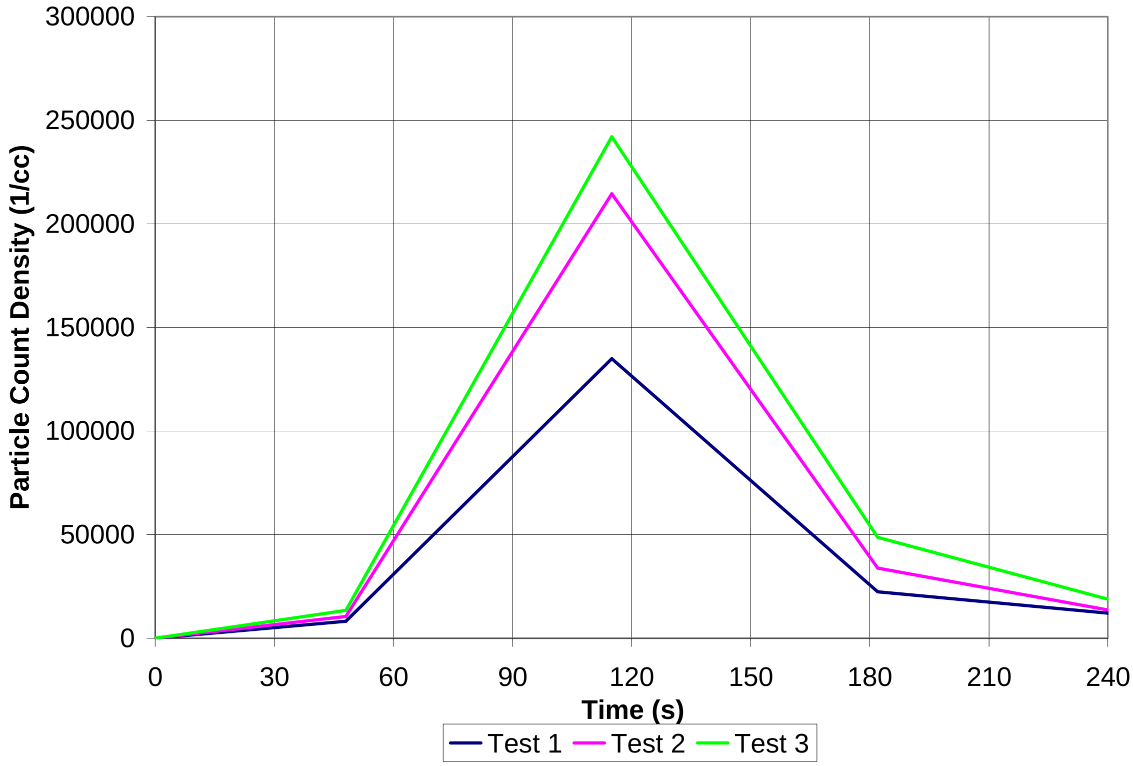

Figure B 29 - PVC insulated wire particle count density.

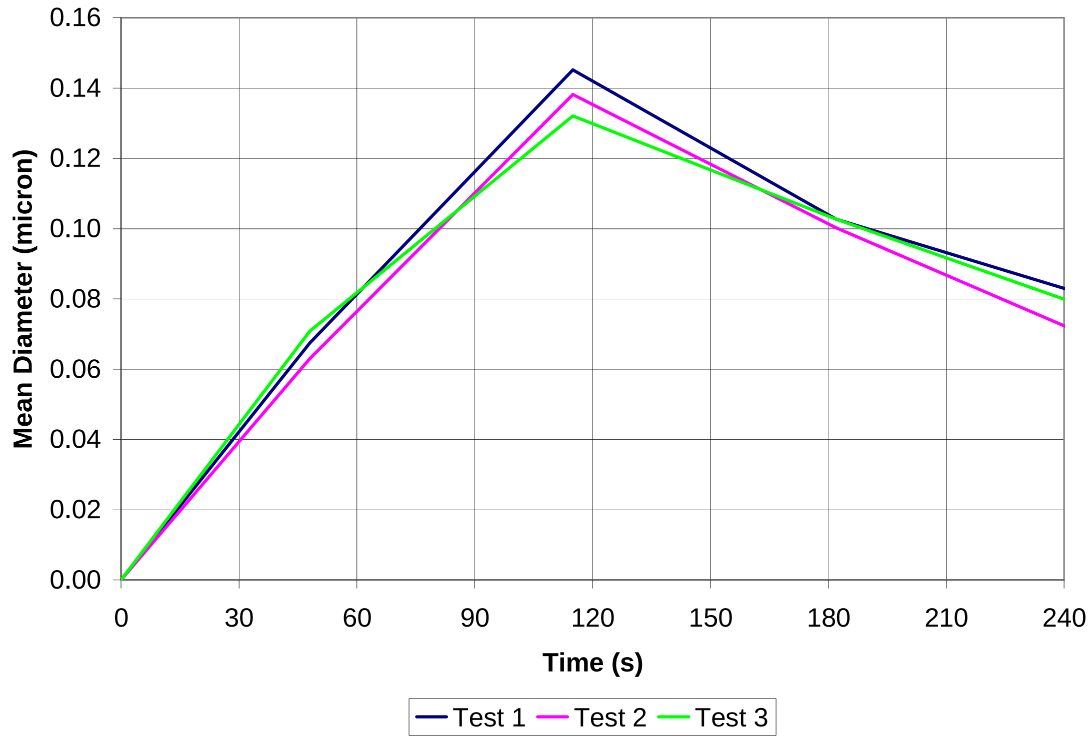

Figure B 30 - PVC insulated wire mean particle diameter.

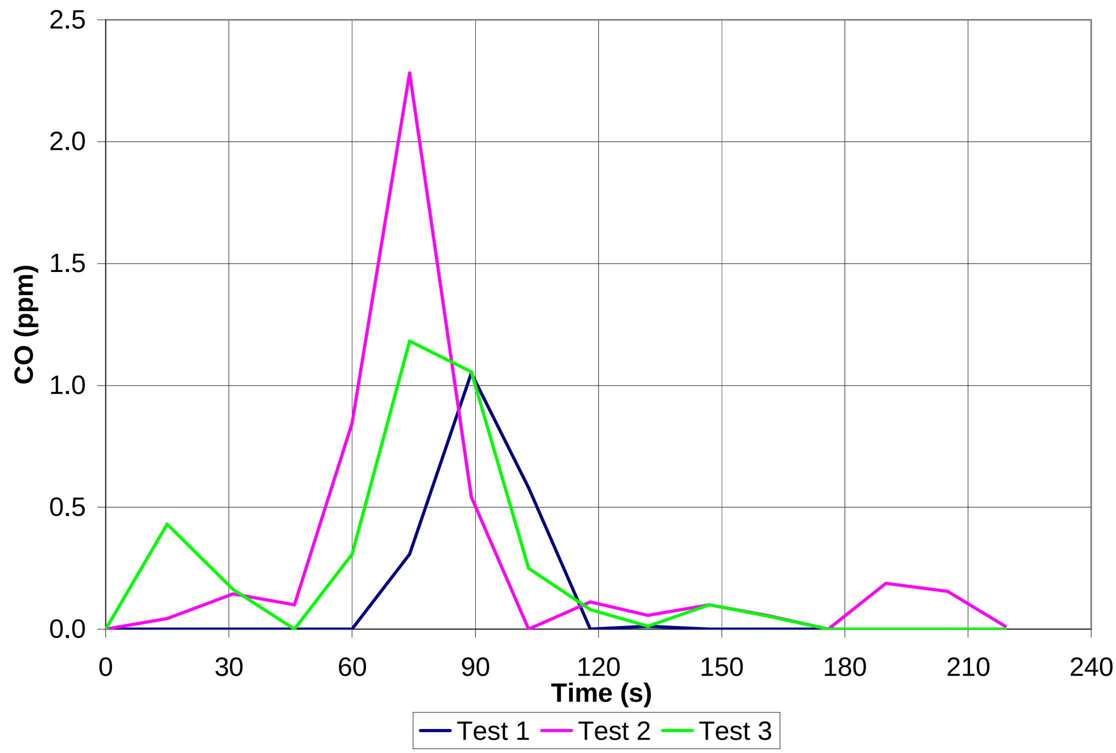

Figure B 31 - PVC insulated wire carbon monoxide output.

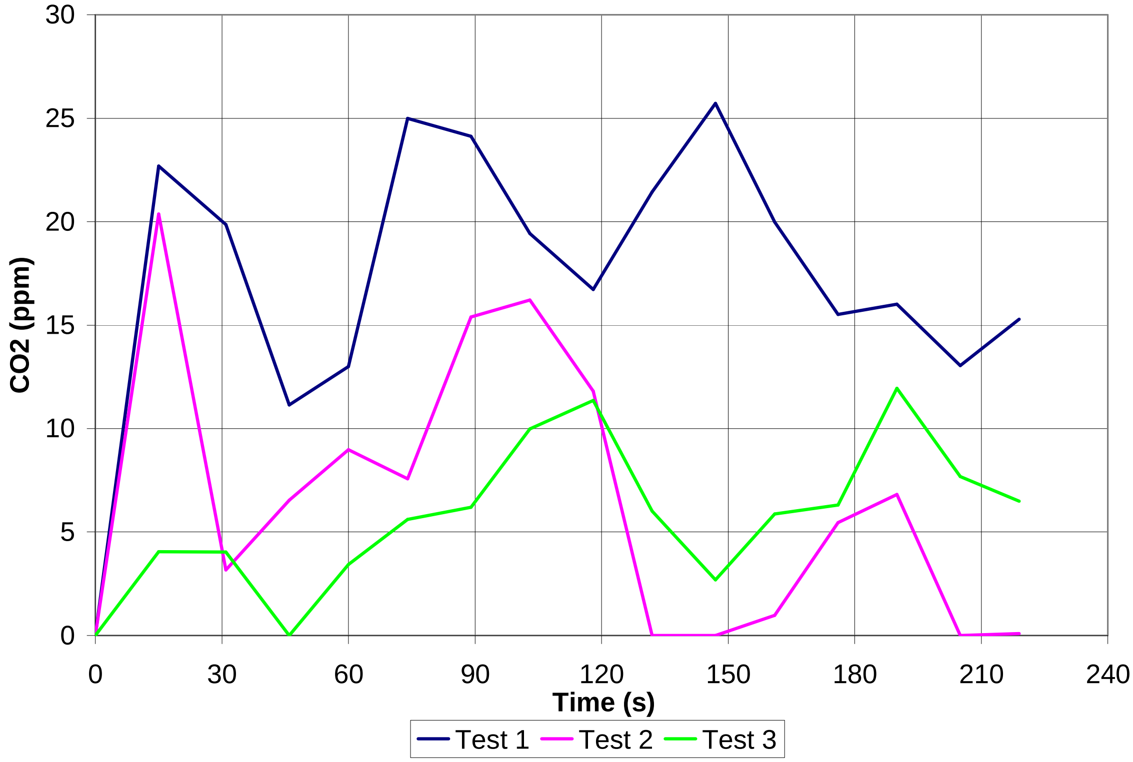

Figure B 32 - PVC insulated wire carbon dioxide output.

Appendix C: FDS Input Files

Appendix C contains the FDS input files used for the models in phase two of this project.

C1: Shredded Office Paper. The Species ID method is used for this simulation.

```
&HEAD CHID='PAPER', TITLE='UL PRELIMINARY IMO SMOKE
  CHARACTERIZATION TEST, SHREDDED OFFICE PAPER' /

&MESH IJK=48, 48, 60, XB=0.000, 1.200, 0.000, 1.200,
  0.000, 1.500 / 2.5 cm Hood grid 48 48 60

&MESH IJK=96, 6, 6, XB=1.200, 3.600, 0.525, 0.675, 1.250,
  1.400 / 2.5 cm Duct grid 96 6 6

&VENT XB=0.0, 0.0, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=1.2, 1.2, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 0.0, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 1.2, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 1.2, 0.0, 0.0,SURF_ID='OPEN'  /


&TIME TWFIN=360.0 /

******MATERIAL PROPERTIES******

&MISC SURF_DEFAULT='INERT', TMPA=25.0 /

&SPEC ID='SMOKE', MW=29.,
  MASS_EXTINCTION_COEFFICIENT=8700. /

&SURF ID='SHREDDED PAPER', HRRPUA=99, RAMP_Q='PAPER',
  MASS_FLUX(1)=0.001264, RAMP_MF(1)='MF' / HRRPUA AND MF
  RAMP FOR PAPER 2

&RAMP ID='PAPER', T= 0.0, F= 0.000 /
&RAMP ID='PAPER', T= 75,  F= 0.122 /
&RAMP ID='PAPER', T= 95,  F= 0.224 /
&RAMP ID='PAPER', T= 100, F= 0.347 /
```

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&RAMP ID='PAPER', T= 105, F= 0.598 /
&RAMP ID='PAPER', T= 110, F= 0.820 /
&RAMP ID='PAPER', T= 118, F= 1.000 /
&RAMP ID='PAPER', T= 120, F= 0.859 /
&RAMP ID='PAPER', T= 125, F= 0.750 /
&RAMP ID='PAPER', T= 135, F= 0.537 /
&RAMP ID='PAPER', T= 145, F= 0.462 /
&RAMP ID='PAPER', T= 155, F= 0.315 /
&RAMP ID='PAPER', T= 165, F= 0.222 /
&RAMP ID='PAPER', T= 175, F= 0.210 /
&RAMP ID='PAPER', T= 227, F= 0.162 /
&RAMP ID='PAPER', T= 320, F= 0.000 /

&RAMP ID='MF', T=   0    , F= 0.00000    /
&RAMP ID='MF', T=   25   , F= 0.01212    /
&RAMP ID='MF', T=   30   , F= 0.06860    /
&RAMP ID='MF', T=   37   , F= 0.10760    /
&RAMP ID='MF', T=   40   , F= 0.13888    /
&RAMP ID='MF', T=   44   , F= 0.08995    /
&RAMP ID='MF', T=   55   , F= 0.15952    /
&RAMP ID='MF', T=   67   , F= 0.63365    /
&RAMP ID='MF', T=   75   , F= 0.79831    /
&RAMP ID='MF', T=   83   , F= 0.89001    /
&RAMP ID='MF', T=   84   , F= 1.00000    /
&RAMP ID='MF', T=   90   , F= 0.79080    /
&RAMP ID='MF', T=   95   , F= 0.87780    /
&RAMP ID='MF', T=   100  , F= 0.59051    /
&RAMP ID='MF', T=   104  , F= 0.30386    /
&RAMP ID='MF', T=   110  , F= 0.13090    /
&RAMP ID='MF', T=   122  , F= 0.03390    /
&RAMP ID='MF', T=   140  , F= 0.03117    /
&RAMP ID='MF', T=   155  , F= 0.11827    /
&RAMP ID='MF', T=   168  , F= 0.12840    /
&RAMP ID='MF', T=   175  , F= 0.11712    /
&RAMP ID='MF', T=   205  , F= 0.05942    /
&RAMP ID='MF', T=   240  , F= 0.04157    /
&RAMP ID='MF', T=   300  , F= 0.00000    /


******FUEL TABLE******

&OBST XB= 0.45, 0.750, 0.450, 0.750, 0.250, 0.700,
  SURF_IDS='SHREDDED PAPER', 'INERT', 'INERT',
  COLOR='SILVER'/  FUEL
&OBST XB= 0.45, 0.750, 0.450, 0.750, 0.225, 0.250,
  SURF_IDS='INERT', 'INERT', 'INERT', COLOR='BROWN'/
  FUEL PLATFORM
```

```
******OBSTRUCTIONS******

&VENT XB= 1.2, 1.2, 0.525, 0.675, 1.25, 1.4,
   SURF_ID='OPEN' / Connection between hood and duct

&SURF ID='EXHAUST FLOW', VOLUME_FLUX= .10615 /
&VENT XB= 3.60, 3.60, 0.525, 0.675, 1.25, 1.4,
   SURF_ID='EXHAUST FLOW', COLOR='BLUE' / EXHAUST FLOW

******INSTRUMENTS******

  ///IMO INSTRUMENTATION///

&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='oxygen mass fraction', ID='O2 MASS FRACTION'
   /  OXYGEN MASS FRACTION
&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='THERMOCOUPLE', ID='DUCT ENTRY TEMP' / TC
   DUCT ENTRY

  ///HOOD THERMOCOUPLES///

&DEVC XYZ= 0.600, 0.600, 1.450, QUANTITY='THERMOCOUPLE',
   ID='PLUME 2.5'  / TC 2.50 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.375, QUANTITY='THERMOCOUPLE',
   ID='PLUME 10.0' / TC 10.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.175, QUANTITY='THERMOCOUPLE',
   ID='PLUME 30.0' / TC 30.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 0.775, QUANTITY='THERMOCOUPLE',
   ID='PLUME 70.0' / TC 70.0 cm FROM TOP OF HOOD

  ///OBSCURATION///

&PROP ID='SMOKE EYE', QUANTITY='path obscuration',
   SPEC_ID='SMOKE'/

&DEVC XB= 3.200, 3.200, 0.525, 0.675, 1.325, 1.325,
   PROP_ID='SMOKE EYE', ID='SMOKE EYE' / SMOKE EYE
&DEVC XYZ= 3.200, 0.600, 1.400, QUANTITY='THERMOCOUPLE',
   ID='SMOKE EYE TEMP' / TC AT SMOKE EYE

  ///VELOCITY///
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&DEVC XB= 3.200, 3.200, 0.600, 0.600, 1.325, 1.325,
   QUANTITY='VELOCITY', ID='DUCT VELOCITY' / DUCT
   VELOCITY AT SMOKE EYE

******MEASUREMENTS******

&SLCF PBX= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBY= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBZ= 1.40, QUANTITY='TEMPERATURE' /

&SLCF PBX= 0.60, QUANTITY='VELOCITY' /
&SLCF PBY= 0.60, QUANTITY='VELOCITY' /
&SLCF PBX= 0.00, QUANTITY='VELOCITY' /
&SLCF PBZ= 1.40, QUANTITY='VELOCITY' /
&SLCF PBX= 3.60, QUANTITY='VELOCITY' /

&SLCF PBZ= 1.40, QUANTITY='SMOKE' /
&SLCF PBY= 0.60, QUANTITY='SMOKE' /


&DUMP DT_PL3D=30., DT_HRR=2.0, DT_DEVC=2.0, DT_SLCF=2.0,
   SMOKE3D_QUANTITY='SMOKE' /

&TAIL /
```

C2: PU Foam with Micro-fiber Fabric (flaming). The mixture fraction model is used for this simulation.

```
&HEAD CHID='FLAMING PU FOAM', TITLE='UL PRELIMINARY IMO
   SMOKE CHARACTERIZATION TEST, FLAMING PU FOAM, MIXTURE
   FRACTION' /

&MESH IJK=48, 48, 60, XB=0.000, 1.200, 0.000, 1.200,
   0.000, 1.500 / 2.5 cm Hood grid 48 48 60

&MESH IJK=96, 6, 6, XB=1.200, 3.600, 0.525, 0.675, 1.250,
   1.400 / 2.5 cm Duct grid 96 6 6

&VENT XB=0.0, 0.0, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=1.2, 1.2, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 0.0, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 1.2, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 1.2, 0.0, 0.0,SURF_ID='OPEN'  /

&TIME TWFIN=640.0 /

******MATERIAL PROPERTIES******

&MISC SURF_DEFAULT='INERT', TMPA=25.0 /

&REAC ID = 'FLAMING PU FOAM'
   SOOT_YIELD = 0.0952
   HEAT_OF_COMBUSTION = 20290.
   IDEAL = .TRUE. /


&SURF ID='FLAMING PU FOAM', HRRPUA=313.3333 ,
   RAMP_Q='FLAMING PU FOAM' / RAMP PRODUCES MAX OF 9.40
   kW

&RAMP ID='FLAMING PU FOAM'    ,T=  0    ,F=  0.000     /
&RAMP ID='FLAMING PU FOAM'    ,T=  60   ,F=  0.108     /
&RAMP ID='FLAMING PU FOAM'    ,T=  80   ,F=  0.189     /
&RAMP ID='FLAMING PU FOAM'    ,T=  100  ,F=  0.321     /
&RAMP ID='FLAMING PU FOAM'    ,T=  120  ,F=  0.388     /
&RAMP ID='FLAMING PU FOAM'    ,T=  140  ,F=  0.526     /
&RAMP ID='FLAMING PU FOAM'    ,T=  160  ,F=  0.657     /
&RAMP ID='FLAMING PU FOAM'    ,T=  180  ,F=  0.724     /
&RAMP ID='FLAMING PU FOAM'    ,T=  190  ,F=  0.800     /
```

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&RAMP ID='FLAMING PU FOAM'    ,T=  200  ,F=  0.868     /
&RAMP ID='FLAMING PU FOAM'    ,T=  210  ,F=  0.779     /
&RAMP ID='FLAMING PU FOAM'    ,T=  220  ,F=  0.834     /
&RAMP ID='FLAMING PU FOAM'    ,T=  230  ,F=  0.789     /
&RAMP ID='FLAMING PU FOAM'    ,T=  240  ,F=  0.721     /
&RAMP ID='FLAMING PU FOAM'    ,T=  250  ,F=  0.888     /
&RAMP ID='FLAMING PU FOAM'    ,T=  260  ,F=  1.000     /
&RAMP ID='FLAMING PU FOAM'    ,T=  270  ,F=  0.987     /
&RAMP ID='FLAMING PU FOAM'    ,T=  280  ,F=  0.995     /
&RAMP ID='FLAMING PU FOAM'    ,T=  290  ,F=  0.958     /
&RAMP ID='FLAMING PU FOAM'    ,T=  300  ,F=  0.944     /
&RAMP ID='FLAMING PU FOAM'    ,T=  320  ,F=  0.811     /
&RAMP ID='FLAMING PU FOAM'    ,T=  340  ,F=  0.535     /
&RAMP ID='FLAMING PU FOAM'    ,T=  360  ,F=  0.419     /
&RAMP ID='FLAMING PU FOAM'    ,T=  380  ,F=  0.306     /
&RAMP ID='FLAMING PU FOAM'    ,T=  400  ,F=  0.260     /
&RAMP ID='FLAMING PU FOAM'    ,T=  420  ,F=  0.213     /
&RAMP ID='FLAMING PU FOAM'    ,T=  600  ,F=  0.000     /


******FUEL TABLE******

&OBST XB= 0.500, 0.700, 0.500, 0.650, 0.325, 0.425,
   SURF_IDS='FLAMING PU FOAM', 'INERT', 'INERT',
   COLOR='YELLOW'/
&OBST XB= 0.300, 0.900, 0.300, 0.900, 0.225, 0.325,
   SURF_IDS='INERT', 'INERT', 'INERT', COLOR='SILVER'/
   FUEL PLATFORM


******OBSTRUCTIONS******

&VENT XB= 1.2, 1.2, 0.525, 0.675, 1.25, 1.4,
   SURF_ID='OPEN' / Connection between hood and duct

&SURF ID='EXHAUST FLOW', VOLUME_FLUX= .10615 /
&VENT XB= 3.60, 3.60, 0.525, 0.675, 1.25, 1.4,
   SURF_ID='EXHAUST FLOW', COLOR='BLUE' / EXHAUST FLOW

******INSTRUMENTS******

  ///IMO INSTRUMENTATION///

&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='carbon dioxide', ID='CO2' /  CARBON DIOXIDE
   MEASUREMENT
```

```
&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='carbon monoxide', ID='CO' /  CARBON MONOXIDE
   MEASUREMENT
&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='extinction coefficient', ID='K' /
   EXTINCTION COEFFICIENT
&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='oxygen mass fraction', ID='O2 MASS FRACTION'
   /  OXYGEN MASS FRACTION
&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='DENSITY', ID='DENSITY' /  DENSITY IN DUCT
&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='soot density', ID='SOOT DENSITY' /  SOOT
   DENSITY IN DUCT
&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='THERMOCOUPLE', ID='DUCT ENTRY TEMP' / TC
   DUCT ENTRY

  ///THERMOCOUPLES///

&DEVC XYZ= 0.600, 0.600, 1.450, QUANTITY='THERMOCOUPLE',
   ID='PLUME 2.5'  / TC 2.50 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.375, QUANTITY='THERMOCOUPLE',
   ID='PLUME 10.0' / TC 10.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.175, QUANTITY='THERMOCOUPLE',
   ID='PLUME 30.0' / TC 30.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 0.775, QUANTITY='THERMOCOUPLE',
   ID='PLUME 70.0' / TC 70.0 cm FROM TOP OF HOOD

  ///OBSCURATION///

&DEVC XB= 3.200, 3.200, 0.500, 0.675, 1.400, 1.400,
   QUANTITY='path obscuration', ID='SMOKE EYE',
   SETPOINT=0.33 / SMOKE EYE
&DEVC XYZ= 3.200, 0.600, 1.400, QUANTITY='THERMOCOUPLE',
   ID='SMOKE EYE TEMP' / TC AT SMOKE EYE

  ///VELOCITY///

&DEVC XB= 3.200, 3.200, 0.500, 0.675, 1.400, 1.400,
   QUANTITY='VELOCITY', ID='DUCT VELOCITY' / DUCT
   VELOCITY AT SMOKE EYE

******MEASUREMENTS******

&SLCF PBX= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBY= 0.60, QUANTITY='TEMPERATURE' /
```

```
&SLCF PBZ= 1.40, QUANTITY='TEMPERATURE' /

&SLCF PBX= 0.60, QUANTITY='VELOCITY' /
&SLCF PBY= 0.60, QUANTITY='VELOCITY' /
&SLCF PBX= 0.00, QUANTITY='VELOCITY' /
&SLCF PBZ= 1.40, QUANTITY='VELOCITY' /
&SLCF PBX= 3.60, QUANTITY='VELOCITY' /

&SLCF PBZ= 1.40, QUANTITY='soot density' /

&DUMP DT_PL3D=30., DT_HRR=2.0, DT_DEVC=2.0 /

&TAIL /
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C3: PU Foam with Micro-fiber Fabric (Flaming). The Species ID method is used for this simulation.

```
&HEAD CHID='FLAMING PU FOAM', TITLE='UL PRELIMINARY IMO
SMOKE CHARACTERIZATION TEST, FLAMING PU FOAM' /

&MESH IJK=48, 48, 60, XB=0.000, 1.200, 0.000, 1.200,
0.000, 1.500 / 2.5 cm Hood grid 48 48 60

&MESH IJK=96, 6, 6, XB=1.200, 3.600, 0.525, 0.675, 1.250,
1.400 / 2.5 cm Duct grid 96 6 6

&VENT XB=0.0, 0.0, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=1.2, 1.2, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 0.0, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 1.2, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 1.2, 0.0, 0.0,SURF_ID='OPEN'  /


&TIME TWFIN=640.0 /

******MATERIAL PROPERTIES******

&MISC SURF_DEFAULT='INERT', TMPA=25.0 /


&SPEC ID='SMOKE', MW=29.,
MASS_EXTINCTION_COEFFICIENT=8700. /


&SURF ID='FLAMING PU FOAM', HRRPUA=313.3333 ,
RAMP_Q='FLAMING PU FOAM', MASS_FLUX(1)=.001854,
RAMP_MF(1)='MF' / RAMP PRODUCES MAX OF 9.40 kW

&RAMP ID='FLAMING PU FOAM'    ,T=  0    ,F=  0.000     /
&RAMP ID='FLAMING PU FOAM'    ,T=  60   ,F=  0.108     /
&RAMP ID='FLAMING PU FOAM'    ,T=  80   ,F=  0.189     /
&RAMP ID='FLAMING PU FOAM'    ,T=  100  ,F=  0.321     /
&RAMP ID='FLAMING PU FOAM'    ,T=  120  ,F=  0.388     /
&RAMP ID='FLAMING PU FOAM'    ,T=  140  ,F=  0.526     /
&RAMP ID='FLAMING PU FOAM'    ,T=  160  ,F=  0.657     /
&RAMP ID='FLAMING PU FOAM'    ,T=  180  ,F=  0.724     /
&RAMP ID='FLAMING PU FOAM'    ,T=  190  ,F=  0.800     /
&RAMP ID='FLAMING PU FOAM'    ,T=  200  ,F=  0.868     /
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&RAMP ID='FLAMING PU FOAM'    ,T=  210  ,F=  0.779     /
&RAMP ID='FLAMING PU FOAM'    ,T=  220  ,F=  0.834     /
&RAMP ID='FLAMING PU FOAM'    ,T=  230  ,F=  0.789     /
&RAMP ID='FLAMING PU FOAM'    ,T=  240  ,F=  0.721     /
&RAMP ID='FLAMING PU FOAM'    ,T=  250  ,F=  0.888     /
&RAMP ID='FLAMING PU FOAM'    ,T=  260  ,F=  1.000     /
&RAMP ID='FLAMING PU FOAM'    ,T=  270  ,F=  0.987     /
&RAMP ID='FLAMING PU FOAM'    ,T=  280  ,F=  0.995     /
&RAMP ID='FLAMING PU FOAM'    ,T=  290  ,F=  0.958     /
&RAMP ID='FLAMING PU FOAM'    ,T=  300  ,F=  0.944     /
&RAMP ID='FLAMING PU FOAM'    ,T=  320  ,F=  0.811     /
&RAMP ID='FLAMING PU FOAM'    ,T=  340  ,F=  0.535     /
&RAMP ID='FLAMING PU FOAM'    ,T=  360  ,F=  0.419     /
&RAMP ID='FLAMING PU FOAM'    ,T=  380  ,F=  0.306     /
&RAMP ID='FLAMING PU FOAM'    ,T=  400  ,F=  0.260     /
&RAMP ID='FLAMING PU FOAM'    ,T=  420  ,F=  0.213     /
&RAMP ID='FLAMING PU FOAM'    ,T=  600  ,F=  0.000     /

&RAMP ID='MF', T=   0    , F= 0.00000    /
&RAMP ID='MF', T=   25   , F= 0.00061    /
&RAMP ID='MF', T=   40   , F= 0.00684    /
&RAMP ID='MF', T=   67   , F= 0.06314    /
&RAMP ID='MF', T=   90   , F= 0.14451    /
&RAMP ID='MF', T=   125  , F= 0.31023    /
&RAMP ID='MF', T=   165  , F= 0.67713    /
&RAMP ID='MF', T=   187  , F= 0.78629    /
&RAMP ID='MF', T=   198  , F= 0.89760    /
&RAMP ID='MF', T=   206  , F= 0.73793    /
&RAMP ID='MF', T=   219  , F= 0.62576    /
&RAMP ID='MF', T=   225  , F= 0.62476    /
&RAMP ID='MF', T=   236  , F= 0.51430    /
&RAMP ID='MF', T=   280  , F= 0.80108    /
&RAMP ID='MF', T=   288  , F= 0.88423    /
&RAMP ID='MF', T=   300  , F= 0.92846    /
&RAMP ID='MF', T=   315  , F= 1.00000    /
&RAMP ID='MF', T=   329  , F= 0.76201    /
&RAMP ID='MF', T=   340  , F= 0.53417    /
&RAMP ID='MF', T=   355  , F= 0.29159    /
&RAMP ID='MF', T=   374  , F= 0.12582    /
&RAMP ID='MF', T=   389  , F= 0.05955    /
&RAMP ID='MF', T=   425  , F= 0.01008    /
&RAMP ID='MF', T=   465  , F= 0.00000    /
```

```
******FUEL TABLE******

&OBST XB= 0.500, 0.700, 0.500, 0.650, 0.325, 0.425,
SURF_IDS='FLAMING PU FOAM', 'INERT', 'INERT',
COLOR='YELLOW'/
&OBST XB= 0.300, 0.900, 0.300, 0.900, 0.225, 0.325,
SURF_IDS='INERT', 'INERT', 'INERT', COLOR='SILVER'/  FUEL
PLATFORM


******OBSTRUCTIONS******

&VENT XB= 1.2, 1.2, 0.525, 0.675, 1.25, 1.4,
SURF_ID='OPEN' / Connection between hood and duct

&SURF ID='EXHAUST FLOW', VOLUME_FLUX= .10615 /
&VENT XB= 3.60, 3.60, 0.525, 0.675, 1.25, 1.4,
SURF_ID='EXHAUST FLOW', COLOR='BLUE' / EXHAUST FLOW

******INSTRUMENTS******

  ///IMO INSTRUMENTATION///

&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
QUANTITY='oxygen mass fraction', ID='O2 MASS FRACTION' /
OXYGEN MASS FRACTION
&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
QUANTITY='THERMOCOUPLE', ID='DUCT ENTRY TEMP' / TC DUCT
ENTRY

  ///HOOD THERMOCOUPLES///

&DEVC XYZ= 0.600, 0.600, 1.450, QUANTITY='THERMOCOUPLE',
ID='PLUME 2.5'  / TC 2.50 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.375, QUANTITY='THERMOCOUPLE',
ID='PLUME 10.0' / TC 10.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.175, QUANTITY='THERMOCOUPLE',
ID='PLUME 30.0' / TC 30.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 0.775, QUANTITY='THERMOCOUPLE',
ID='PLUME 70.0' / TC 70.0 cm FROM TOP OF HOOD

  ///OBSCURATION///

&PROP ID='SMOKE EYE', QUANTITY='path obscuration',
SPEC_ID='SMOKE'/
```

```
&DEVC XB= 3.200, 3.200, 0.525, 0.675, 1.325, 1.325,
PROP_ID='SMOKE EYE', ID='SMOKE EYE' / SMOKE EYE
&DEVC XYZ= 3.200, 0.600, 1.400, QUANTITY='THERMOCOUPLE',
ID='SMOKE EYE TEMP' / TC AT SMOKE EYE

  ///VELOCITY///

&DEVC XB= 3.200, 3.200, 0.600, 0.600, 1.325, 1.325,
QUANTITY='VELOCITY', ID='DUCT VELOCITY' / DUCT VELOCITY
AT SMOKE EYE

******MEASUREMENTS******

&SLCF PBX= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBY= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBZ= 1.40, QUANTITY='TEMPERATURE' /

&SLCF PBX= 0.60, QUANTITY='VELOCITY' /
&SLCF PBY= 0.60, QUANTITY='VELOCITY' /
&SLCF PBX= 0.00, QUANTITY='VELOCITY' /
&SLCF PBZ= 1.40, QUANTITY='VELOCITY' /
&SLCF PBX= 3.60, QUANTITY='VELOCITY' /

&SLCF PBZ= 1.40, QUANTITY='SMOKE' /
&SLCF PBY= 0.60, QUANTITY='SMOKE' /


&DUMP DT_PL3D=30., DT_HRR=2.0, DT_DEVC=2.0, DT_SLCF=2.0,
SMOKE3D_QUANTITY='SMOKE' /

&TAIL /
```

C4: Printed Circuit Board. The Species ID method is used for this simulation.

```
&HEAD CHID='CIRCUIT BOARD', TITLE='UL PRELIMINARY IMO
   SMOKE CHARACTERIZATION TEST, CIRCUIT BOARD' /

&MESH IJK=48, 48, 60, XB=0.000, 1.200, 0.000, 1.200,
   0.000, 1.500 / 2.5 cm Hood grid 48 48 60

&MESH IJK=96, 6, 6, XB=1.200, 3.600, 0.525, 0.675, 1.250,
   1.400 / 2.5 cm Duct grid 96 6 6

&VENT XB=0.0, 0.0, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=1.2, 1.2, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 0.0, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 1.2, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 1.2, 0.0, 0.0,SURF_ID='OPEN'  /


&TIME TWFIN=300.0 /

******MATERIAL PROPERTIES******

&MISC SURF_DEFAULT='INERT', TMPA=25.0 /


&SPEC ID='SMOKE', MW=29.,
   MASS_EXTINCTION_COEFFICIENT=8700. /


&SURF ID='CIRCUIT BOARD', HRRPUA=1243.36, RAMP_Q='CIRCUIT
   BOARD', MASS_FLUX(1)=0.030095, RAMP_MF(1)='MF' /
   HRRPUA RAMP FOR CIRCUIT BOARD 5


&RAMP ID='CIRCUIT BOARD', T=0.0, F=0.448 /
&RAMP ID='CIRCUIT BOARD', T=10., F=0.441 /
&RAMP ID='CIRCUIT BOARD', T=15., F=0.460 /
&RAMP ID='CIRCUIT BOARD', T=20., F=0.450 /
&RAMP ID='CIRCUIT BOARD', T=25., F=0.547 /
&RAMP ID='CIRCUIT BOARD', T=30., F=0.570 /
&RAMP ID='CIRCUIT BOARD', T=35., F=0.526 /
&RAMP ID='CIRCUIT BOARD', T=40., F=0.648 /
&RAMP ID='CIRCUIT BOARD', T=45., F=0.626 /
&RAMP ID='CIRCUIT BOARD', T=50., F=0.786 /
&RAMP ID='CIRCUIT BOARD', T=55., F=0.829 /
```

```
&RAMP ID='CIRCUIT BOARD', T=60., F=0.894 /
&RAMP ID='CIRCUIT BOARD', T=64., F=1.000 /
&RAMP ID='CIRCUIT BOARD', T=65., F=0.788 /
&RAMP ID='CIRCUIT BOARD', T=70., F=0.873 /
&RAMP ID='CIRCUIT BOARD', T=75., F=0.870 /
&RAMP ID='CIRCUIT BOARD', T=80., F=0.742 /
&RAMP ID='CIRCUIT BOARD', T=85., F=0.706 /
&RAMP ID='CIRCUIT BOARD', T=90., F=0.666 /

&RAMP ID='MF', T=   0.   , F=      0.00000    /
&RAMP ID='MF', T=   10.  , F=      0.00526    /
&RAMP ID='MF', T=   15.  , F=      0.04284    /
&RAMP ID='MF', T=   20.  , F=      0.10157    /
&RAMP ID='MF', T=   35.  , F=      0.57530    /
&RAMP ID='MF', T=   45.  , F=      0.78514    /
&RAMP ID='MF', T=   52.  , F=      1.00000    /
&RAMP ID='MF', T=   65.  , F=      0.52835    /
&RAMP ID='MF', T=   75.  , F=      0.34499    /
&RAMP ID='MF', T=   85.  , F=      0.24077    /
&RAMP ID='MF', T=   95.  , F=      0.13552    /
&RAMP ID='MF', T=   105.      , F=      0.08139    /
&RAMP ID='MF', T=   115.      , F=      0.03738    /
&RAMP ID='MF', T=   125.      , F=      0.02844    /
&RAMP ID='MF', T=   135.      , F=      0.02357    /
&RAMP ID='MF', T=   145.      , F=      0.01610    /
&RAMP ID='MF', T=   155.      , F=      0.01091    /
&RAMP ID='MF', T=   165.      , F=      0.00791    /
&RAMP ID='MF', T=   175.      , F=      0.00659    /
&RAMP ID='MF', T=   185.      , F=      0.00599    /
&RAMP ID='MF', T=   195.      , F=      0.00489    /
&RAMP ID='MF', T=   200.      , F=      0.00000    /


******FUEL TABLE******

&OBST XB= 0.550, 0.625, 0.575, 0.600, 0.400, 0.475,
  SURF_IDS='CIRCUIT BOARD', 'INERT', 'INERT',
  COLOR='YELLOW'/ resolved dimensions
&OBST XB= 0.450, 0.750, 0.450, 0.750, 0.225, 0.375,
  SURF_IDS='INERT', 'INERT', 'INERT', COLOR='SILVER'/
  FUEL PLATFORM


******OBSTRUCTIONS******

&VENT XB= 1.2, 1.2, 0.525, 0.675, 1.25, 1.4,
  SURF_ID='OPEN' / Connection between hood and duct
```

```
&SURF ID='EXHAUST FLOW', VOLUME_FLUX= .11106 /
&VENT XB= 3.60, 3.60, 0.525, 0.675, 1.25, 1.4,
   SURF_ID='EXHAUST FLOW', COLOR='BLUE' / EXHAUST FLOW

******INSTRUMENTS******

  ///IMO INSTRUMENTATION///

&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='oxygen mass fraction', ID='O2 MASS FRACTION'
   /  OXYGEN MASS FRACTION
&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='THERMOCOUPLE', ID='DUCT ENTRY TEMP' / TC
   DUCT ENTRY

  ///HOOD THERMOCOUPLES///

&DEVC XYZ= 0.600, 0.600, 1.450, QUANTITY='THERMOCOUPLE',
   ID='PLUME 2.5'  / TC 2.50 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.375, QUANTITY='THERMOCOUPLE',
   ID='PLUME 10.0' / TC 10.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.175, QUANTITY='THERMOCOUPLE',
   ID='PLUME 30.0' / TC 30.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 0.775, QUANTITY='THERMOCOUPLE',
   ID='PLUME 70.0' / TC 70.0 cm FROM TOP OF HOOD

  ///OBSCURATION///

&PROP ID='SMOKE EYE', QUANTITY='path obscuration',
   SPEC_ID='SMOKE'/

&DEVC XB= 3.200, 3.200, 0.525, 0.675, 1.325, 1.325,
   PROP_ID='SMOKE EYE', ID='SMOKE EYE' / SMOKE EYE
&DEVC XYZ= 3.200, 0.600, 1.400, QUANTITY='THERMOCOUPLE',
   ID='SMOKE EYE TEMP' / TC AT SMOKE EYE

  ///VELOCITY///

&DEVC XB= 3.200, 3.200, 0.600, 0.600, 1.325, 1.325,
   QUANTITY='VELOCITY', ID='DUCT VELOCITY' / DUCT
   VELOCITY AT SMOKE EYE

******MEASUREMENTS******

&SLCF PBX= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBY= 0.60, QUANTITY='TEMPERATURE' /
```

```
&SLCF PBZ= 1.40, QUANTITY='TEMPERATURE' /

&SLCF PBX= 0.60, QUANTITY='VELOCITY' /
&SLCF PBY= 0.60, QUANTITY='VELOCITY' /
&SLCF PBX= 0.00, QUANTITY='VELOCITY' /
&SLCF PBZ= 1.40, QUANTITY='VELOCITY' /
&SLCF PBX= 3.60, QUANTITY='VELOCITY' /

&SLCF PBZ= 1.40, QUANTITY='SMOKE' /
&SLCF PBY= 0.60, QUANTITY='SMOKE' /

&DUMP DT_PL3D=30., DT_HRR=2.0, DT_DEVC=2.0, DT_SLCF=2.0,
   SMOKE3D_QUANTITY='SMOKE' /

&TAIL /
```

C5: Computer Case ABS Plastic. The Species ID method is used for this simulation.

```
&HEAD CHID='Computer Case', TITLE='UL PRELIMINARY IMO
   SMOKE CHARACTERIZATION TEST, COMPUTER CASE' /

&MESH IJK=48, 48, 60, XB=0.000, 1.200, 0.000, 1.200,
   0.000, 1.500 / 2.5 cm Hood grid 48 48 60

&MESH IJK=96, 6, 6, XB=1.200, 3.600, 0.525, 0.675, 1.250,
   1.400 / 2.5 cm Duct grid 96 6 6

&VENT XB=0.0, 0.0, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=1.2, 1.2, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 0.0, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 1.2, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 1.2, 0.0, 0.0,SURF_ID='OPEN'  /


&TIME TWFIN=340.0 /

******MATERIAL PROPERTIES******

&MISC SURF_DEFAULT='INERT', TMPA=25.0 /


&SPEC ID='SMOKE', MW=29.,
   MASS_EXTINCTION_COEFFICIENT=8700. /

&SURF ID='COMPUTER CASE', HRRPUA=640.,
   MASS_FLUX(1)=0.041487632, RAMP_MF(1)='MF' / PRODUCES
   0.400 kW

&RAMP ID='MF', T=   0    ,F=  0.0000     /
&RAMP ID='MF', T=   15   ,F=  0.0032     /
&RAMP ID='MF', T=   30   ,F=  0.0504     /
&RAMP ID='MF', T=   60   ,F=  0.3177     /
&RAMP ID='MF', T=   75   ,F=  0.6274     /
&RAMP ID='MF', T=   90   ,F=  0.7876     /
&RAMP ID='MF', T=   105  ,F=  0.9017     /
&RAMP ID='MF', T=   115  ,F=  1.0000     /
&RAMP ID='MF', T=   130  ,F=  0.9406     /
&RAMP ID='MF', T=   145  ,F=  0.5849     /
&RAMP ID='MF', T=   150  ,F=  0.4969     /
&RAMP ID='MF', T=   165  ,F=  0.2450     /
&RAMP ID='MF', T=   185  ,F=  0.0921     /
```

```
&RAMP ID='MF', T=   200  ,F=  0.0354     /
&RAMP ID='MF', T=   230  ,F=  0.0028     /
&RAMP ID='MF', T=   250  ,F=  0.0000     /



******FUEL TABLE******

&OBST XB= 0.575, 0.600, 0.575, 0.600, 0.500, 0.625,
  SURF_IDS='COMPUTER CASE', 'INERT', 'INERT',
  COLOR='YELLOW'/  FUEL
&OBST XB= 0.450, 0.750, 0.450, 0.750, 0.225, 0.300,
  SURF_IDS='INERT', 'INERT', 'INERT', COLOR='SILVER'/
  FUEL PLATFORM


******OBSTRUCTIONS******

&VENT XB= 1.2, 1.2, 0.525, 0.675, 1.25, 1.4,
  SURF_ID='OPEN' / Connection between hood and duct

&SURF ID='EXHAUST FLOW', VOLUME_FLUX= .115913 /
&VENT XB= 3.60, 3.60, 0.525, 0.675, 1.25, 1.4,
  SURF_ID='EXHAUST FLOW', COLOR='BLUE' / EXHAUST FLOW

******INSTRUMENTS******

  ///IMO INSTRUMENTATION///

&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
  QUANTITY='oxygen mass fraction', ID='O2 MASS FRACTION'
  /  OXYGEN MASS FRACTION
&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
  QUANTITY='THERMOCOUPLE', ID='DUCT ENTRY TEMP' / TC
  DUCT ENTRY

  ///HOOD THERMOCOUPLES///

&DEVC XYZ= 0.600, 0.600, 1.450, QUANTITY='THERMOCOUPLE',
  ID='PLUME 2.5'  / TC 2.50 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.375, QUANTITY='THERMOCOUPLE',
  ID='PLUME 10.0' / TC 10.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.175, QUANTITY='THERMOCOUPLE',
  ID='PLUME 30.0' / TC 30.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 0.775, QUANTITY='THERMOCOUPLE',
  ID='PLUME 70.0' / TC 70.0 cm FROM TOP OF HOOD
```

```
  ///OBSCURATION///

&PROP ID='SMOKE EYE', QUANTITY='path obscuration',
   SPEC_ID='SMOKE'/

&DEVC XB= 3.200, 3.200, 0.525, 0.675, 1.325, 1.325,
   PROP_ID='SMOKE EYE', ID='SMOKE EYE' / SMOKE EYE
&DEVC XYZ= 3.200, 0.600, 1.400, QUANTITY='THERMOCOUPLE',
   ID='SMOKE EYE TEMP' / TC AT SMOKE EYE

  ///VELOCITY///

&DEVC XB= 3.200, 3.200, 0.600, 0.600, 1.325, 1.325,
   QUANTITY='VELOCITY', ID='DUCT VELOCITY' / DUCT
   VELOCITY AT SMOKE EYE

******MEASUREMENTS******

&SLCF PBX= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBY= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBZ= 1.40, QUANTITY='TEMPERATURE' /

&SLCF PBX= 0.60, QUANTITY='VELOCITY' /
&SLCF PBY= 0.60, QUANTITY='VELOCITY' /
&SLCF PBX= 0.00, QUANTITY='VELOCITY' /
&SLCF PBZ= 1.40, QUANTITY='VELOCITY' /
&SLCF PBX= 3.60, QUANTITY='VELOCITY' /

&SLCF PBZ= 1.40, QUANTITY='SMOKE' /
&SLCF PBY= 0.60, QUANTITY='SMOKE' /


&DUMP DT_PL3D=30., DT_HRR=2.0, DT_DEVC=2.0, DT_SLCF=2.0,
   SMOKE3D_QUANTITY='SMOKE' /

&TAIL /
```

C6: PU Foam with Micro-fiber Fabric (smoldering). The Species ID method is used for this simulation.

```
&HEAD CHID='SMOLDERING PU FOAM', TITLE='UL PRELIMINARY
   IMO SMOKE CHARACTERIZATION TEST, SMOLDERING PU FOAM' /

&MESH IJK=48, 48, 60, XB=0.000, 1.200, 0.000, 1.200,
   0.000, 1.500 / 2.5 cm Hood grid 48 48 60

&MESH IJK=96, 6, 6, XB=1.200, 3.600, 0.525, 0.675, 1.250,
   1.400 / 2.5 cm Duct grid 96 6 6

&VENT XB=0.0, 0.0, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=1.2, 1.2, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 0.0, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 1.2, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 1.2, 0.0, 0.0,SURF_ID='OPEN'  /


&TIME TWFIN=5000.0 /

******MATERIAL PROPERTIES******

&MISC SURF_DEFAULT='INERT', TMPA=25.0 /


&SPEC ID='SMOKE', MW=29.,
   MASS_EXTINCTION_COEFFICIENT=8700. /

&SURF ID='FUEL PACKAGE', MASS_FLUX(1)=0.000238977,
   RAMP_MF(1)='MF', COLOR='GRAY' / SMOKE INJECTION


&RAMP ID='MF', T=   0    ,F=  0.0000     /
&RAMP ID='MF', T=   2300 ,F=  0.0101     /
&RAMP ID='MF', T=   2500 ,F=  0.0184     /
&RAMP ID='MF', T=   3000 ,F=  0.1186     /
&RAMP ID='MF', T=   3250 ,F=  0.1634     /
&RAMP ID='MF', T=   3500 ,F=  0.3581     /
&RAMP ID='MF', T=   3750 ,F=  0.7659     /
&RAMP ID='MF', T=   3850 ,F=  1.0000     /
&RAMP ID='MF', T=   4000 ,F=  0.4068     /
&RAMP ID='MF', T=   4100 ,F=  0.2632     /
&RAMP ID='MF', T=   4200 ,F=  0.1992     /
```

```
&RAMP ID='MF', T=   4300 ,F=  0.1762     /
&RAMP ID='MF', T=   4400 ,F=  0.1498     /
&RAMP ID='MF', T=   4600 ,F=  0.1248     /
&RAMP ID='MF', T=   4700 ,F=  0.1315     /


&SURF ID='SMOLDERING PU FOAM' /

&SURF ID='HOTPLATE', TMP_FRONT=524.84, RAMP_T='HOTPLATE'
   / HOTPLATE TEMPERATURE RAMP FOR SMOLDERING FIRES

&RAMP ID='HOTPLATE', T= 0.00, F= 0.000  /
&RAMP ID='HOTPLATE', T= 0.01, F= 0.046  /
&RAMP ID='HOTPLATE', T= 180., F= 0.471  /
&RAMP ID='HOTPLATE', T= 6000, F= 1.000  /75 MINUTE
   HOTPLATE RAMP MAX TEMP 524.84C


******HOT PLATE******

&OBST XB= 0.500, 0.700, 0.525, 0.675, 0.350, 0.450,
   SURF_IDS='FUEL PACKAGE', 'INERT', 'INERT',
   COLOR='YELLOW'/
&VENT XB= 0.450, 0.750, 0.450, 0.750, 0.325, 0.325,
   SURF_ID='HOTPLATE', COLOR='GRAY' / HOTPLATE HEATED
   SURFACE
&OBST XB= 0.350, 0.850, 0.350, 0.850, 0.175, 0.325,
   SURF_IDS='INERT', 'INERT', 'INERT', COLOR='SILVER'/
   HOTPLATE MODELED AS 26.5 X 23.6 IN FOR SYMMETRY


******OBSTRUCTIONS******

&VENT XB= 1.2, 1.2, 0.525, 0.675, 1.25, 1.4,
   SURF_ID='OPEN' / Connection between hood and duct

&SURF ID='EXHAUST FLOW', VOLUME_FLUX= .10800 /
&VENT XB= 3.60, 3.60, 0.525, 0.675, 1.25, 1.4,
   SURF_ID='EXHAUST FLOW', COLOR='BLUE' / EXHAUST FLOW

******INSTRUMENTS******

  ///IMO INSTRUMENTATION///

&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='oxygen mass fraction', ID='O2 MASS FRACTION'
   /  OXYGEN MASS FRACTION
```

```
&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='THERMOCOUPLE', ID='DUCT ENTRY TEMP' / TC
   DUCT ENTRY

  ///HOOD THERMOCOUPLES///

&DEVC XYZ= 0.600, 0.600, 1.450, QUANTITY='THERMOCOUPLE',
   ID='PLUME 2.5'  / TC 2.50 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.375, QUANTITY='THERMOCOUPLE',
   ID='PLUME 10.0' / TC 10.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.175, QUANTITY='THERMOCOUPLE',
   ID='PLUME 30.0' / TC 30.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 0.775, QUANTITY='THERMOCOUPLE',
   ID='PLUME 70.0' / TC 70.0 cm FROM TOP OF HOOD

  ///OBSCURATION///

&PROP ID='SMOKE EYE', QUANTITY='path obscuration',
   SPEC_ID='SMOKE'/

&DEVC XB= 3.200, 3.200, 0.525, 0.675, 1.325, 1.325,
   PROP_ID='SMOKE EYE', ID='SMOKE EYE' / SMOKE EYE
&DEVC XYZ= 3.200, 0.600, 1.400, QUANTITY='THERMOCOUPLE',
   ID='SMOKE EYE TEMP' / TC AT SMOKE EYE

  ///VELOCITY///

&DEVC XB= 3.200, 3.200, 0.600, 0.600, 1.325, 1.325,
   QUANTITY='VELOCITY', ID='DUCT VELOCITY' / DUCT
   VELOCITY AT SMOKE EYE

******MEASUREMENTS******

&SLCF PBX= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBY= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBZ= 1.40, QUANTITY='TEMPERATURE' /

&SLCF PBX= 0.60, QUANTITY='VELOCITY' /
&SLCF PBY= 0.60, QUANTITY='VELOCITY' /
&SLCF PBX= 0.00, QUANTITY='VELOCITY' /
&SLCF PBZ= 1.40, QUANTITY='VELOCITY' /
&SLCF PBX= 3.60, QUANTITY='VELOCITY' /

&SLCF PBZ= 1.40, QUANTITY='SMOKE' /
&SLCF PBY= 0.60, QUANTITY='SMOKE' /
```

```
&DUMP DT_PL3D=30., DT_HRR=2.0, DT_DEVC=2.0, DT_SLCF=2.0,
   SMOKE3D_QUANTITY='SMOKE' /

&TAIL /
```

C7: Ponderosa Pine. The Species ID method is used for this simulation.

```
&HEAD CHID='PONDEROSA PINE INT ONE', TITLE='UL
   PRELIMINARY IMO SMOKE CHARACTERIZATION TEST, PONDEROSA
   PINE' /

&MESH IJK=48, 48, 60, XB=0.000, 1.200, 0.000, 1.200,
   0.000, 1.500 / 2.5 cm Hood grid 48 48 60

&MESH IJK=96, 6, 6, XB=1.200, 3.600, 0.525, 0.675, 1.250,
   1.400 / 2.5 cm Duct grid 96 6 6

&VENT XB=0.0, 0.0, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=1.2, 1.2, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 0.0, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 1.2, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 1.2, 0.0, 0.0,SURF_ID='OPEN'  /


&TIME TWFIN=6500.0 /

******MATERIAL PROPERTIES******

&MISC SURF_DEFAULT='INERT', TMPA=25.0 /


&SPEC ID='SMOKE', MW=29.,
   MASS_EXTINCTION_COEFFICIENT=8700. /

&SURF ID='FUEL PACKAGE', MASS_FLUX(1)=0.00108459,
   RAMP_MF(1)='MF', COLOR='GRAY' / SMOKE INJECTION

&RAMP ID='MF', T=   0    ,F=  0.0000     /
&RAMP ID='MF', T=   1000 ,F=  0.0091     /
&RAMP ID='MF', T=   1500 ,F=  0.0199     /
&RAMP ID='MF', T=   2000 ,F=  0.0617     /
&RAMP ID='MF', T=   3000 ,F=  0.1289     /
&RAMP ID='MF', T=   3500 ,F=  0.1999     /
&RAMP ID='MF', T=   3600 ,F=  0.2928     /
&RAMP ID='MF', T=   3700 ,F=  0.4301     /
&RAMP ID='MF', T=   3800 ,F=  0.7143     /
&RAMP ID='MF', T=   3900 ,F=  0.9066     /
&RAMP ID='MF', T=   4006 ,F=  1.0000     /
&RAMP ID='MF', T=   4500 ,F=  0.4164     /
&RAMP ID='MF', T=   5000 ,F=  0.4832     /
```

```
&RAMP ID='MF', T=   5500 ,F=  0.2108     /
&RAMP ID='MF', T=   6000 ,F=  0.0578     /
&RAMP ID='MF', T=   6400 ,F=  0.0468     /

&SURF ID='HOTPLATE', TMP_FRONT=524.84, RAMP_T='HOTPLATE'
   / HOTPLATE TEMPERATURE RAMP FOR SMOLDERING FIRES

&RAMP ID='HOTPLATE', T= 0.00, F= 0.000  /
&RAMP ID='HOTPLATE', T= 0.01, F= 0.046  /
&RAMP ID='HOTPLATE', T= 180., F= 0.471  /
&RAMP ID='HOTPLATE', T= 6000, F= 1.000  /75 MINUTE
   HOTPLATE RAMP MAX TEMP 524.84c


******HOT PLATE******

&OBST XB= 0.525, 0.675, 0.550, 0.650, 0.325, 0.350,
   SURF_IDS='FUEL PACKAGE', 'INERT', 'INERT',
   COLOR='KHAKI'/
&VENT XB= 0.450, 0.750, 0.450, 0.750, 0.325, 0.325,
   SURF_ID='HOTPLATE', COLOR='GRAY' / HOTPLATE HEATED
   SURFACE
&OBST XB= 0.350, 0.850, 0.350, 0.850, 0.175, 0.325,
   SURF_IDS='INERT', 'INERT', 'INERT', COLOR='SILVER'/
   HOTPLATE MODELED AS 26.5 X 23.6 IN FOR SYMMETRY


******OBSTRUCTIONS******

&VENT XB= 1.2, 1.2, 0.525, 0.675, 1.25, 1.4,
   SURF_ID='OPEN' / Connection between hood and duct

&SURF ID='EXHAUST FLOW', VOLUME_FLUX= .11292 /
&VENT XB= 3.60, 3.60, 0.525, 0.675, 1.25, 1.4,
   SURF_ID='EXHAUST FLOW', COLOR='BLUE' / EXHAUST FLOW

******INSTRUMENTS******

  ///IMO INSTRUMENTATION///

&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
   QUANTITY='THERMOCOUPLE', ID='DUCT ENTRY TEMP' / TC
   DUCT ENTRY

  ///HOOD THERMOCOUPLES///
```

```
&DEVC XYZ= 0.600, 0.600, 1.450, QUANTITY='THERMOCOUPLE',
   ID='PLUME 2.5'  / TC 2.50 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.375, QUANTITY='THERMOCOUPLE',
   ID='PLUME 10.0' / TC 10.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.175, QUANTITY='THERMOCOUPLE',
   ID='PLUME 30.0' / TC 30.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 0.775, QUANTITY='THERMOCOUPLE',
   ID='PLUME 70.0' / TC 70.0 cm FROM TOP OF HOOD

  ///OBSCURATION///

&PROP ID='SMOKE EYE', QUANTITY='path obscuration',
   SPEC_ID='SMOKE'/

&DEVC XB= 3.200, 3.200, 0.525, 0.675, 1.325, 1.325,
   PROP_ID='SMOKE EYE', ID='SMOKE EYE' / SMOKE EYE
&DEVC XYZ= 3.200, 0.600, 1.400, QUANTITY='THERMOCOUPLE',
   ID='SMOKE EYE TEMP' / TC AT SMOKE EYE

  ///VELOCITY///

&DEVC XB= 3.200, 3.200, 0.600, 0.600, 1.325, 1.325,
   QUANTITY='VELOCITY', ID='DUCT VELOCITY' / DUCT
   VELOCITY AT SMOKE EYE

******MEASUREMENTS******

&SLCF PBX= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBY= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBZ= 1.40, QUANTITY='TEMPERATURE' /

&SLCF PBX= 0.60, QUANTITY='VELOCITY' /
&SLCF PBY= 0.60, QUANTITY='VELOCITY' /
&SLCF PBX= 0.00, QUANTITY='VELOCITY' /
&SLCF PBZ= 1.40, QUANTITY='VELOCITY' /
&SLCF PBX= 3.60, QUANTITY='VELOCITY' /

&SLCF PBZ= 1.40, QUANTITY='SMOKE' /
&SLCF PBY= 0.60, QUANTITY='SMOKE' /

&DUMP DT_PL3D=30., DT_HRR=2.0, DT_DEVC=2.0, DT_SLCF=2.0,
   SMOKE3D_QUANTITY='SMOKE' /

&TAIL /
```

C8: Cotton Linen Fabric. The Species ID method is used for this simulation.

```
&HEAD CHID='COTTON LINEN FABRIC INT ONE', TITLE='UL
PRELIMINARY IMO SMOKE CHARACTERIZATION TEST, COTTON LINEN
FABRIC' /

&MESH IJK=48, 48, 60, XB=0.000, 1.200, 0.000, 1.200,
0.000, 1.500 / 2.5 cm Hood grid 48 48 60

&MESH IJK=96, 6, 6, XB=1.200, 3.600, 0.525, 0.675, 1.250,
1.400 / 2.5 cm Duct grid 96 6 6

&VENT XB=0.0, 0.0, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=1.2, 1.2, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 0.0, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 1.2, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 1.2, 0.0, 0.0,SURF_ID='OPEN'  /


&TIME TWFIN=6000.0 /

******MATERIAL PROPERTIES******

&MISC SURF_DEFAULT='INERT', TMPA=25.0 /


&SPEC ID='SMOKE', MW=29.,
MASS_EXTINCTION_COEFFICIENT=8700. /

&SURF ID='FUEL PACKAGE', MASS_FLUX(1)=0.000104204,
RAMP_MF(1)='MF', TMP_FRONT=524.84, RAMP_T='HOTPLATE',
COLOR='GRAY' / SMOKE INJECTION

&RAMP ID='MF', T=   0    ,F=  0.0000     /
&RAMP ID='MF', T=   2000 ,F=  0.0096     /
&RAMP ID='MF', T=   2500 ,F=  0.1401     /
&RAMP ID='MF', T=   3000 ,F=  0.1414     /
&RAMP ID='MF', T=   3500 ,F=  0.1053     /
&RAMP ID='MF', T=   4000 ,F=  0.0867     /
&RAMP ID='MF', T=   4500 ,F=  0.0676     /
&RAMP ID='MF', T=   4900 ,F=  0.1080     /
&RAMP ID='MF', T=   5000 ,F=  0.2304     /
&RAMP ID='MF', T=   5100 ,F=  0.6401     /
&RAMP ID='MF', T=   5190 ,F=  1.0000     /
&RAMP ID='MF', T=   5300 ,F=  0.4467     /
```

```
&RAMP ID='MF', T=   5400 ,F=  0.0364     /
&RAMP ID='MF', T=   5500 ,F=  0.0127     /
&RAMP ID='MF', T=   5600 ,F=  0.0147     /
&RAMP ID='MF', T=   5700 ,F=  0.0126     /

&RAMP ID='HOTPLATE', T= 0.00, F= 0.000  /
&RAMP ID='HOTPLATE', T= 0.01, F= 0.046  /
&RAMP ID='HOTPLATE', T= 180., F= 0.471  /
&RAMP ID='HOTPLATE', T= 6000, F= 1.000  /75 MINUTE
HOTPLATE RAMP MAX TEMP 524.84C


******HOT PLATE******

&VENT XB= 0.450, 0.750, 0.450, 0.750, 0.325, 0.325,
SURF_ID='FUEL PACKAGE', COLOR='ANTIQUE WHITE' / HOTPLATE
HEATED SURFACE
&OBST XB= 0.350, 0.850, 0.350, 0.850, 0.175, 0.325,
SURF_IDS='INERT', 'INERT', 'INERT', COLOR='SILVER'/
HOTPLATE MODELED AS 26.5 X 23.6 IN FOR SYMMETRY



******OBSTRUCTIONS******

&VENT XB= 1.2, 1.2, 0.525, 0.675, 1.25, 1.4,
SURF_ID='OPEN' / Connection between hood and duct

&SURF ID='EXHAUST FLOW', VOLUME_FLUX= .095541 /
&VENT XB= 3.60, 3.60, 0.525, 0.675, 1.25, 1.4,
SURF_ID='EXHAUST FLOW', COLOR='BLUE' / EXHAUST FLOW

******INSTRUMENTS******

  ///IMO INSTRUMENTATION///

&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.325,
QUANTITY='THERMOCOUPLE', ID='DUCT ENTRY TEMP' / TC DUCT
ENTRY

  ///HOOD THERMOCOUPLES///

&DEVC XYZ= 0.600, 0.600, 1.450, QUANTITY='THERMOCOUPLE',
ID='PLUME 2.5'  / TC 2.50 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.375, QUANTITY='THERMOCOUPLE',
ID='PLUME 10.0' / TC 10.0 cm FROM TOP OF HOOD
```

```
&DEVC XYZ= 0.600, 0.600, 1.175, QUANTITY='THERMOCOUPLE',
ID='PLUME 30.0' / TC 30.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 0.775, QUANTITY='THERMOCOUPLE',
ID='PLUME 70.0' / TC 70.0 cm FROM TOP OF HOOD

  ///OBSCURATION///

&PROP ID='SMOKE EYE', QUANTITY='path obscuration',
SPEC_ID='SMOKE'/

&DEVC XB= 3.200, 3.200, 0.525, 0.675, 1.325, 1.325,
PROP_ID='SMOKE EYE', ID='SMOKE EYE' / SMOKE EYE
&DEVC XYZ= 3.200, 0.600, 1.325, QUANTITY='THERMOCOUPLE',
ID='SMOKE EYE TEMP' / TC AT SMOKE EYE

  ///VELOCITY///

&DEVC XB= 3.200, 3.200, 0.600, 0.600, 1.325, 1.325,
QUANTITY='VELOCITY', ID='DUCT VELOCITY' / DUCT VELOCITY
AT SMOKE EYE

******MEASUREMENTS******

&SLCF PBX= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBY= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBZ= 1.40, QUANTITY='TEMPERATURE' /

&SLCF PBX= 0.60, QUANTITY='VELOCITY' /
&SLCF PBY= 0.60, QUANTITY='VELOCITY' /
&SLCF PBX= 0.00, QUANTITY='VELOCITY' /
&SLCF PBZ= 1.40, QUANTITY='VELOCITY' /
&SLCF PBX= 3.60, QUANTITY='VELOCITY' /

&SLCF PBZ= 1.40, QUANTITY='SMOKE' /
&SLCF PBY= 0.60, QUANTITY='SMOKE' /

&DUMP DT_PL3D=30., DT_HRR=2.0, DT_DEVC=2.0, DT_SLCF=2.0,
SMOKE3D_QUANTITY='SMOKE' /

&TAIL /
```

C9: PVC Insulated Wire. The Species ID method is used for this simulation.

```
&HEAD CHID='PVC INSULATED WIRE', TITLE='UL PRELIMINARY
IMO SMOKE CHARACTERIZATION TEST, PVC INSULATED WIRE' /

&MESH IJK=48, 48, 60, XB=0.000, 1.200, 0.000, 1.200,
0.000, 1.500 / 2.5 cm Hood grid 48 48 60

&MESH IJK=96, 6, 6, XB=1.200, 3.600, 0.525, 0.675, 1.250,
1.400 / 2.5 cm Duct grid 96 6 6

&VENT XB=0.0, 0.0, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=1.2, 1.2, 0.0, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 0.0, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 1.2, 1.2, 0.0, 0.225,SURF_ID='OPEN'  /
&VENT XB=0.0, 1.2, 0.0, 1.2, 0.0, 0.0,SURF_ID='OPEN'  /


&TIME TWFIN=500.0 /

******MATERIAL PROPERTIES******

&MISC SURF_DEFAULT='INERT', TMPA=25.0 /


&SPEC ID='SMOKE', MW=29.,
MASS_EXTINCTION_COEFFICIENT=8700. /

&SURF ID='FUEL PACKAGE', MASS_FLUX(1)=0.000463,
RAMP_MF(1)='MF', COLOR='GRAY' / SMOKE INJECTION



&RAMP ID='MF', T=   0    ,F=  0.0000     /
&RAMP ID='MF', T=   40   ,F=  0.0000     /
&RAMP ID='MF', T=   45   ,F=  0.0212     /
&RAMP ID='MF', T=   50   ,F=  0.1045     /
&RAMP ID='MF', T=   55   ,F=  0.3323     /
&RAMP ID='MF', T=   60   ,F=  0.7189     /
&RAMP ID='MF', T=   65   ,F=  1.0000     /
&RAMP ID='MF', T=   70   ,F=  0.6464     /
&RAMP ID='MF', T=   75   ,F=  0.5651     /
&RAMP ID='MF', T=   80   ,F=  0.4570     /
&RAMP ID='MF', T=   85   ,F=  0.3890     /
&RAMP ID='MF', T=   90   ,F=  0.3412     /
```

```
&RAMP ID='MF', T=   95   ,F=  0.2127     /
&RAMP ID='MF', T=   100  ,F=  0.1307     /
&RAMP ID='MF', T=   110  ,F=  0.0807     /
&RAMP ID='MF', T=   120  ,F=  0.0478     /
&RAMP ID='MF', T=   130  ,F=  0.0279     /
&RAMP ID='MF', T=   140  ,F=  0.0191     /
&RAMP ID='MF', T=   150  ,F=  0.0114     /
&RAMP ID='MF', T=   160  ,F=  0.0000     /


******FUEL PLATFORM******

&OBST XB= 0.475, 0.725, 0.475, 0.500, 0.225, 0.250,
SURF_IDS='FUEL PACKAGE', 'INERT', 'INERT', COLOR='BLACK'/
&OBST XB= 0.475, 0.500, 0.500, 0.700, 0.225, 0.250,
SURF_IDS='FUEL PACKAGE', 'INERT', 'INERT', COLOR='BLACK'/
&OBST XB= 0.475, 0.725, 0.700, 0.725, 0.225, 0.250,
SURF_IDS='FUEL PACKAGE', 'INERT', 'INERT', COLOR='BLACK'/
&OBST XB= 0.700, 0.725, 0.500, 0.700, 0.225, 0.250,
SURF_IDS='FUEL PACKAGE', 'INERT', 'INERT', COLOR='BLACK'/
&OBST XB= 0.350, 0.850, 0.350, 0.850, 0.200, 0.225,
SURF_IDS='INERT', 'INERT', 'INERT', COLOR='SILVER'/
PLATFORM


******OBSTRUCTIONS******

&VENT XB= 1.2, 1.2, 0.525, 0.675, 1.25, 1.4,
SURF_ID='OPEN' / Connection between hood and duct

&SURF ID='EXHAUST FLOW', VOLUME_FLUX= .1133925 /
&VENT XB= 3.60, 3.60, 0.525, 0.675, 1.25, 1.4,
SURF_ID='EXHAUST FLOW', COLOR='BLUE' / EXHAUST FLOW

******INSTRUMENTS******

  ///IMO INSTRUMENTATION///

&DEVC XB= 1.400, 1.400, 0.500, 0.675, 1.325, 1.475,
QUANTITY='THERMOCOUPLE', ID='DUCT ENTRY TEMP' / TC DUCT
ENTRY

  ///HOOD THERMOCOUPLES///

&DEVC XYZ= 0.600, 0.600, 1.450, QUANTITY='THERMOCOUPLE',
ID='PLUME 2.5'  / TC 2.50 cm FROM TOP OF HOOD
```

```
&DEVC XYZ= 0.600, 0.600, 1.375, QUANTITY='THERMOCOUPLE',
ID='PLUME 10.0' / TC 10.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 1.175, QUANTITY='THERMOCOUPLE',
ID='PLUME 30.0' / TC 30.0 cm FROM TOP OF HOOD
&DEVC XYZ= 0.600, 0.600, 0.775, QUANTITY='THERMOCOUPLE',
ID='PLUME 70.0' / TC 70.0 cm FROM TOP OF HOOD

  ///OBSCURATION///

&PROP ID='SMOKE EYE', QUANTITY='path obscuration',
SPEC_ID='SMOKE'/

&DEVC XB= 3.200, 3.200, 0.525, 0.675, 1.325, 1.325,
PROP_ID='SMOKE EYE', ID='SMOKE EYE' / SMOKE EYE
&DEVC XYZ= 3.200, 0.600, 1.400, QUANTITY='THERMOCOUPLE',
ID='SMOKE EYE TEMP' / TC AT SMOKE EYE

  ///VELOCITY///

&DEVC XB= 3.200, 3.200, 0.600, 0.600, 1.325, 1.325,
QUANTITY='VELOCITY', ID='DUCT VELOCITY' / DUCT VELOCITY
AT SMOKE EYE

******MEASUREMENTS******

&SLCF PBX= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBY= 0.60, QUANTITY='TEMPERATURE' /
&SLCF PBZ= 1.40, QUANTITY='TEMPERATURE' /

&SLCF PBX= 0.60, QUANTITY='VELOCITY' /
&SLCF PBY= 0.60, QUANTITY='VELOCITY' /
&SLCF PBX= 0.00, QUANTITY='VELOCITY' /
&SLCF PBZ= 1.40, QUANTITY='VELOCITY' /
&SLCF PBX= 3.60, QUANTITY='VELOCITY' /

&SLCF PBZ= 1.40, QUANTITY='SMOKE' /
&SLCF PBY= 0.60, QUANTITY='SMOKE' /

&DUMP DT_PL3D=30., DT_HRR=2.0, DT_DEVC=2.0, DT_SLCF=2.0,
SMOKE3D_QUANTITY='SMOKE' /

&TAIL /
```

References

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