Tube Furnace Measurements of Combustion Byproducts

A Draft of the Major Qualifying Project Report
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Abstract

The goal of this project was to measure yields of combustion byproducts using a tube furnace and to test the sensitivity of these measurements to changes in test parameters and methodology. Multiple testing parameters were varied on four separate materials and the effects on the yields of combustion byproducts were observed. Toxic gas data were compiled and analyzed. From this research a set of recommendations was created and presented to the National Institute of Standards and Technology in Gaithersburg, Maryland.

Authorship Page

1. Abstract
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2. Acknowledgements
    a. Written by Kyle Geder
    b. Revised by all group members
    c. Jonathan Levin
3. Introduction
    a. Written by Jonathan Levin
    b. Revised by Kyle Geder
    c. Edited by all group members
4. Background
    a. Introduction
        i. Written by Jonathan Levin
        ii. Revised by all group members
        iii. Edited by all group members
    b. Fire Hazard Analysis
        i. Written by Kyle Geder and Adam Schwartz
        ii. Revised by Kyle Geder and Jonathan Levin
        iii. Edited by all group members
    c. Toxicity
        i. Written by Kyle Geder
        ii. Revised by Kyle Geder and Adam Schwartz
        iii. Edited by all group members
    d. Toxicity Studies
        i. Written by Jonathan Levin
        ii. Revised by Kyle Geder
        iii. Edited by Jonathan Levin
    e. Code Development
        i. Written by Kyle Geder
        ii. Revised by Kyle Geder and Jonathan Levin
        iii. Edited by Kyle Geder and Jonathan Levin
5. Methodology
    a. Introduction
        i. Written by Adam Schwartz
        ii. Revised by Jonathan Levin
        iii. Edited by Jonathan Levin and Adam Schwartz
    b. Review of Existing Test Methods
        i. Written by Jonathan Levin
        ii. Revised by Kyle Geder
        iii. Edited by Kyle Geder and Jonathan Levin

    c. Developing Order of Tests
        i. Written by Adam Schwartz
        ii. Revised by Jonathan Levin
        iii. Edited by Jonathan Levin
    d. Test Procedure
        i. Written by Kyle Geder
        ii. Revised by Jonathan Levin
        iii. Edited by Jonathan Levin and Adam Schwartz
    e. Test Parameters
        i. Written by Jonathan Levin
        ii. Revised by Kyle Geder
        iii. Edited by Jonathan Levin
    f. Compiling and Analyzing Data
        i. Written by Adam Schwartz
        ii. Revised by Jonathan Levin
        iii. Edited by Adam Schwartz
    g. FDS Simulations
        i. Written by Kyle Geder
        ii. Revised by Jonathan Levin
        iii. Edited by Kyle Geder
6. Results and Discussion
    a. Test Results
        i. Written by Adam Schwartz
        ii. Revised by Jonathan Levin
        iii. Edited by Jonathan Levin
    b. FDS Results
        i. Written by Kyle Geder
        ii. Revised by all group members
        iii. Edited by all group members
7. Conclusions
    a. Written by Kyle Geder and Adam Schwartz
    b. Revised by Jonathan Levin
    c. Edited by Jonathan Levin
8. Recommendations
    a. Written by Kyle Geder and Adam Schwartz
    b. Revised by Jonathan Levin
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Table of Contents

Table of Figures

Table of Tables

Nomenclature

ASET: Available Safe Egress Time

BFRL: Building and Fire Research Laboratory

CH_2O: formaldehyde

CH_4: methane

CO: carbon monoxide

CO_2: carbon dioxide

FDS: fire dynamics simulator

FEC: fractional effective concentration

FED: fractional effective dose

FHA: fire hazard analysis

FTIR: Fourier Transform Infrared

HCl: hydrochloric acid

HCN: hydrogen cyanide

HRR: heat release rate

ISO: International Standards Organization

kW/m^2: kilowatts per square meter

LC_{50}: Lethal Concentration 50

LD_{50}: Lethal Dose 50

L/min: liters per minute

MJ/kg: megajoules per kilogram

mm/min: millimeters per minute

NIAID: National Institute of Allergy and Infectious Disease

NBS: National Bureau of Standards

NDIR: Non-Dispersing Infrared

NIST: National Institute of Standards and Technology

O_2: oxygen

PVC: polyvinyl chloride

PMMA: polymethyl methacrylate

RSET: Required Safe Egress Time

SMV: Smokeview

SwRI: Southwest Research Institute

T: temperature

Introduction

The majority of fire-related fatalities are due to the inhalation of toxic gases (Babrauskas, et al., 1991). Studies dating back to the 1930s show that many victims of fatal fires succumb to inhalation of toxic effluent gases. However, there was not much testing done to record fire toxicity levels up until the 1970s. Since then, research groups across the world have developed numerous methods for testing toxicity of fire effluent gases. Due to the cost and time consumption of full-scale testing, many of the test methods are designed using bench-scale apparatus. The research discussed in this report validated the use of one bench-scale apparatus in particular, the tube furnace.

In order to validate the tube furnace method as an applicable test method for fire toxicity, the group tested the tube furnace's sensitivity to various test parameters. All of the research discussed in this report was conducted at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD. For a description of NIST, refer to Appendix A. The tested parameters included furnace temperature, material conformation and size, feed velocity, and primary air flow rate. The group also tested four different materials: polymethyl methacrylate (PMMA), sofa, particleboard, and electric cable. NIST had already conducted research using different testing apparatus and a full-scale situation, and used the same four materials. Therefore, toxicity data for these four materials is widely available for comparison.

The group used a Fourier Transform Infrared (FTIR) Spectrometer and a Non-Dispersing Infrared (NDIR) Spectrometer to analyze the effluent gases and collect data. After collecting the data, the group analyzed the toxicity levels and made comparisons amongst the results for CO and CO_2 that variation of different parameters yielded. In the future, NIST will be able to use the group's conclusions and recommendations to refine the test method and to compare the results with other bench-scale methods. In doing so, NIST will be able to determine which bench-scale apparatus best simulates a full-scale toxicity test.

Background

In the field of fire research, fire hazard analysis is one of the many important subjects examined. The results of a fire hazard analysis help to determine whether a building's occupants will have enough time to evacuate safely during an emergency. In determining the time needed for occupant evacuation, one must perform a toxicity assessment, because the occupants are exposed to the toxic byproducts of combustion during a fire. Consequently, this exposure is one of the many factors that contribute to slower egress times. In the past, toxicity assessment has been performed numerous times on the bench-scale level, and less frequently at full-scale. The following section of this report includes details on what a fire hazard analysis is and how it applies to toxicity and the underlying goal of this project, as well as a review of previous toxicity assessment studies.

Fire Hazard Analysis

Historically, the majority of fire safety regulations have been based on designing by disaster, i.e., changing codes and standards following major loss. However, when one wants to consider a full range of potential outcomes of a fire emergency, one must perform a fire hazard analysis (FHA). Performing a hazard analysis goes hand in hand with performing a risk assessment. According to Richard Bukowski, an engineer at NIST, "hazard analysis can be thought of as a component of risk analysis. That is, a risk analysis is a set of hazard analyses that have been weighted by their likelihood of occurrence" (1997). In other words, a fire hazard analysis of a given situation is performed when assessing overall risk of an entire building or situation.

Performing an FHA is a straightforward procedure that can be broken down into seven steps of engineering analysis. Refer to Appendix B for a detailed description of the process of performing an FHA.

One of the major goals of performing an FHA is the preservation of life in an emergency. Preserving life means that all occupants are able to escape, or egress. Egress is defined as a means of travel from any point in a building or facility to an exit or public way. When performing an FHA, egress is one of many important factors to consider. However, it is difficult to devise an exact formula to determine the required egress time during a fire, because of the many variables that can affect a fire such as fuel source, wind speed, enclosure size, etc. Likewise, human reaction is not the same for every situation and not all humans behave similarly in an egress situation. In an effort to alleviate complexity, a set of regulations have been set in ISO 13571 to help determine the available safe egress time (ASET). According to the standards, ASET must be greater than the required safe egress time (RSET) in order for safe and timely egress to take place (ISO, 2007). When determining ASET, many factors are considered. The following section explains one of these many constituents, toxicity.

Toxicity

When combustible material undergoes a combustion reaction, toxic gases are emitted into the air. Thus, the concentration of these toxic gases in the air is associated with the term toxicity. Toxicity may vary depending on the material burned and the manner in which it is burned. Depending on the chemical makeup of the combustible material, two different types of toxins can be emitted, asphyxiant gases and irritant gases.

Asphyxiant gases are toxins that cause the exposed subject to intake insufficient amounts of oxygen leading to asphyxiation. Some examples of asphyxiant gases are carbon monoxide (CO) and hydrogen cyanide (HCN). When inhaled, CO enters the upper respiratory tract and lungs and begins replacing the oxygen in the bloodstream. As an effect the brain, heart, and body of the exposed subject are starved of oxygen. High amounts of CO in the bloodstream are likely to cause disorientation, loss of consciousness and even death (National Institute of Allergy and Infections Disease [NIAID], 2007). On the other hand, HCN is lethal in much smaller doses than CO. Inhalation of HCN inhibits cellular respiration where cells extract oxygen from the blood and convert the energy in sugar molecules into useful forms of energy for cells. Exposure to HCN can lead to seizures, respiratory failure, and death (NIAID, 2007).

On the other hand, irritant gases are toxins that burn and irritate the sensory organs they are exposed to upon contact as well as the lungs when inhaled. Examples of irritant gases are halogen acids, such as hydrochloric acid (HCl). Another common irritant gas that exists as an effluent gas of fire is an aldehyde, such as formaldehyde (CH_2O). Overall, inhalation of HCl gas or formaldehyde, like other severe irritant gases, can lead to death along with the burning and irritation of the skin and sensory organs. Due to the severity of irritant gases, as well as asphyxiant gases, it has been a focus of many research laboratories to attempt to study toxicity during a fire.

Toxicity Studies

In an attempt to study toxicity levels during fires, numerous efforts have been previously made. Due to the fact that full-scale testing takes a lot of time and material and therefore high cost, a majority of the testing has been bench-scale. Four different testing apparatus have been widely used in bench-scale testing, the cup furnace, radiant heat furnace, cone calorimeter, and tube furnace. Each of these testing apparatus has been implemented multiple times by different research groups interested in evaluating toxicity, each yielding their own test method. Many of these different methods along with the applied testing apparatus are observed in a paper titled, "Evaluation of Toxic Potency Values for Smoke from Products and Materials" by Richard G. Gann and Julie L. Neviaser (2004).

One characteristic that many of the bench-scale tests mentioned by Gann and Neviaser have in common is the utilization of animal testing. Animal testing, although no longer used in many parts of the world for toxicity tests, was a prominent part of the various toxicity testing procedures for years (Cimons, 2001). Animals were normally placed in closed chambers in which the fire effluent gases accumulated. The toxicity levels of the effluent gases from the burning material were then determined by calculating the lethal concentration 50 (LC_{50}). The LC_{50}, also referred to as LD_{50} when dealing with dosage instead of concentration, is "the concentration of toxic gas or fire effluent statistically calculated form concentration-response data to produce lethality in 50% of test animals of a given species under specified conditions" (Hull, 2007). In other words, the toxic level of an effluent gas was determined when it caused death to half of the animals in the chamber.

Depending on which type of gas, asphyxiant or irritant, two other parameters are also calculated when determining toxicity. For asphyxiant gases, the fractional effective dose (FED) is calculated. The FED is "the ratio of exposure dose for an asphyxiant toxicant to that exposure dose of the asphyxiant expected to produce a specified effect on an exposed subject of average susceptibility" (Hull, 2007). If the LD_{50} is the expected dosage of the asphyxiant, then the FED is ratio of the amount of that asphyxiant in the air compared to the already measured LD_{50} of that gas. Likewise, for irritant gases, the fractional effective concentration (FEC) is "the ratio of the concentration of an irritant to that expected to produce a specified effect on an exposed subject of average susceptibility" (Hull, 2007). The FED and FEC were the benchmarks for determining toxic potency of a fire effluent gas.

Bench Scale Toxicity ApparatusAlthough all of the methods listed in Gann and Neviaser's report included some form of animal testing, not all used the same testing apparatus. Gann and Neviaser made mention of methods involving the cup furnace, radiant heat furnace, and tube furnace in their report (2004). One of the cup furnace methods, the NBS Cup Furnace method is discussed in the "NIST Technical Note 1284: The Role of Bench-Scale Test Data in Assessing Real-Scale Fire Toxicity" (Babrauskas, et al., 1991). This report also includes bench-scale tests using a radiant heat furnace and a cone calorimeter and medium and full-scale tests.

NIST Cup Furnace

The NBS Cup Furnace method used a cup furnace with a 200 L animal exposure chamber attached to its top. The animal exposure chamber contained six animal ports and multiple gas sampling ports as shown below in Figure 1 (Birky, et al., 1982).

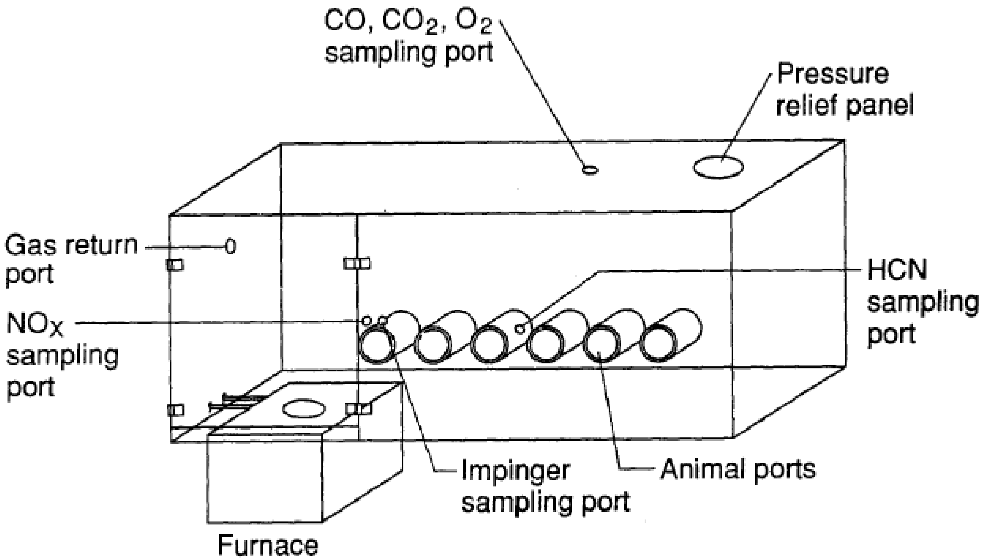


Figure 1: NBS Cup Furnace method.
(Source: Babrauskas, et al., 1991)

When running toxicity tests using the NBS Cup Furnace, the sample fuel was combusted in the furnace, and the effluent gases were released into the animal chamber. The animals were then exposed for 30 minutes to the effluent gases. During the tests, effluent gas concentrations were analyzed by NDIR spectrometers and through ion chromatography. All surviving test animals were then observed for a 14 day period, and all deaths recorded were considered to be due to the toxic gases. After the observation period, the LC_{50} values were determined (Babrauskas, et al., 1991).

NIST/SwRI Method

Another test method mentioned by Gann and Neviaser is the radiant heat method. One of these methods is also mentioned in the "NIST Technical Note 1284: The Role of Bench-Scale Test Data in Assessing Real-Scale Fire Toxicity" and is named the NIST/SwRI Method. The NIST/SwRI Method used the same animal chamber setup as the NBS Cup Furnace with the exception of a radiant heat source used instead of a cup furnace (Babrauskas, et al., 1991). See Figure 2 below for a schematic of the apparatus used in the NIST/SwRI Method.

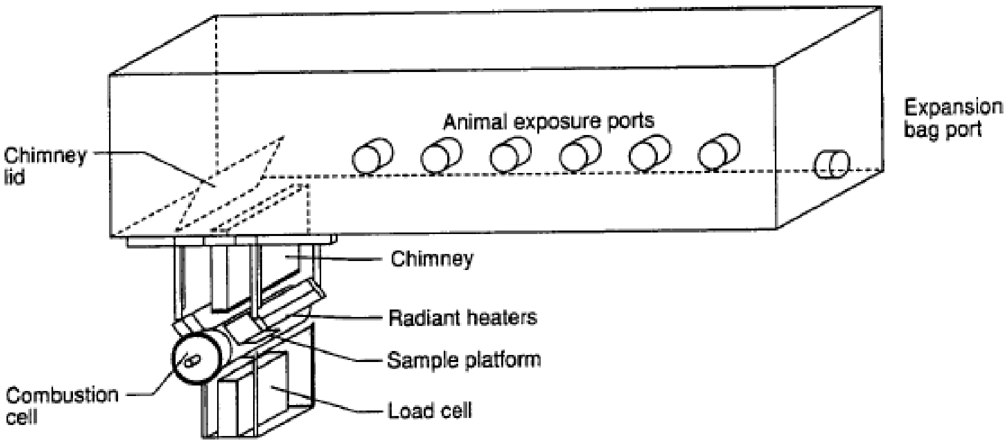
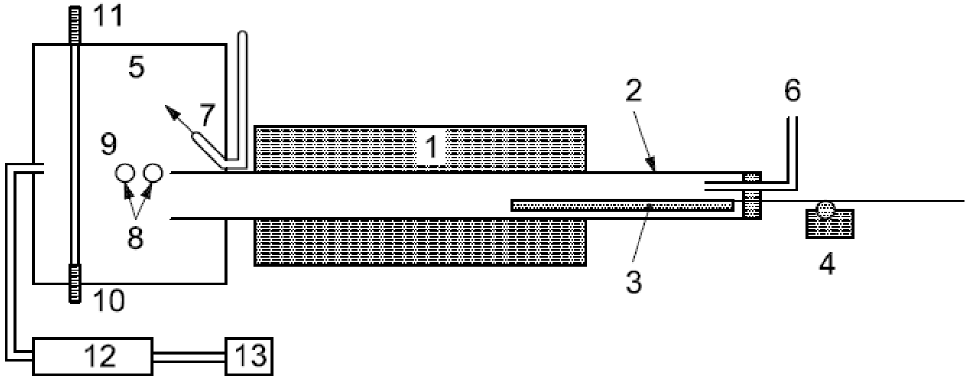


Figure 2: NIST/SwRI Method.
(Source: Babrauskas, et al., 1991)

In contrast with the NBS Cup Furnace, the NIST/SwRI Method was designed to simulate post-flashover conditions. Flashover occurs when all of the combustibles in an enclosed space ignite spontaneously. The NBS Cup Furnace was not particularly designed to simulate post-flashover conditions. On the other hand, the NIST/SwRI Method implemented a similar animal exposure procedure. However, NIST's report does not include information on whether the specimens were observed for the following 14 days as in the NBS Cup Furnace testing (Babrauskas, et al., 1991).

Tube Furnace Method

The third and final method mentioned by Gann and Neviaser is the Tube Furnace Method. Although researchers at NIST have not done much work with a tube furnace, it has been used in various other studies. One such study, also mentioned in Gann and Neviaser's work, is the University of San Francisco Method (2004). However, this method did not include a traditional tube furnace. Instead, this method applied a semi-hemispherical animal chamber connected to a tube with a boat containing the combustible sample centered in the middle of the tube (Cumming et al., 1979). A schematic of a more traditionally used tube furnace for toxicity studies is displayed in Figure 3.



Key

1	tube furnace
2	quartz furnace tube
3	test-specimen boat
4	test-specimen boat drive mechanism
5	mixing and measurement chamber
6	primary air inlet
7	secondary air inlet
8	ports for sampling lines
9	smoke-particle filter
10	tube containing light source
11	tube containing photodetector
12	gas bubblers
13	pump with flow meter

Figure 3: Tube Furnace Method.
(Source: ISO 19700, 2006)

The Tube Furnace Method used in the applied methodology for this report is very similar to the one shown above in Figure 3. As described in ISO 19700:

> The apparatus consists of a tube furnace and a quartz tube which passes through the furnace and into a mixing and measurement chamber. A drive mechanism pushes the specimen boat into the furnace at a preset, controlled rate. A constant, predetermined stream of primary air is provided at the furnace-tube entry and a preset, secondary supply into the mixing and measurement chamber. Gas samples are taken from the mixing and measurement chamber. (2006)

In this experiment, the gas samples are analyzed using FTIR spectroscopy. An FTIR is a spectrometer that “consists of two mirrors located at a right angle to each other and oriented perpendicularly, with a beamsplitter placed at the vertex of the right angle at a 45^{o} angle relative to the two mirrors” (Wolfram Research, 2008). The movable mirror and the beamsplitter produce an interference pattern as the two split beams interfere with one another when redirected back into one beam. Finally, the interference patterns produced encode the corresponding spectrum (Wolfram Research, 2008). A schematic of the mirror orientation is shown below in Figure 4.

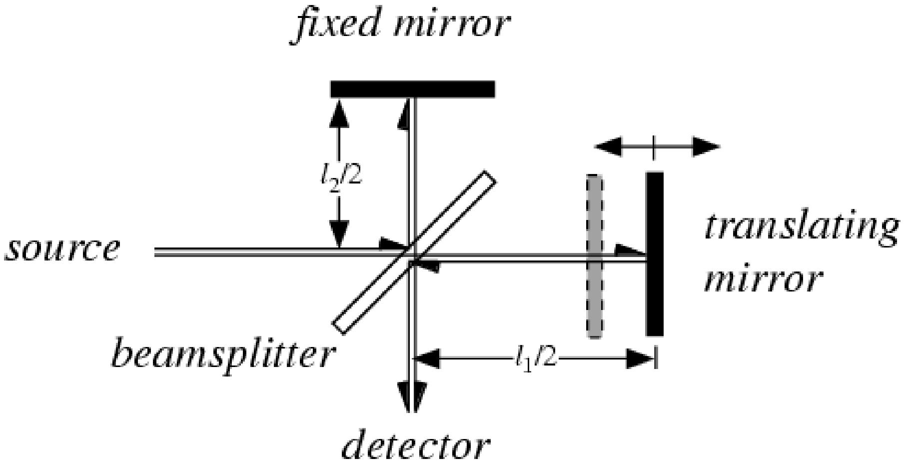


Figure 4: Mirror setup for a Fourier Transform Infrared spectrometer.
(Source: Wolfram Research, 2008)

Like most other spectrometers, the FTIR is used to analyze gas compositions. When used in conjunction with the tube furnace, the FTIR can produce a spectrum of compositions over time, typically the period of combustion. This is useful in the sense that one can observe the combustion visually and analytically in terms of gas compositions at the same time.

Cone Calorimeter

Along with the three methods described in Gann and Neviaser's report, NIST has also done toxicity testing with a cone calorimeter. Although originally developed "as an improved technique for measuring rate of heat release on bench-scale specimens" (Babrauskas, et al., 1991), the cone calorimeter can also be used in conjunction with a gas analyzer for toxicity testing. NIST used ion chromatography for the analysis of the combustion effluent gases in their research.

The cone calorimeter's operation is based on the oxygen consumption principal. This principal states "for most combustibles there is a unique constant, 13.1 MJ/kg O_2, relating the amount of heat released during a combustion reaction and the amount of oxygen consumed from the air" (Babrauskas, et al., 1991). The sample is combusted using an electric cone-shaped heater, and the effluent gases are exhausted into a hood where they are sent for further analysis if necessary. See Figure 5 below for a schematic of a cone calorimeter.

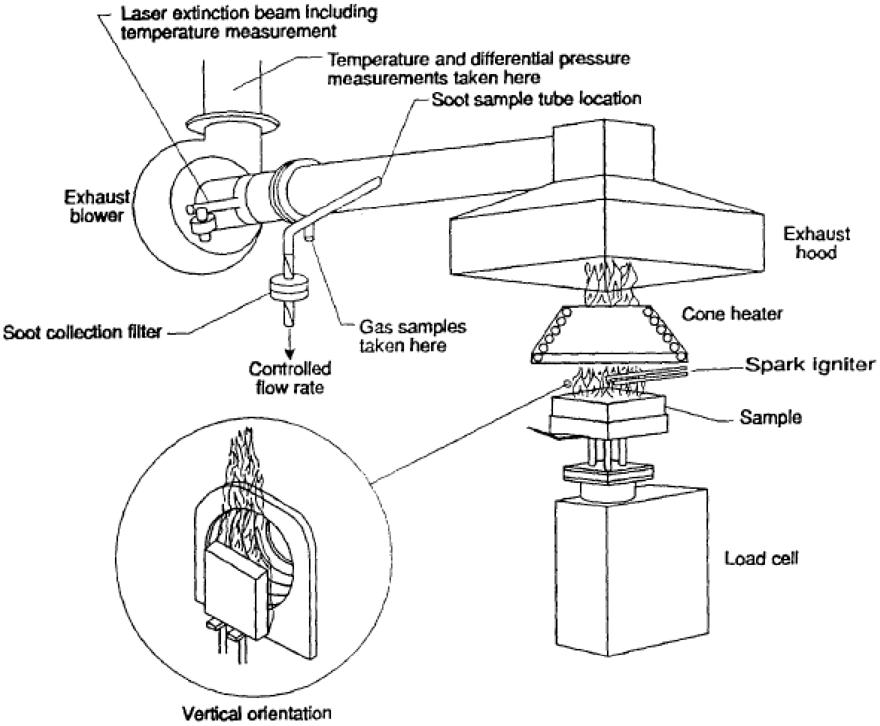


Figure 5: Cone calorimeter.
(Source: Babrauskas, et al., 1991)

Full-Scale Testing

With multiple bench-scale tests done, a full-scale test was necessary in order to obtain the most accurate fire toxicity data. The "NIST Technical Note 1453: Smoke Component Yields form Room-scale Fire Tests" presents the methods and results for a full-scale toxicity test done on NIST's facilities. A two-compartment assembly with an open doorway as the only source of ventilation between the two rooms was used for the tests (Averill, et al., 2003). See Figure 6 below for a schematic of the assembly.

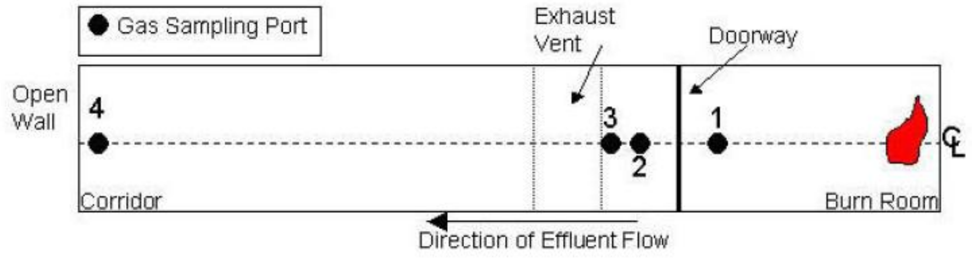


Figure 6: Two-compartment assembly used in full-scale toxicity testing at NIST.
(Source: Averill, et al., 2003)

Four different fuel sources were burnt in the burn room. These fuel sources, of which guided the fuel sources used in the methodology applied in this report, included sofas, particleboard bookcases, rigid PVC, and electric power cables. Multiple gas sampling ports allowed for observation of the absorbance of effluent gases into the walls. Effluent gases were measured using FTIR spectroscopy and gas chromatography (Averill, et al., 2003).

Since NIST has done full-scale testing, along with all the aforementioned bench-scale tests except the tube furnace, comparison can now be made as to which bench-scale apparatus yields the most accurate results. However, before doing so, NIST along with the help of the authors of this paper needed to perform their own tube-furnace tests. With all the data, NIST will be able to propose a standard for studying bench-scale toxicity using a tube furnace. For information on how standards are developed, refer to Appendix C.

Methodology

The goal of this project was to measure yields of combustion byproducts using a tube furnace and to test the sensitivity of the method. In order to test the sensitivity, multiple testing parameters were varied, and their effects on the results were observed. NIST will use our data with data to compare the tube furnace method with other bench-scale test methods, as well as to their full-scale tests. After completing their comparison, NIST will use the data to propose an ISO standard for using the tube furnace for bench-scale toxicity testing.

Project goals:

- Obtain background information on toxicity testing
- Establish order for testing
- Determine naming system for testing
- Acquire data
- Analyze data
- Assist NIST with comparison

How goals were accomplished:

- Completed literature review using resources at NIST
- Ordered tests based on time efficiency
- Designed naming system to easily link data with test name
- Ran tests on tube furnace while taking detailed notes
- Compared different parameters of tube furnace test to verify data
- Provided thorough analysis and recommendations on tube furnace method

Project Timeline

Refer to Table 1 below for the group's project timeline.

Task	Week						
	1	2	3	4	5	6	7
Background Research	■	■					
Data Collection		■	■	■	■		
Data Analysis		■	■	■	■		
FDS Simulations		■	■	■	■		
Complete Final Report		■	■	■	■	■	■
Final Presentation							■

Table 1: Project Timeline.

Review of Existing Test Methods

Before running tests in the laboratory, more comprehensive background research was done on the different types of test methods used in past toxicity research. Included with these different types of tests were the different testing apparatus used. Nathan Marsh, a chemical engineer at NIST and one of the leaders of this project, provided numerous papers on previous tube furnace studies. Additional papers on toxicity, ISO standards, and NIST technical reports were obtained from the Building and Fire Research Laboratory (BFRL) Library.

The research was guided by a paper written by Richard Gann and Julie Neviaser entitled "Evaluation of Toxic Potency Values for Smoke from Products and Materials" (2004). This paper is a critical review of multiple toxicity testing apparatus and methods. As previously mentioned this paper included reviews of the cup furnace methods, radiant heat methods, tube furnace methods and the specific individual studies that used each method. More thorough research on each method provided a good sense of the positives and negatives of each apparatus and method along with the differences and similarities of each. Having this information was advantageous when making recommendations at the completion of this project.

Order of Tests

The order the tests scheduled in was determined by grouping the test parameters and arranging them in a manner that would allow the tests to be completed efficiently and accurately as possible. A base testing matrix was provided and included the following test parameters: material, conformation, furnace temperature, primary air flow rate, feed velocity of the material, and the size of the material. The group modified the matrix to include a test number and an identification code, and the matrix can be found in Appendix D. In addition, a description of the identification code can be obtained in Appendix E.

In determining the order to the tests in the matrix, the biggest contributing factor was the furnace temperature. This was because the furnace took up to an hour to heat up to the required temperature and several hours to cool to ambient temperature. Due to the nature of the furnace, the group attempted to run only one temperature each day.

Another important factor in determining the test order was the material being tested. The group tested four different materials: polymethyl methacrylate (PMMA), foam and fabric, particleboard, and electric cable. The order of the tests was chosen so that more than one material would not be tested on the same day. This kept the different material toxins and residues from being compounded in the mixing chamber, which would have yielded less accurate data.

Lastly, the tests were grouped by feed velocity of the material into the furnace. A laptop computer controlled the feed velocity of the material. In order to save time, the feed rate was adjusted as few times as possible.

Test Parameters

As mentioned, the group tested four types of material. Each material was tested at two different temperatures, 650 ^{o}C and 825 ^{o}C. These conditions were intended to simulate pre-flashover and post-flashover conditions respectively. At each temperature, the group tested each material, with the exception of PMMA at various primary air flow rates. The standard that the tests were based from, ISO/TS19700, suggested that the primary air flow rate be set to 10 L/min (ISO, 2006) for tests at 650 ^{o}C. The group increased this flow by 30% and rant test at 13 L/min as well. At 825 ^{o}C, the flow rates were adjusted to keep similar stoichiometry by multiplying the average O_2 depletion from the corresponding run at 650 ^{o}C by a factor of 1.1933. This method was provided in ISO/TS19700 (ISO, 2006).

Besides the primary air flow rate, the group also varied the feed velocity of the material to see if the experiment was sensitive to feed velocity. With the exception of PMMA, which was only run at the standard feed velocity of 40 mm/min, the group tested each material at feed velocities of 40 mm/min and a 50% increase at 60 mm/min for both temperatures. The primary air flows were also increased by 50% for the runs at 60 mm/min to maintain a constant equivalence ratio.

Finally, the group varied the material conformation and size of each material at both temperatures, with the exception of PMMA. Again, this was done to see if the experiment was sensitive to both of these parameter. The group tested the electric cable and particle board at two different conformations, 45 cm strips and diced. Multiple attempts were made to test the sofa in a diced conformation. However, the group experienced difficulty in keeping the diced foam in place on the quartz boat, and the diced foam was burning too fast. As a result, it was agreed that the group would not test any diced foam. Additionally, the group tested the electric cable and particle board at two different sizes, standard and double. For the tests that called for double size, the group used two side by side samples of material. Because of the large size of the foam sample, the group tested a half-sized sample instead of the double material. Once again, the primary air flows were adjusted accordingly to maintain a constant equivalence ratio.

Test Procedure

After developing an order of how the tests were to be run and a naming convention, Nathan Marsh provided formal startup, testing, and shutdown procedures. The startup and shutdown procedures were followed once for each day of testing, while the testing procedure was followed during individual tests. Refer to Appendices F, G, and H for startup, shutdown, and testing procedures.

Once daily startup procedures were followed, one group member set up the first laboratory notebook entry. Each notebook entry contained information including identification code, sample description, sample weight for before and after the test, initial and average gas concentrations as observed from the NDIR, the depletion of oxygen, and all other observations from each run. Refer to Appendix I for a sample page from the laboratory notebook.

While one group member was preparing the notebook, another member began to prepare the sample. With the exception of the electric cable, all samples were properly sized and provided to the group. Before each test, a group member massed each sample individually, and then again once they placed the sample into the quartz boat. Before the boat was loaded, the group took a picture of the sample inside the boat. Once the boat was loaded and the system was closed, the group member in charge of the notebook set up the NDIR and FTIR file names and checked to make sure the primary and secondary air flows matched the flows needed for each run. When the NDIR and FTIR began collecting data, the boat with the loaded sample began passing through the tube at the set feed velocity. Upon completion of the run, the sample was allowed to cool and then massed on final time. A picture of the boat and what remained of the sample were then taken. The group repeated this procedure three times for each test number to ensure accuracy. See Figure 7 below for a picture of the tube furnace apparatus used for all of the testing.

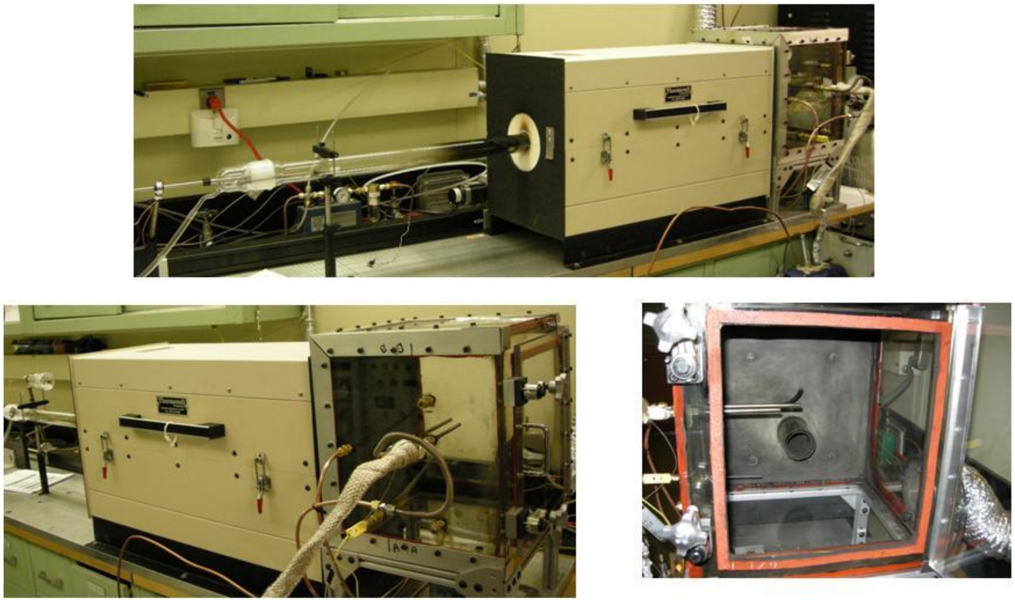


Figure 7: NIST tube furnace from various angles.

Compiling and Analyzing Data

The NDIR and FTIR were equipped with instruments that automatically recorded the data from each run. The NDIR recorded the CO_2, CO, and O_2 levels along with the position and flow rates. The FTIR was used to record the other toxin levels such as CH_4 and HCN and also to ensure the accuracy of the NDIR. After each run was over, the data was copied into a template designed in Microsoft Excel in order to graph the data and take the averages of the byproduct levels over different time spans. Based on the graphs, the group determined where the steady state burning occurred. From this, the appropriate time span was chosen with the corresponding averages. These averages were then compiled and can be found in Appendix J.

FDS Simulations

A thorough analysis of the effluent gas concentrations and the thermo-fluid mechanics throughout the tube and collection box were conducted by the group members. Fire dynamics simulator (FDS), a relatively new technology that models fire-driven fluid flow through a computational fluid dynamics model, was used in conjunction with Smokeview (SMV), a visually based program that is used to display the output of FDS. An input file representing the tube furnace was constructed with the help of Nathan Marsh and Brian Klein. The group ran simulations with respect to upstream airflow and materials combusted. Data regarding temperature, CO, CO_2 and O_2 concentrations were recorded in multiple locations of the collection box. Temperature and velocity profiles of the tube and collection box were also documented.

The group ran FDS simulations representing a sample of PMMA burning at a heat release rate (HRR) of 600 kW/m^2 and a sample of bookcase burning at a heat release rate (HRR) of 100 kW/m^2. Simulations were also run doubling the HRR and primary airflow to gather data for comparison. Graphs were compiled for analysis of temperature and effluent gases. Finally group members formulated conclusions and recommendations made to NIST.

Results and Discussion

The following section includes results from the laboratory work and results from the FDS simulations. Each section includes commentary on the actual results obtained and a comparison of the measured results to those expected based on principles of chemistry and fire dynamics.

Test Results and Repeatability

For the laboratory test results, data tables including average concentrations for given runs and the percent change between the two runs were compiled. These averages were determined by taking the average concentrations over a time period, in which the group estimated a steady state burn was occurring. Since each run was done three times to ensure repeatability of the results, the average of the data from the three runs was then determined and included in these tables. Each table includes the effect of varying a test parameter on the concentration of CO_2. Also, the average CO concentrations were included run for each run. The group also collected data on gases that could not be analyzed in the NDIR due to the limitations of the appartatus, such as HCN and HCl. Although NDIR data is not presented in this report, NIST will analyze this data which will be valuable for future studies of the tube furnace.

Tables 3 through 11 below show the average concentrations of CO_2 for each material at each different test parameter. However, PMMA was only run at two different temperatures, while the rest of the parameters remained untested. These averages were obtained by averaging the steady state values from the three repeated runs for each test. In all cases, the tests showed good repeatability with a low standard deviation for all gases. An example of the test repeatability is shown below for Test 1, PMMA at 650 ^{o}C, in Table 2.

Material	Conformation	Temperature (^oC)	CO_2 (% by vol.)	CO (ppm)	O_2 (% by vol.)
PMMA	Whole	650	2.26	0	18.30
PMMA	Whole	650	2.31	-1	18.23
PMMA	Whole	650	2.27	0	18.28
		Average	2.28	0	18.27
		Standard Deviation	0.03	1	0.03

Table 2: Repeatability data for Test 1.

Since nearly all tests showed good repeatability, the group considered the data to be valid and was able to draw conclusions.

Temperature

When the temperature was varied, the concentration of combustion byproducts also changed. Table 3 shows a comparison of each material tested at both 650 ^oC and 825 ^oC.

	Material	Temperature (^oC)	CO_2 (% by vol.)	% Change of CO_2	CO (ppm)
Test 1	PMMA	650	2.28	75.9%	0
Test 17	PMMA	825	0.55		2472
Test 2	Particleboard	650	1.71	76.0%	-4
Test 18	Particleboard	825	0.41		1086
Test 7	Foam	650	1.18	60.2%	348
Test 23	Foam	825	0.47		2021
Test 12	Cable	650	1.05	50.5%	1078
Test 28	Cable	825	0.52		656

Table 3: Average concentrations of combustion byproducts for each material tested at different temperatures.

When the temperature was increased from 600°C to 825°C, CO_2 levels decreased to approximately less than half of the original values for all four materials. For three of the four materials, there was a substantial increase in CO concentrations. Cable was the only material that did not show an increase in CO with the increased temperature. The CO levels in cable decreased as the temperature was increased. This could be due to the metal pieces of the cable coming closer to their melting points and starting to decompose.

An increase in CO concentrations coinciding with an increase in temperature corresponds to less complete combustion at higher furnace temperatures. However, combustion involving an open flame is expected to come closer to completion as temperature increases. One reason for this unexpected result may be that the flame is burning in an enclosed space possibly limiting oxidation.

Conformation

When the group varied the conformation of each material, the byproduct concentrations remained relatively similar. Tables 4 and 5 below show a comparison of each material, with the exception of PMMA, tested at two different conformations, long strips and diced.

	Material	Conformation	CO_2 (% by vol.)	% Difference of CO_2	CO (ppm)
Test 2	Particleboard	Whole	1.71	2.9%	-4
Test 3	Particleboard	Diced	1.66		-8
Test 7	Foam	Whole	1.18	No Data	348
Test 8	Foam	Diced	No Data		
Test 12	Cable	Whole	1.05	15.2%	1077
Test 13	Cable	Diced	1.21		1192

Table 4: Average concentrations of combustion byproducts for different conformations at 650 °C.

	Material	Conformation	CO_2 (% by vol.)	% Difference of CO_2	CO (ppm)
Test 18	Particleboard	Whole	0.41	24.4%	1086
Test 19	Particleboard	Diced	0.31		680
Test 23	Foam	Whole	0.47	No Data	2021
Test 24	Foam	Diced	No Data		
Test 28	Cable	Whole	0.31	3.2%	603
Test 29	Cable	Diced	0.30		549

Table 5: Average concentrations of combustion byproducts for different conformations at 825 °C.

CO levels decreased, when the sample conformation was changed from whole to diced, but not significantly. The diced sample provides a greater surface area for the oxygen to come in contact, which in turn may allow for more complete combustion. Because the CO_2 levels did not vary greatly at either conformation, it shows that the conformation of the material has little effect on the burn rate of the material.

The group was unable to obtain reliable and repeatable test results for diced foam, due to the low density and fast burn rate of the foam. Because of the larger surface area and air pockets in the foam, the flame would burn out of the furnace and draw back into the tube during all testing. This unexpected burn behavior prevented the group from collecting data that met expected values for nearly all tests. Once the foam was diced, it would burn even more quickly due to an even greater increase in surface area. Also, because of the low density, the primary air that flowed through the tube would blow the diced pieces of foam around.

Primary Air Flow

As the primary air flow was increased from 10 to 13 L/min, a 30% increase, (which increased the equivalence ratio as well), there was slightly less CO_2 produced and a nominally equal amount or small decrease in observed CO. Tables 6 and 7 below show a comparison of each material, with the exception of PMMA, tested at two different primary air flows for each temperature.

	Material	Primary Air Flow (L/min)	CO_2 (% by vol.)	% Difference of CO_2	CO (ppm)
Test 2	Particleboard	10	1.71	6.4%	-4
Test 4	Particleboard	13	1.82		-10
Test 7	Foam	10	1.18	27.1%	348
Test 9	Foam	13	0.86		305
Test 12	Cable	10	1.05	2.9%	1078
Test 14	Cable	13	1.02		935

Table 6: Average concentrations of combustion byproducts for different primary air flow rates at 650 ^{o}C.

	Material	Primary Air Flow (L/min)	CO_2 (% by vol.)	% Difference of CO_2	CO (ppm)
Test 18	Particleboard	2.2	0.41	43.9%	1086
Test 20	Particleboard	1.5	0.23		1015
Test 23	Foam	2.5	0.47	29.8%	2021
Test 25	Foam	1.7	0.33		2202
Test 28	Cable	1.9	0.31	32.2%	603
Test 30	Cable	1.3	0.21		1384

Table 7: Average concentrations of combustion byproducts for different primary air flow rates at 825 ^{o}C.

Assuming that 10 L/min was sufficient for complete combustion, the group expected minimal changes by increasing the primary air. This hypothesis holds true at 650 ^{o}C, with the exception of foam. However, at 825 ^{o}C, the difference in CO_2 levels became more severe. One thing that may have caused this result is the fact that at 825 ^{o}C, the primary air flows were very low possibly starving the combustion process of enough oxygen. In contrast, the CO levels remained similar for the particleboard and foam, but not the cable. It was difficult to make any correlations based on this data, so the group decided that for lower temperatures and higher primary flows, the tube furnace is not sensitive to an increase in primary air flow, but at higher temperatures the data was inconclusive.

Feed Velocity

As the feed velocity was increased from 40mm/min to 60mm/min, a 50% increase, the CO_2 levels increased, although not exactly 50% as expected. Tables 8 and 9 below show a comparison of each material, with the exception of PMMA, tested at two different feed velocities for each temperature.

	Material	Feed Velocity (mm/min)	CO_2 (% by vol.)	% Difference of CO_2	CO (ppm)
Test 2	Particleboard	40	1.71	22.2%	-4
Test 6	Particleboard	60	2.09		-2
Test 7	Foam	40	1.18	61.0%	348
Test 11	Foam	60	0.46		39
Test 12	Cable	40	1.05	42.9%	1078
Test 16	Cable	60	1.50		1299

Table 8: Average concentrations of combustion byproducts for different feed velocities at 650 °C.

	Material	Feed Velocity (mm/min)	CO_2 (% by vol.)	% Difference of CO_2	CO (ppm)
Test 18	Particleboard	40	0.41	51.2%	1086
Test 21	Particleboard	60	0.62		2008
Test 23	Foam	40	0.47	21.3%	2021
Test 27	Foam	60	0.37		2825
Test 28	Cable	40	0.31	80.6%	603
Test 32	Cable	60	0.58		1757

Table 9: Average concentrations of combustion byproducts for different feed velocities at 825 °C.

Since the material was fed at a faster rate, and the same amount of material was combusted, the burn rate of the material was expected to proportionally increase with the 50% increase in feed velocity. Although there was not exactly a 50% increase in all runs, each run at 60 mm/min showed a substantial increase in CO_2 levels, with the exception of foam which behaved opposite of what was expected. This data proves that changing the mass charge has an effect on the results.

Size

When the material size was doubled, or cut in half for foam, the CO_2 levels increased proportionally. Foam samples were cut in half because the foam pieces were too large. Tables 10 and 11 below show a comparison of each material, with the exception of PMMA, tested at two different sizes.

	Material	Material Size	CO_2 (% by vol.)	% Difference of CO_2	CO (ppm)
Test 2	Particleboard	Whole	1.71	97.7%	-4
Test 5	Particleboard	Double	3.38		-7
Test 7	Foam	Whole	1.18	67.8%	348
Test 10	Foam	Half	0.38		124
Test 12	Cable	Whole	1.05	86.7%	1078
Test 15	Cable	Double	1.96		2150

Table 10: Average concentrations of combustion byproducts for different sample sizes at 650 °C.

	Material	Material Size	CO_2 (% by vol.)	% Difference of CO_2	CO (ppm)
Test 18	Particleboard	Whole	0.41	51.2%	1086
Test 21	Particleboard	Double	0.62		2008
Test 23	Foam	Whole	0.47	80.9%	2021
Test 26	Foam	Half	0.09		519
Test 28	Cable	Whole	0.31	129.0%	603
Test 31	Cable	Double	0.71		1353

Table 11: Average concentrations of combustion byproducts for different sample sizes at 825 °C.

As expected, when the material size was adjusted and the primary air flow was adjusted accordingly to maintain a constant equivalence ratio, the amount of CO_2 changed proportionally. This was due to the fact that either double or half of the material was burning in the same amount of time, and the stoichiometry did not change. Therefore, either double or half of the amount of CO_2 was expected.

At 650 ^{o}C the results match what was expected. However, at 825 ^{o}C, the CO_2 levels did not correlate to exactly what was expected for the bookcase or the foam. In examining the CO data though, the combustion occurred as expected. Although the data did not correlate completely, this data shows for the most part that material size does have an effect on the results.

FDS Results

The group ran four simulations in FDS with two different types of fuel. Two simulations were run with laminated particle board (bookcase) and two with a thermoplastic (PMMA). The simulations provided data from two separate locations in the mixing chamber. Temperature, carbon dioxide, carbon monoxide, and oxygen concentrations were recorded. The bookcase results were compared to the tube furnace experimental data, however, the PMMA data wasn't comparable to any experimental data available. See Table 12 below for steady state average concentrations for all runs.

	T (°C)	CO_2 (mole fraction)	O_2 (mole fraction)
Bookcase 1 / Probe 1	35	0.0008	0.206
Bookcase 1 / Probe 2	30	0.0007	0.206
Bookcase 2 / Probe 1	45	0.0014	0.205
Bookcase 2 / Probe 2	35	0.0013	0.205
PMMA 1 / Probe 1	35	0.0048	0.198
PMMA 1 / Probe 2	30	0.0043	0.200
PMMA 2 / Probe 1	45	0.0085	0.193
PMMA 2 / Probe 2	35	0.0075	0.194

Table 12: Steady state averages for FDS simulations (CO values were all 0)

Temperature was representative of the experimental thermocouple data so that wasn't analyzed in depth. The CO data was all zero from FDS because the program assumes complete combustion. CO_2 was the only data that significant conclusions could be drawn from.

Primary airflow was set to 10 L/min in the first bookcase simulation and secondary airflow was accordingly 40 L/min. The sample vent was assigned a HRR of 100 kW/m^2. Figure 8 below illustrates the CO_2 concentrations at each of the sample probe locations for the first bookcase FDS simulation.

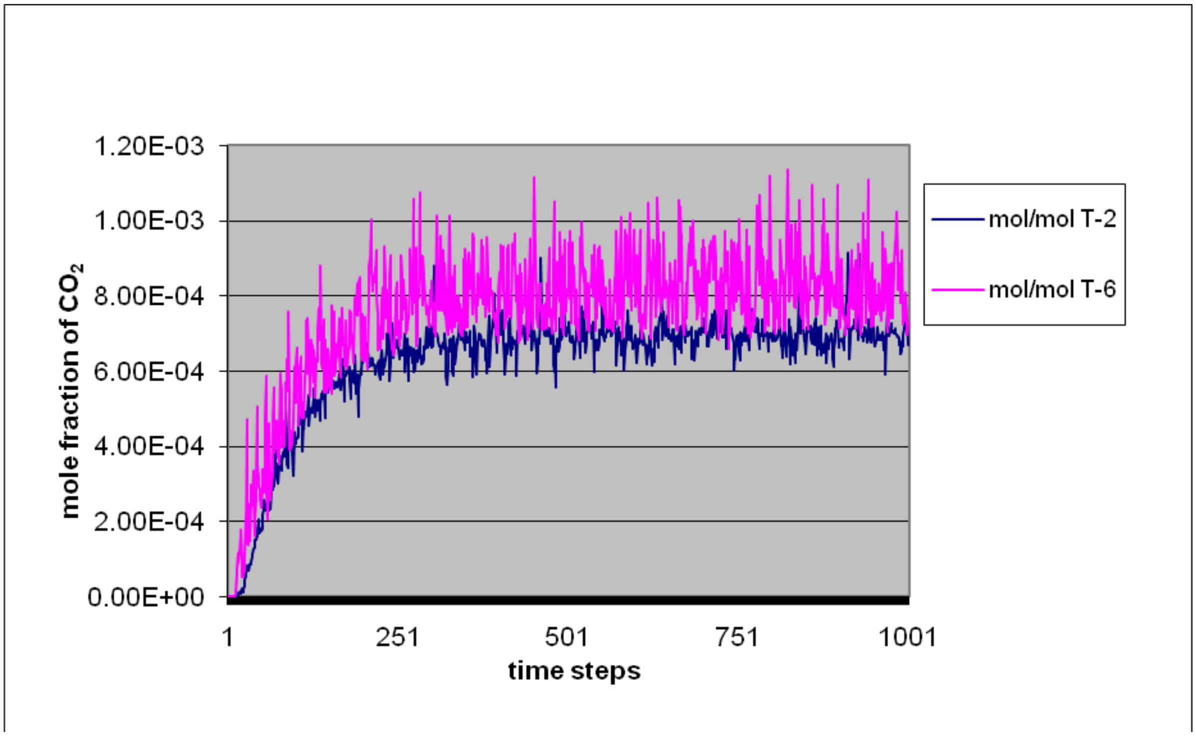


Figure 8: CO_2 concentrations at each probe location for first bookcase FDS simulation.

The graph's x-axis has units of time steps which are approximately 1 time step for every 0.6 seconds. Each simulation was the equivalent of 5 minutes real time. The results are slightly skewed by about 20% which indicates insufficient mixing in the chamber. This is a result of the direction of the secondary airflow. It is located in the correct position but directs air straight to the back of the mixing chamber instead of at a 45 degree angle as specified in the standard. The correction of the secondary airflow will correct insufficient mixing issues. Although the data is skewed by approximately 20% from each probe location, conclusions can still be drawn from the data. In the experiment mixing chamber the argument can be made that mixing is less than 20% insufficient, which illustrates that experimental conditions are close to well mixed.

As expected when the HRR and primary airflow were doubled the combustion rate was doubled and as a result CO_2 concentrations were doubled as well. Figure 9 below illustrates the increase of CO_2 concentrations by a factor of 2 from Figure 8.

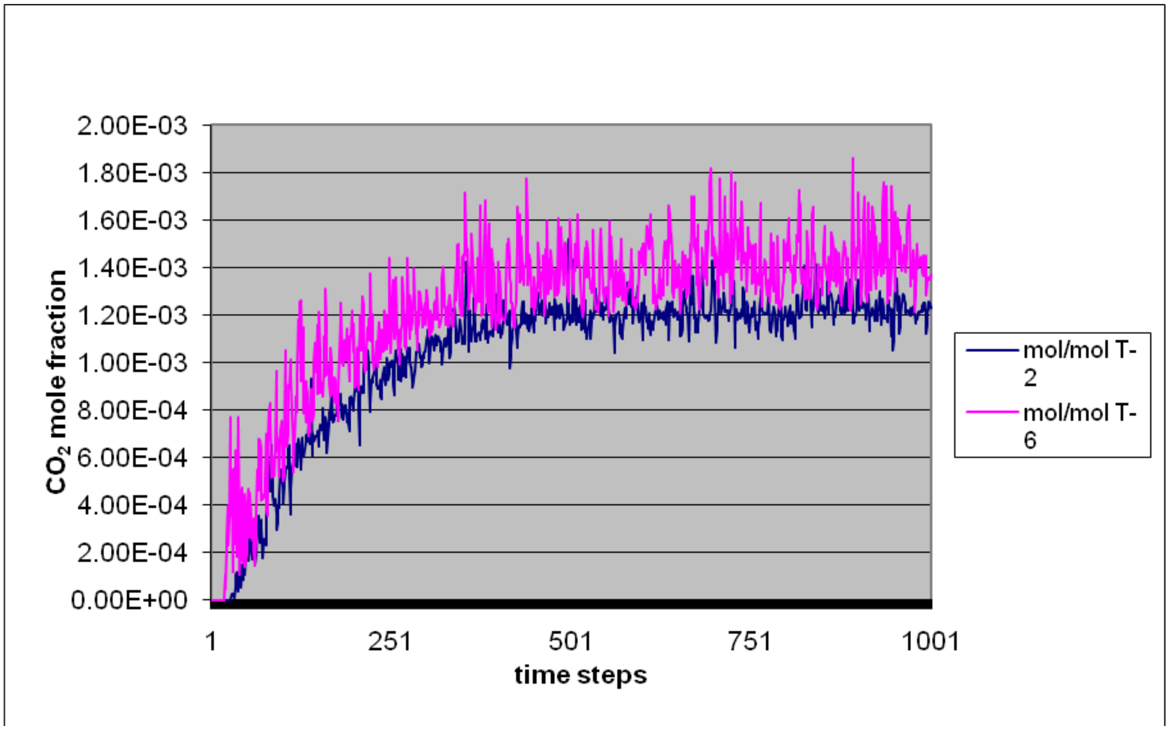


Figure 9: CO_2 concentrations at each probe location for second bookcase FDS simulation.

When compared to experimental data, each of the bookcase CO_2 concentrations was low by a factor of 10. This was caused by two differences from the simulations to the experiment. First, the surface area of the sample vent in the simulation had a lower surface area then the sample in the experiment by a factor of 4. The sample vent is dimensionless while the bookcase in the experiment is a three-dimensional rectangle. The low surface area decreases the combustion from radiation and limits the CO_2 concentrations produced. Second, the simulation assumes that all radiation in the tube is normal to the sample surface. This isn't representative of the experiment as radiation comes from all directions in the tube. Accounting for both of these differences would significantly increase the CO_2 concentrations and be much more representative of the actual experimental results. The PMMA simulations results were not analyzed because there was no experimental data available to compare them with.

FDS Conclusions

The group concluded that the FDS simulation was not a good indicator of what was happening experimentally. Compared to experimental data, FDS CO_2 concentrations were low by a factor of 10. It was found that temperature in the mixing chamber was representative to experimental temperatures. However, with adjustments to the input parameters such as airflow rates, HRR and planar area of combustion, and a finer grid size, the data should match up more accurately. For example, based on the bookcase simulation data, the group concluded that doubling the HRR and primary airflow would result in an increase in CO_2 concentrations by approximately a factor of 2.

Conclusions

A total of 32 tests were run, each being triplicated to ensure repeatability. Based on the results from those tests, the group was able to make conclusions on both the appropriateness of the tube furnace for testing each of the four materials and on the sensitivities of the tube furnace to the various operations. The following sections provide conclusions based on the experimental data.

The results demonstrated that the apparatus was appropriate for all of the materials with the exception of foam. Consistently the foam behaved opposite of what was expected. Also, the foam could not be tested for conformation because of its low density. The primary air flow through the tube caused the low density diced pieces of foam to blow out of the quartz boat, thus, making it extremely difficult to test.

It was concluded that the furnace temperature had an effect on the amount of CO_2 produced, but not as expected. It was expected that with a higher furnace temperature, the burn rate would also increase, yielding a higher concentration of CO_2, but that did not occur. Instead, when the furnace temperature was increased, a decrease in burning rate was observed. This could be due to a decrease in the primary air flow per the standard for runs at 825 ^oC. Due to the low primary air flows, combustion may not have been as complete and an increased pyrolysis rate may have occurred. The pyrolysis also could have been occurring faster than the material could combust, which could account for the lower CO_2 levels at the higher temperature runs.

Next, the group concluded that the conformation of the material had no effect on the combustion byproducts. The data showed that there were small differences in the gas concentrations, which were within the standard deviation, when testing the conformation. The gas concentrations were relatively the same when only the conformation was changed. From this it was concluded that the conformation did not affect the combustion of the material.

Varying the primary air flow rate at the lower temperature had little effect on the concentrations of gases. It was expected that there would not be much change in the concentrations when the primary air flow was increased by 30%, because the total air in the mixing chamber remained constant at 50 L/min for every test. Since the total air never changed, the dilution in the mixing chamber was not affected by the primary air flow. Had the gases been analyzed right at the end of the tube, there's a possibility the results may have differed.

At the higher temperature, when the primary air flow was increased by 30%, the concentrations were much lower than what was expected for CO_2, however, the CO levels did not change. The constant CO concentrations show that the same amount of combustion was occurring. However, the unexpected decrease in CO_2 discredits that claim. There is a possibility that since the CO_2 levels were already showing up lower than expected at higher temperatures, that it was just the temperature that was causing this unexpected result and not the increase in primary air.

It was concluded that the size of the specimen was proportional to the mass burn rate. As expected, when the size of the specimen was doubled, and the equivalence ratio was maintained, the mass burn rate approximately doubled. The specimen was fed at the same rate and the total air in the box was constant.

The feed velocity was also proportional to the mass burn rate. Similar to the size tests, when testing the affect of the feed velocity the equivalence ratio was preserved. It was expected that the mass burn rate would increase 50% with a 50% increase in the feed velocity because the same amount of material was burning in less time. The data proved that this was true.

Recommendations

All of the recommendations presented here are based on experience and observations from the experimental phase of the project. The aim of the group's recommendations is to minimize problems. The key is to minimize problems with the conduct of the experiments and to help ensure that other groups that use this standard can replicate the results. Included in the following section are recommendations for altering the test parameters, modifying the apparatus, more precise data analysis, and improved FDS simulations.

Test Parameters

One suggestion the group has, is to test a wider range of primary air flow rates without preserving the equivalence ratio. More air flow rates should be tested to ensure that the burn rate is not affected by the primary air flow, which was the drawn conclusion thus far. With the issues arising at a higher temperature, another suggestion would be to have a different method to calculate the primary air flow rate when increasing the furnace temperature, instead of being based on the oxygen depletion from the runs at 650 ^{o}C.

The next recommendation is to test more temperatures to observe whether CO_2 levels actually decrease with an increase in temperature. This suggestion arose because the data from the experiment did not match what was expected to happen. With an increase in temperature, it is expected that the CO_2 levels would increase with temperature. Due to the fact this did not occur, more temperatures should be tested to see if the equipment is adequate for higher temperatures or to determine if the conclusions are indeed correct.

Because of the difficulties testing foam, the group made recommendations for future testing of foam. If the standard includes foam for testing, it is recommended that half the size of the foam be used. Using half the size would eliminate the problem of not being able to double the size for the foam. When run at full size, the foam barely fits in the tube which may have blocked some of the primary air flowing through the tube. This also is important when comparing data because the data should be consistent, that is all the testing should not have double sized material with one material at half size instead of full size.

Apparatus

In regards to the apparatus itself, one recommendation is to test to ensure the mixing chamber contents are well mixed. The FDS simulations showed a difference in the CO_2 levels at the two different measure locations meaning the contents were not completely well mixed throughout the chamber. In the actual experiment, the probe should be moved to another location, or a second probe should be added to test how well-mixed the mixing chamber is.

Next, it is suggested to have a window in the furnace to observe what is occurring during the run. Currently, during each run, the combustion cannot directly be observed to see where the actual burning is occurring. Instead the combustion of the material can only be viewed from obscure angles. Because of this issue, the group suggests having a viewing window on the side of the furnace. It is important to be able to observe what is occurring during the run with the flame as well as the smoke.

Data Analysis

One suggestion for improved data analysis is to calculate mass loss based on percent loss of original weight. When analyzing the data, it is unclear how the mass loss would be of importance without knowing the original weight. Because of this, it is suggested that the mass loss is calculated as a percent of the original weight. This would allow the data to be used in a more efficient and unambiguous manner.

FDS Simulations

Finally, the group also made recommendations for improving the FDS simulations. There were multiple areas regarding improvements to the group's FDS simulations but the biggest restraint on the project was time. There was not a significant amount of things that need to be changed but rather things that need to be investigated further. Also, there was not a significant amount of simulations conducted because each run was very time consuming.

The secondary airflow needs to be readjusted to a 45 degree angle. Doing this would ensure well mixed conditions in the mixing chamber and reduce discrepancies in data from the probe locations. If this did not completely fix the insufficient mixing issues then the sensors need to be repositioned to areas with well mixed conditions.

Next, the sample needs to be readjusted to more accurately model the planar area of the sample combusting. The simulation sample was estimated based on approximations to what was happening. Since the furnace cannot be opened during experiments it was impossible to tell the exact dimensions of the combusting area of the sample.

HRRs were provided by NIST and need to be reevaluated. Changing HRRs would significantly alter the simulation data. The group recommends increasing the gasification rate by increasing the irradiated sample surface. Sample surface currently is low by a factor of 4. Finally, the computational resolution of the sample needs to be enhanced. Simulation run time drastically increases with enhanced resolution; however, it is necessary to produce the most accurate experiment representation. Cell density increases as computational resolution is increased which will enable programmers to position all objects in the simulation to their exact locations. It would also significantly increase the overall performance of each simulation.

The group believes that the recommendations presented for changes to the test parameters, tube furnace apparatus, and data analysis will provide for improved measurement of combustion byproducts using the tube furnace. Likewise, recommendations for varying the input parameters in the FDS simulations will provide for results that more closely match experimental data.

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Appendix A: Brief Background of NIST

The sponsoring organization for this project is the National Institute of Standards and Technology (NIST). “Founded in 1901, NIST is a non-regulatory federal agency within the U.S. Department of Commerce. NIST's mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life” (NIST, 2001). NIST carries out its mission through four cooperative programs. NIST Laboratories conduct research used for the advancement of the nation’s technology infrastructure. The Baldridge National Quality Program conducts outreach programs to help promote performance excellence among various U.S. organizations. The Hollings Manufacturing Extension Partnership offers technical and business assistance to smaller manufacturers through a nationwide network of local centers. A newly created program, the Technology Innovation Program, is planned to provide industry, universities and consortia cost-shared awards for research on potentially revolutionary technologies that address critical national and societal needs (NIST, 2001).

NIST employs roughly 2,800 engineers, technicians, scientists, and support and administrative employees. NIST also hosts roughly 2,600 associates and facility users from industry, academia, and other government agencies. In addition, NIST collaborates around the country with 1,600 manufacturing specialists and staff at approximately 440 MEP service locations. NIST has an operational budget of approximately $843 million and operates in two locations: Gaithersburg, MD and Boulder, CO (NIST, 2001).

The Building and Fire Research Laboratory (BFRL) located within NIST works, “To promote U.S. innovation and competitiveness by anticipating and meeting the measurement science, standards, and technology needs of the U.S. building and fire safety industries in ways that enhance economic security and improve the quality of life" (NIST, 2008). The BFRL accomplishes its goal through the continual study of computer-integrated construction practices; fire science and fire safety engineering; building materials; and mechanical, structural, and environmental engineering (NIST, 2008).

Appendix B: Detailed Process of a Fire Hazard Analysis (FHA)

The first step of an FHA is to select a target outcome. Most common target outcomes involve the avoidance of fatalities of occupants in the building. The second step is determining the scenario(s) of concern that could result in that outcome. Next, design fire(s) are selected. This step is very important to conducting a valid analysis, because “the purpose of the design fire is similar to the assumed loading in a structural analysis; i.e., to answer the question of whether the design will perform as intended under the assumed challenge” (Bukowski, 1997). An appropriate method(s) for prediction is selected in the fourth step. In order to choose an appropriate model, a solid understanding of the assumptions and limitations of the model in question are necessary. In the fifth step, an evacuation calculation is performed. Comparable to selecting an appropriate method(s) for prediction, it is also important to predict a relevant egress model. A sound understanding of the egress methods is necessary to obtain an accurate model. The sixth step is analyzing the impact of exposure. According to Bukowski, “In most cases, the exposure will be to people, and the methods used to assess the impacts of exposure of people to heat and combustion gases involves the application of combustion toxicology models” (1997). The seventh and final step is accounting for uncertainty. A discussion of uncertainty should be included in the FHA report.

Appendix C: Code Development Process

The government, public and private sectors commonly coordinate with various organizations to conduct research in which standards are implemented, but occasionally such organizations will conduct research on their own accord. If NIST performs research that proves old standards incorrect or misleading then often groups such as the International Standards Organization (ISO) will amend their documents based upon the new conclusions proposed by NIST.

The world's largest developer and publisher of International Standards is ISO. ISO is a network comprised of international standards of 157 countries across the globe. The system is coordinated by one member from each of the countries involved. Though ISO is a non-governmental organization it still holds a unique position between the public and private sectors of standards development. This coincides with a portion of its members holding government positions in their respective countries as well as a portion of its members involved with the private sector. The bridging of the public and private sectors allow for compromise between the requirements of business organizations and the needs of society such as stakeholder groups like users and consumers (ISO, 2008a).

When the member bodies of the ISO come to agreement on standards they become an international standard. When a standard becomes international it may be used in any of the participating countries that make up ISO. International standards are developed by ISO technical committees (TC) and subcommittees (SC) in a six-step process. The first step requires a new proposal to be agreed upon by the majority of the members of the TC/SC with at least 5 members agreeing to work with the development of the standard personally. A group of experts constructs a working draft of the standard in the second step. Once a working draft is established it is again voted on by the TC/SC until a consensus is reached in step 3. At which point, the draft international standard (DIS) is circulated to all members of ISO over a period of 5 months in step 4. ISO states, “It is approved for submission as a final draft International Standard (FDIS) if a two-thirds majority of the P-members of the TC/SC are in favor and not more than one-quarter of the total number of votes cast are negative” (ISO, 2008b). Once a FDIS has been approved in step 6, only minor editorial changes are made to the final document. The international standard is then published and made available to the public (ISO, 2008b).

Appendix D: Final Test Matrix

Idetification Code	Test Number	Product	T_{run}	Conformation	Air Flows		Specimen		
				1 - Whole	Primary	Secondary	Feed Rate	Size	Objective
(see below)			°C	2 - Diced	l/min	l/min	mm/min		
Test Number, Product Letter, Conformation, Temp, Primary Air Flow, Feed Rate, Size, Run Number									
1-P-1-650-10-40-1-xxx	1	PMMA	650	Long Strip	See 9.3.4	50 – Prim.	40	1	3
2-B-1-650-10-40-1-xxx	2	Bookcase	650	Long strip, with laminate face up	See 9.3.4	50 – Prim.	40	1	1.a, (b)
3-B-2-650-10-40-1-xxx	3	Bookcase	650	Diced strip, with same mass as 1.a	See 9.3.4	50 – Prim.	40	1	2.c
4-B-1-650-1.3-40-1-xxx	4	Bookbase	650	Long strip, with laminate face up	1.3 (9.3.4)	50 – Prim.	40	1	2.d
5-B-1-650-2-40-2-xxx	5	Bookcase	650	Long strip, with laminate face up	2 (9.3.4)	50 – Prim.	40	2	2.e.1
6-B-1-650-1.5-60-1-xxx	6	Bookcase	650	Long strip, with laminate face up	1.5 (9.3.4)	50 – Prim.	60	1	2.e.2
7-S-1-650-10-40-1-xxx	7	Sofa	650	Long strip of foam, with proportionate layer of fabric on tip	See 9.3.4	50 – Prim.	40	1	1.a, (b)
8-S-2-650-10-40-1-xxx	8	Sofa	650	Diced, with same mass and proportion as 1.a	See 9.3.4	50 – Prim.	40	1	2.c
9-S-1-650-13-40-1-xxx	9	Sofa	650	Long strip of foam, with proportionate layer of fabric on tip	1.3 (9.3.4)	50 – Prim.	40	1	2.d
10-S-650-20-40-2-xxx	10	Sofa	650	Long strip of foam, with proportionate layer of fabric on tip	2 (9.3.4)	50 – Prim.	40	2	2.e.1
11-S-650-15-60-1-xxx	11	Sofa	650	Long strip of foam, with proportionate layer of fabric on tip	1.5 (9.3.4)	50 – Prim.	60	1	2.e.2
12-C-1-650-10-40-1-xxx	12	Cable	650	Full-length, intact strip(s)	See 9.3.4	50 – Prim.	40	1	1.a, (b)
13-C-2-650-10-40-1-xxx	13	Cable	650	Diced, with same mass as 1.a	See 9.3.4	50 – Prim.	40	1	2.c
14-C-1-650-13-40-1-xxx	14	Cable	650	Full-length, intact strip(s)	1.3 (9.3.4)	50 – Prim.	40	1	2.d
15-C-2-650-20-40-2-xxx	15	Cable	650	Full-length, intact strip(s)	2 (9.3.4)	50 – Prim.	40	2	2.e.1
16-C-1-650-15-60-1-xxx	16	Cable	650	Full-length, intact strip(s)	1.5 (9.3.4)	50 – Prim.	60	1	2.e.2
17-P-1-825-3-40-1-xxx	17	PMMA	825	Long Strip	See 9.4.4	50 – Prim.	40	1	3
18-B-1-825-5-40-1-xxx	18	Bookcase	825	Long strip, with laminate face up	See 9.4.4	50 – Prim.	40	1	1.a, (b)
19-B-2-825-1-40-1-xxx	19	Bookcase	825	Diced strip, with same mass as 1.a	See 9.4.4	50 – Prim.	40	1	2.c
20-B-1-825-3-40-1-xxx	20	Bookbase	825	Long strip, with laminate face up	2/3 (9.4.4)	50 – Prim.	40	1	2.d
21-B-1-825-10-40-2-xxx	21	Bookcase	825	Long strip, with laminate face up	2 (9.4.4)	50 – Prim.	40	2	2.e.1
22-B-1-825-5-60-1-xxx	22	Bookcase	825	Long strip, with laminate face up	1.5 (9.4.4)	50 – Prim.	60	1	2.e.2
23-S-1-825-2-40-1-xxx	23	Sofa	825	Long strip of foam, with proportionate layer of fabric on tip	See 9.4.4	50 – Prim.	40	1	1.a, (b)
24-S-2-825-2-40-1-xxx	24	Sofa	825	Diced, with same mass and proportion as 1.a	See 9.4.4	50 – Prim.	40	1	2.c
25-S-1-825-1-40-1-xxx	25	Sofa	825	Long strip of foam, with proportionate layer of fabric on tip	2/3 (9.4.4)	50 – Prim.	40	1	2.d
26-S-1-825-4-40-1-xxx	26	Sofa	825	Long strip of foam, with proportionate layer of fabric on tip	2 (9.4.4)	50 – Prim.	40	2	2.e.1
27-S-1-825-2-60-1-xxx	27	Sofa	825	Long strip of foam, with proportionate layer of fabric on tip	1.5 (9.4.4)	50 – Prim.	60	1	2.e.2
28-C-1-825-40-5-1-xxx	28	Cable	825	Full-length, intact strip(s)	See 9.4.4	50 – Prim.	40	1	1.a, (b)
29-C-2-825-5-40-1-xxx	29	Cable	825	Diced, with same mass as 1.a	See 9.4.4	50 – Prim.	40	1	2.c
30-C-1-825-3-40-1-xxx	30	Cable	825	Full-length, intact strip(s)	2/3 (9.4.4)	50 – Prim.	40	1	2.d
31-C-1-825-10-40-2-xxx	31	Cable	825	Full-length, intact strip(s)	2 (9.4.4)	50 – Prim.	40	2	2.e.1
32-C-1-825-2-60-1-xxx	32	Cable	825	Full-length, intact strip(s)	1.5 (9.4.4)	50 – Prim.	60	1	2.e.2

Appendix E: Identification Code Explained

The naming system was designed to allow users to identify the test parameters by looking at the file name and not having to open the file. Results from each test were stored with a file name equivalent to the test's identification code. Identification codes were arranged by assigning each parameter of the test either a letter or number to identify the test parameter (i.e. 1-P-1-650-10-40-1-001). The identification code was arranged in the following order:

1. Test number
2. Product letter
3. Conformation
4. Temperature
5. Primary air flow
6. Feed velocity
7. Size
8. Run number

Appendix F: Startup Procedure

Startup:

1) Set valve on left end of bench to Air
2) Turn on Motion Flow Controllers
3) Turn on Air (both sides of room)
4) Open valve on N_2 cylinder
5) Run LabView (filename “test” or similar)
6) Set Primary and Secondary Air flow rates and LED’s green
7) Verify flow rates reported back (horizontal green bars)
8) Turn on furnace
9) Set furnace set point (arrows + “enter”)
10) Plug in motion controller
11) Put ice water coil in bucket, fill with ice, top off with water
12) Connect the rest of the sample train snug with wrenches
13) Put dry ice around the glass trap (HEAVY GLOVES!)
14) Check NDIR calibration and record
15) NDIR valve to “chamber”
16) Turn on pumps (NDIR + FTIR)
17) Check O_2 (span value) on NDIR and record

Appendix G: Shutdown Procedure

Shutdown:

1) Turn off furnace
2) Turn off Motion Flow Controllers
3) Unplug motion controller (top plug)
4) Turn off air (both sides of room)
5) Close valve on N_2 tank
6) Verify CO/CO_2 tank valve is closed
7) Stop / exit LabView
8) Turn off pump(s)
9) NDIR to standby (MAIN / F7)
10) Disconnect dry ice trap (both sides)
11) Return unused dry ice to cooler
12) Open disk filter housing, dispose of filter (record anything unusual)
13) Disconnect ice water coil
14) Pour ice water in sink
15) Blow out ice water coil*

***To blow out the ice water coil:**

1) Hold coil over trash and open valve
2) Hang coil in trash
3) Connect top of coil to air line
4) Plug other end of coil
5) Turn on air
6) Reverse 1-5

Appendix H: Detailed Test Procedure

Before Each Test:

1) Verify LabView is stopped
2) Verify desired Furnace T on controller
3) Verify CO / CO_2 / O_2 baseline is within bounds (± 10 ppm / ± 0.04 % / 20.5 % to 21 %)
4) Verify NDIR flows within bounds (Ch. 1 and Ch. 2: 1.00 L/min to 1.10 L/min; Ch. 2: 0.2 L/min)
5) Record sample description and dimensions
6) Weigh sample and record (GLOVES)
7) Weigh sample in boat and record (GLOVES)
8) Take a photograph of sample with label
9) Load sample boat into tube furnace (GLOVES)
10) Set push rod over boat end
11) Place cap on tube, attach springs, rotate cap to form seal
12) Check the thumbscrew on the pushrod
13) Enter new file name and start Autoquant (3.3 P/P is normal on FTIR)
14) Enter new file name and start LabView
15) Verify Primary and Secondary Air flow rates (look at both the set point AND the value reported back)
16) Press button to start motion controller

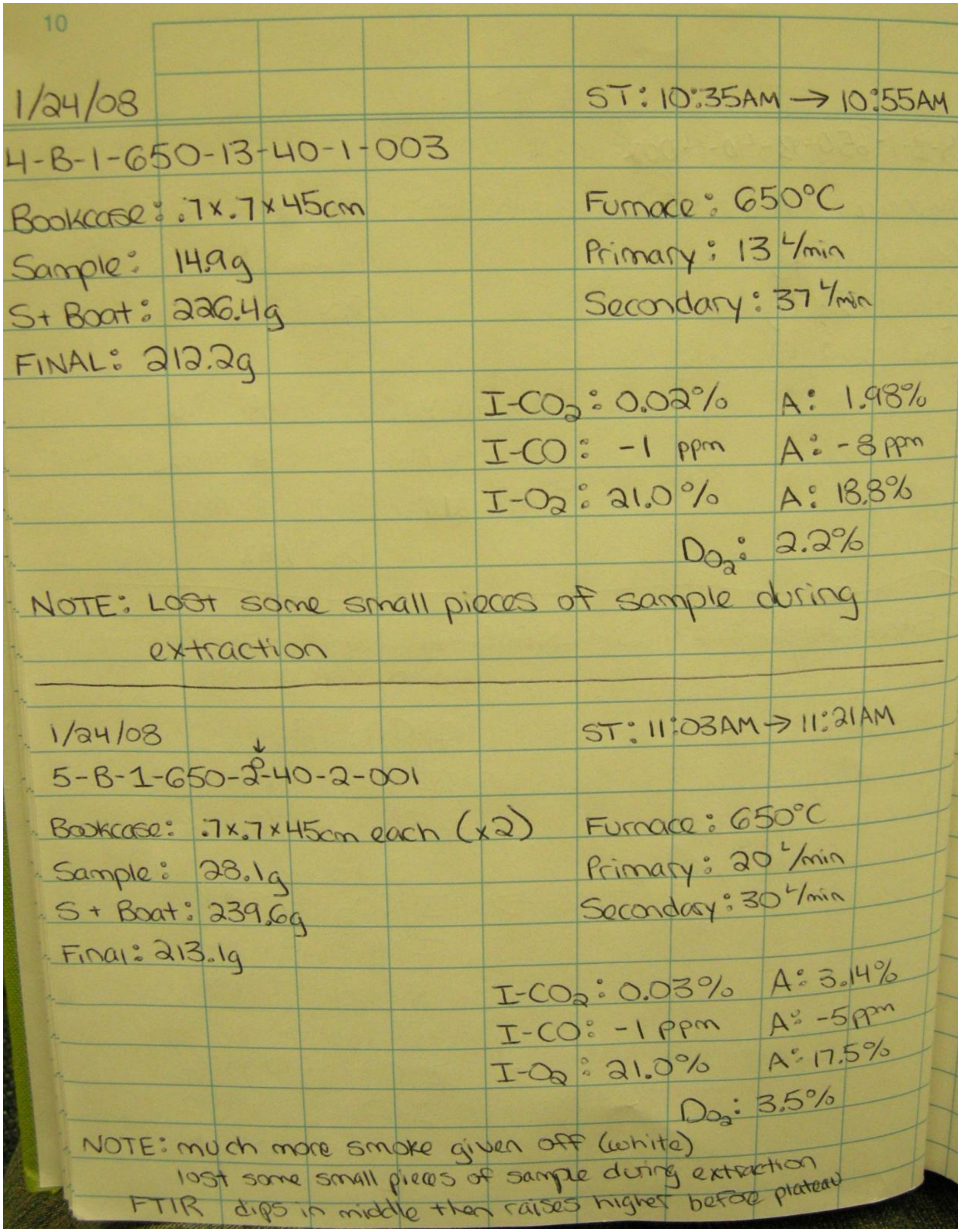
During Each Test:

1) Observe steady state and record gas concentrations (CO / CO_2 / O_2 from the NDIR and anything "interesting" from the FTIR
2) Calculate D_{O2} (Oxygen Depletion)

After Each Test:

1) If the sample smolders at all, turn the valve at the left end of the bench from Air to N_2
2) Wait 5 minutes for sample boat to cool, and then weigh before cleaning (GLOVES)
3) Weigh the boat with the burned sample (GLOVES)
4) Take photograph with label

Appendix I: Sample Page from Laboratory Notebook



10

1/24/08 ST: 10:35AM → 10:55AM

4-B-1-650-13-40-1-003

Bookcase: .7x.7x45cm Furnace: 650°C

Sample: 14.9g Primary: 13 L/min

S+Boat: 226.4g Secondary: 37 L/min

FINAL: 212.2g

$I\text{-}CO_2$: 0.02% A: 1.98%

I-CO: -1 ppm A: -8 ppm

$I\text{-}O_2$: 21.0% A: 18.8%

D_{O_2}: 2.2%

NOTE: Lost some small pieces of sample during extraction

1/24/08 ST: 11:03AM → 11:21AM

5-B-1-650-2-40-2-001

Bookcase: .7x.7x45cm each (x2) Furnace: 650°C

Sample: 28.1g Primary: 20 L/min

S + Boat: 239.6g Secondary: 30 L/min

Final: 213.1g

$I\text{-}CO_2$: 0.03% A: 3.14%

I-CO: -1 ppm A: -5 ppm

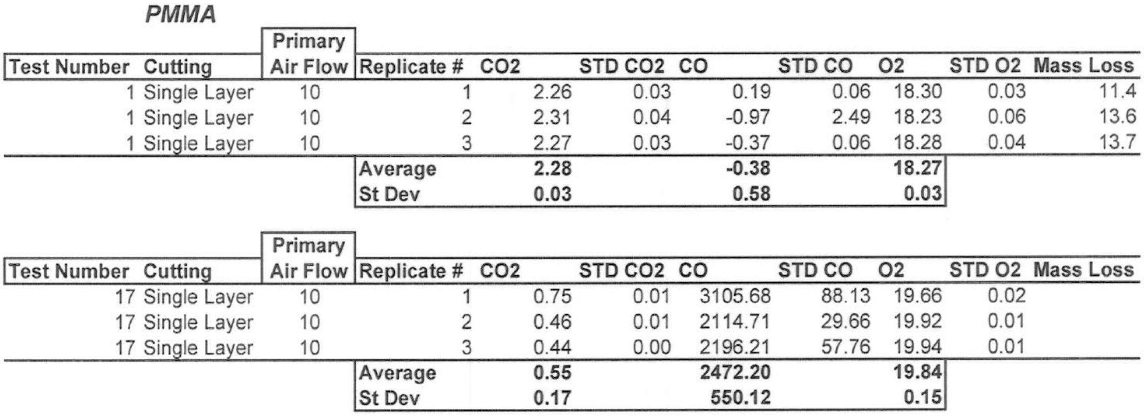
$I\text{-}O_2$: 21.0% A: 17.5%

D_{O_2}: 3.5%

NOTE: much more smoke given off (white)
lost some small pieces of sample during extraction
FTIR dips in middle then raises higher before plateau

Figure 11: Sample entry from laboratory notebook taken on January 24, 2008.

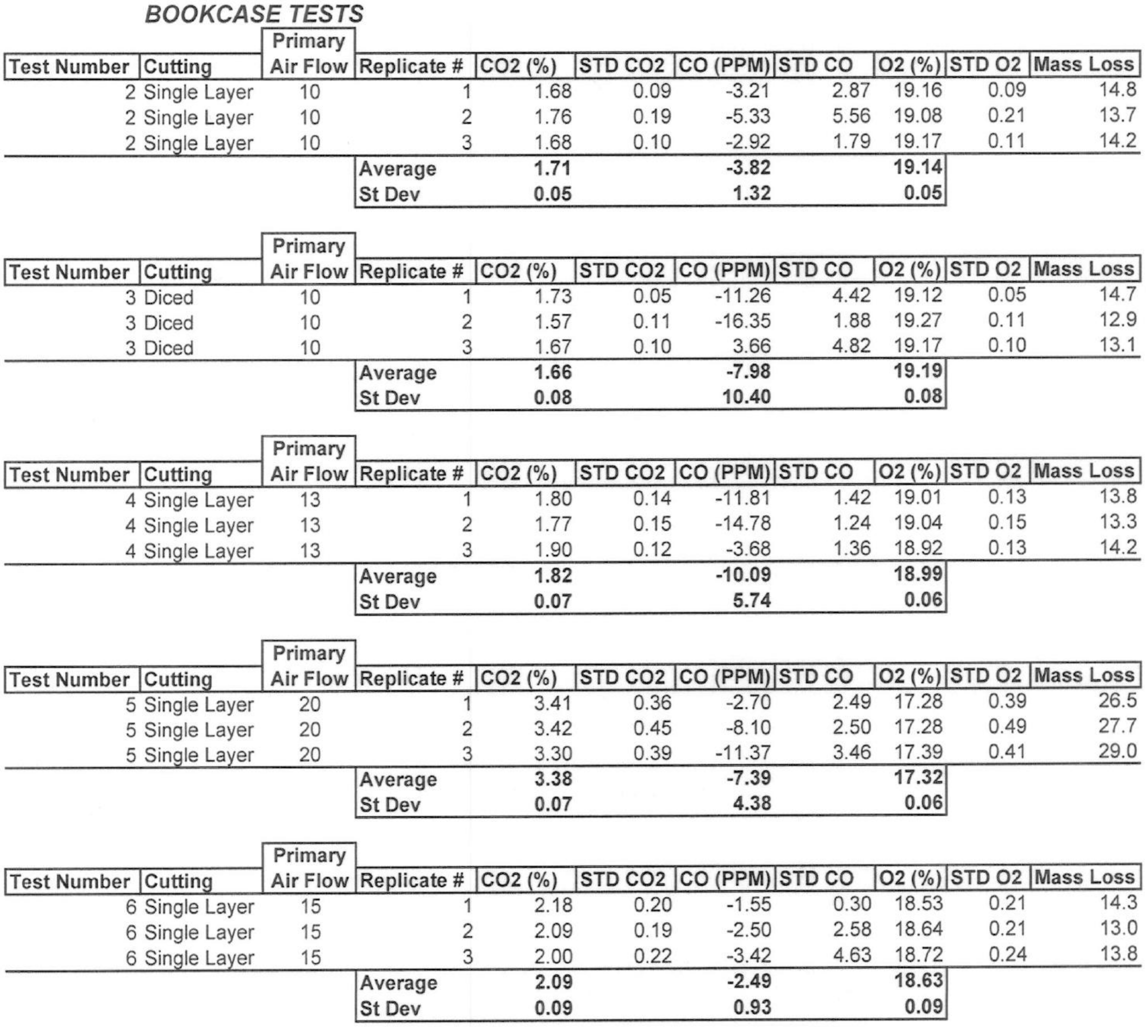
Appendix J: Steady State Average Concentrations for Each Run



PMMA

Test Number	Cutting	Primary Air Flow	Replicate #	CO2	STD CO2	CO	STD CO	O2	STD O2	Mass Loss
1	Single Layer	10	1	2.26	0.03	0.19	0.06	18.30	0.03	11.4
1	Single Layer	10	2	2.31	0.04	-0.97	2.49	18.23	0.06	13.6
1	Single Layer	10	3	2.27	0.03	-0.37	0.06	18.28	0.04	13.7
			Average	**2.28**		**-0.38**		**18.27**		
			St Dev	**0.03**		**0.58**		**0.03**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2	STD CO2	CO	STD CO	O2	STD O2	Mass Loss
17	Single Layer	10	1	0.75	0.01	3105.68	88.13	19.66	0.02	
17	Single Layer	10	2	0.46	0.01	2114.71	29.66	19.92	0.01	
17	Single Layer	10	3	0.44	0.00	2196.21	57.76	19.94	0.01	
			Average	**0.55**		**2472.20**		**19.84**		
			St Dev	**0.17**		**550.12**		**0.15**		



BOOKCASE TESTS

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
2	Single Layer	10	1	1.68	0.09	-3.21	2.87	19.16	0.09	14.8
2	Single Layer	10	2	1.76	0.19	-5.33	5.56	19.08	0.21	13.7
2	Single Layer	10	3	1.68	0.10	-2.92	1.79	19.17	0.11	14.2
			Average	**1.71**		**-3.82**		**19.14**		
			St Dev	**0.05**		**1.32**		**0.05**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
3	Diced	10	1	1.73	0.05	-11.26	4.42	19.12	0.05	14.7
3	Diced	10	2	1.57	0.11	-16.35	1.88	19.27	0.11	12.9
3	Diced	10	3	1.67	0.10	3.66	4.82	19.17	0.10	13.1
			Average	**1.66**		**-7.98**		**19.19**		
			St Dev	**0.08**		**10.40**		**0.08**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
4	Single Layer	13	1	1.80	0.14	-11.81	1.42	19.01	0.13	13.8
4	Single Layer	13	2	1.77	0.15	-14.78	1.24	19.04	0.15	13.3
4	Single Layer	13	3	1.90	0.12	-3.68	1.36	18.92	0.13	14.2
			Average	**1.82**		**-10.09**		**18.99**		
			St Dev	**0.07**		**5.74**		**0.06**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
5	Single Layer	20	1	3.41	0.36	-2.70	2.49	17.28	0.39	26.5
5	Single Layer	20	2	3.42	0.45	-8.10	2.50	17.28	0.49	27.7
5	Single Layer	20	3	3.30	0.39	-11.37	3.46	17.39	0.41	29.0
			Average	**3.38**		**-7.39**		**17.32**		
			St Dev	**0.07**		**4.38**		**0.06**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
6	Single Layer	15	1	2.18	0.20	-1.55	0.30	18.53	0.21	14.3
6	Single Layer	15	2	2.09	0.19	-2.50	2.58	18.64	0.21	13.0
6	Single Layer	15	3	2.00	0.22	-3.42	4.63	18.72	0.24	13.8
			Average	**2.09**		**-2.49**		**18.63**		
			St Dev	**0.09**		**0.93**		**0.09**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
18	Single Layer	2.2	1	0.57	0.01	1673.42	192.56	20.09	0.01	
18	Single Layer	2.2	2	0.34	0.01	794.03	170.06	20.33	0.04	
18	Single Layer	2.2	3	0.31	0.01	791.23	104.86	20.44	0.01	
			Average	**0.41**		**1086.23**		**20.29**		
			St Dev	**0.14**		**508.53**		**0.18**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
19	Single Layer	2.2	2	0.30	0.00	582.76	46.35	20.44	0.01	
19	Single Layer	2.2	3	0.33	0.01	810.88	99.91	20.40	0.01	
19	Single Layer	2.2	4	0.32	0.01	645.80	115.15	20.41	0.02	
			Average	**0.31**		**679.81**		**20.42**		
			St Dev	**0.02**		**117.80**		**0.02**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
20	Single Layer	3.5	1	1.09	0.00	71.80	94.54	19.66	0.00	13.4
20	Single Layer	3.5	2	1.05	0.01	669.15	241.50	19.68	0.01	14.6
20	Single Layer	3.5	3							14.2
			Average	**1.07**		**370.47**		**19.67**		
			St Dev	**0.03**		**422.39**		**0.01**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
20r	Single Layer	1.5	1	0.22	0.01	1186.11	61.49	20.49	0.01	
20r	Single Layer	1.5	2	0.22	0.01	621.77	197.30	20.51	0.01	
20r	Single Layer	1.5	3	0.25	0.01	1236.28	79.79	20.46	0.01	
			Average	**0.23**		**1014.72**		**20.49**		
			St Dev	**0.02**		**341.23**		**0.03**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
21	Single Layer	10.4	1	2.14	0.06	22.60	16.24	18.62	0.07	28.5
21	Single Layer	10.4	2	2.10	0.11	326.43	382.43	18.65	0.15	28.3
21	Single Layer	10.4	3	2.12	0.04	15.13	15.28	18.62	0.05	27.5
			Average	**2.12**		**121.39**		**18.63**		
			St Dev	**0.02**		**177.61**		**0.01**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
21r	Single Layer	4.3	1	0.65	0.01	2095.97	364.70	20.00	0.02	
21r	Single Layer	4.3	2	0.637	0.005	2151.634	166.374	20.010	0.009	
21r	Single Layer	4.3	3	0.57	0.01	1777.02	144.09	20.10	0.01	
			Average	**0.62**		**2008.21**		**20.04**		
			St Dev	**0.04**		**202.14**		**0.06**		

SOFA TESTS

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
7	Single Layer	10	1	1.27	0.24	320.63	62.45	19.30	0.26	10.1
7	Single Layer	10	2	1.24	0.15	253.87	59.22	19.34	0.15	10.3
7	Single Layer	10	3	1.03	0.47	470.78	173.07	19.57	0.55	9.4
			Average	**1.18**		**348.43**		**19.40**		
			St Dev	**0.13**		**111.09**		**0.15**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
9	Single Layer	13	1	0.83	0.19	202.48	38.33	19.91	0.22	10.0
9	Single Layer	13	2	0.87	0.32	289.41	56.89	19.85	0.36	10.6
9	Single Layer	13	3	0.89	0.17	424.52	46.27	19.81	0.19	10.6
			Average	**0.86**		**305.47**		**19.86**		
			St Dev	**0.03**		**111.89**		**0.05**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
10	Single Layer	5	4	0.34	0.12	124.50	68.57	20.32	0.13	
10	Single Layer	5	5	0.38	0.10	90.23	30.41	20.26	0.11	
10	Single Layer	5	6	0.44	0.12	157.34	85.95	20.20	0.14	
			Average	**0.38**		**124.02**		**20.26**		
			St Dev	**0.05**		**33.56**		**0.06**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
11	Single Layer	15	1	0.46	0.34	96.65	74.84	20.26	0.45	9.7
11	Single Layer	15	2	0.52	0.30	17.90	21.83	20.19	0.38	9.9
11	Single Layer	15	3	0.38	0.25	2.76	21.83	20.36	0.33	10.1
			Average	**0.46**		**39.11**		**20.27**		
			St Dev	**0.07**		**50.41**		**0.08**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
23	Single Layer	2.5	1	0.49	0.01	1895.54	130.76	20.24	0.01	9.8
23	Single Layer	2.5	2	0.48	0.01	2538.25	151.89	20.23	0.01	10.3
23	Single Layer	2.5	3	0.44	0.02	1629.46	227.02	20.33	0.02	8.5
			Average	**0.47**		**2021.09**		**20.27**		
			St Dev	**0.03**		**467.22**		**0.05**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
25	Single Layer	1.7	1	0.35	0.01	2302.65	131.78	20.39	0.01	10.2
25	Single Layer	1.7	2	0.33	0.01	2146.64	159.30	20.41	0.02	10.1
25	Single Layer	1.7	3	0.33	0.01	2158.06	330.38	20.19	0.02	9.6
			Average	**0.33**		**2202.45**		**20.33**		
			St Dev	**0.01**		**86.96**		**0.12**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
26	Single Layer	1	1a							
26	Single Layer	1	2a	0.09	0.00	575.99	40.85	20.59	0.00	
26	Single Layer	1	3a	0.09	0.01	461.39	119.12	20.58	0.01	
			Average	**0.09**		**518.69**		**20.59**		
			St Dev	**0.00**		**81.04**		**0.00**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
27	Single Layer	1.6	1	0.32	0.01	2679.62	138.17	20.17	0.01	9.0
27	Single Layer	1.6	2b	0.40	0.01	2743.41	198.18	20.02	0.01	
27	Single Layer	1.6	3	0.38	0.02	3053.25	158.63	19.99	0.01	
			Average	**0.37**		**2825.43**		**20.06**		
			St Dev	**0.04**		**199.87**		**0.10**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
100	Single Layer	10	1	1.15	0.33	298.66	99.91	19.46	0.38	7.2
100	Single Layer	10	2	0.95	0.33	231.19	67.39	19.69	0.39	7.1

100	Single Layer	10	3	0.86	0.23	142.80	49.39	19.79	0.25	7.0
			Average	**0.99**		**224.22**		**19.65**		
			St Dev	**0.15**		**78.16**		**0.17**		

CABLE TESTS

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
12	Single Layer	10	1	1.09	0.04	1022.95	53.53	19.37	0.06	10.7
12	Single Layer	10	2	1.03	0.05	943.72	79.81	19.45	0.06	7.2
12	Single Layer	10	3	1.03	0.08	1266.87	159.09	19.47	0.10	10.8
			Average	**1.05**		**1077.85**		**19.43**		
			St Dev	**0.03**		**168.43**		**0.05**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
13	Diced	10	1	1.27	0.09	1134.58	78.85	19.18	0.10	10.8
13	Diced	10	2	1.18	0.12	1283.05	302.81	19.25	0.17	11.0
13	Diced	10	3a	1.18	0.10	1159.61	157.64	19.26	0.13	10.9
			Average	**1.21**		**1192.41**		**19.23**		
			St Dev	**0.05**		**79.49**		**0.05**		

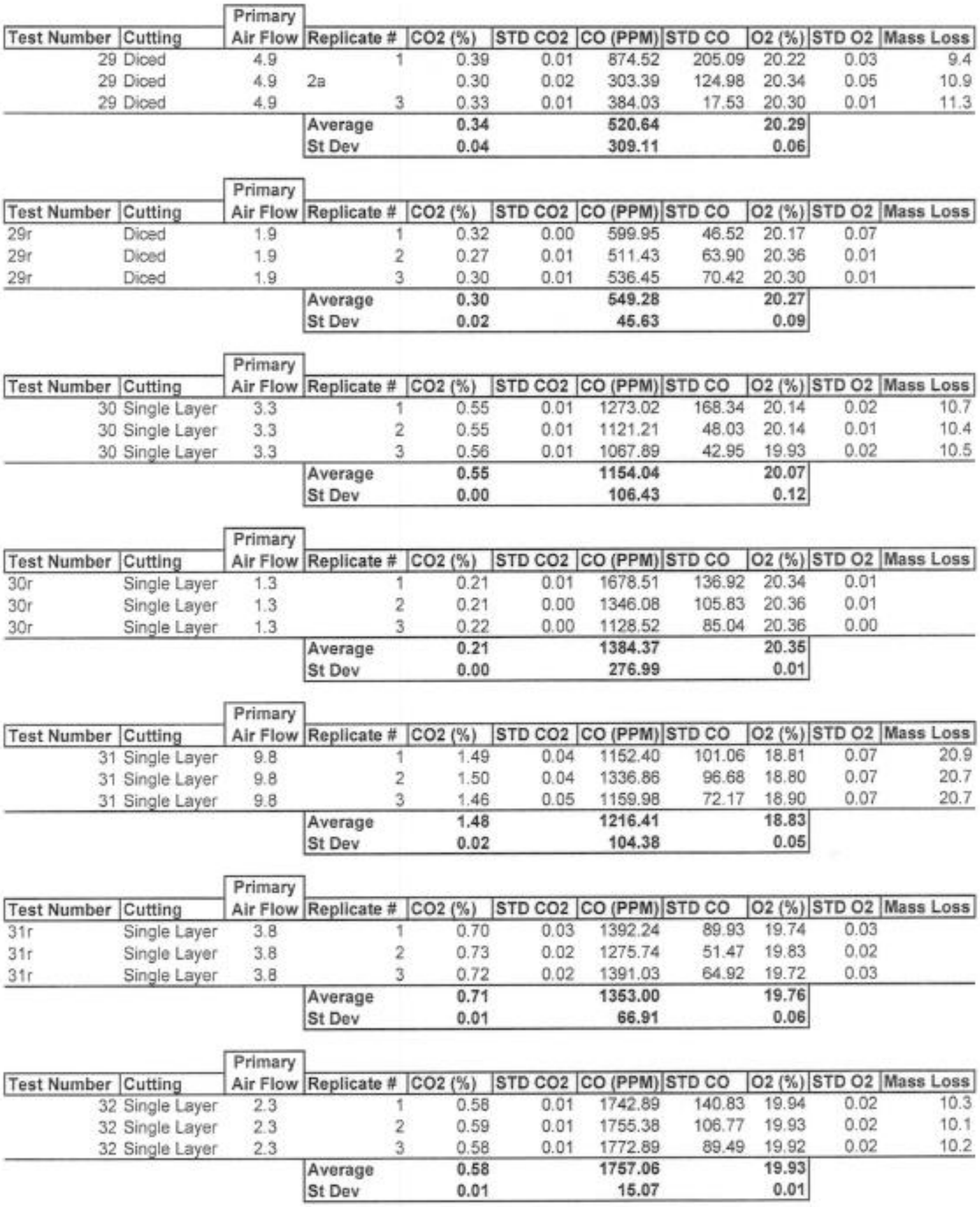
Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
14	Single Layer	13	2	1.04	0.05	958.59	104.82	19.42	0.06	10.7
14	Single Layer	13	3	1.00	0.03	948.79	104.61	19.48	0.04	10.4
14	Single Layer	13	4	1.03	0.07	898.85	39.35	19.42	0.09	10.6
			Average	**1.02**		**935.41**		**19.44**		
			St Dev	**0.02**		**32.04**		**0.03**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
15	Single Layer	20	1	1.88	0.20	1919.26	224.70	18.22	0.26	
15	Single Layer	20	2	1.99	0.08	1861.16	73.50	18.03	0.10	
15	Single Layer	20	3	2.00	0.14	2668.10	290.13	17.96	0.23	
			Average	**1.96**		**2149.50**		**18.07**		
			St Dev	**0.07**		**450.05**		**0.14**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
16	Single Layer	15	1	1.49	0.10	1327.30	106.09	18.86	0.14	10.0
16	Single Layer	15	2	1.53	0.08	1314.97	80.23	18.80	0.11	10.1
16	Single Layer	15	3	1.49	0.13	1253.79	78.09	18.85	0.17	10.1
			Average	**1.50**		**1298.69**		**18.83**		
			St Dev	**0.02**		**39.37**		**0.03**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
28	Single Layer	4.9	1	0.65	0.01	839.82	38.52	19.91	0.02	10.9
28	Single Layer	4.9	2	0.55	0.01	716.66	77.83	20.02	0.02	10.7
28	Single Layer	4.9	3	0.36	0.02	412.89	81.11	20.30	0.03	10.7
			Average	**0.52**		**656.45**		**20.08**		
			St Dev	**0.14**		**219.74**		**0.20**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
28r	Single Layer	1.9	2	0.34	0.00	663.58	18.94	20.16	0.01	
28r	Single Layer	1.9	3	0.32	0.00	618.86	18.63	20.19	0.01	
28r	Single Layer	1.9	4	0.28	0.00	527.32	15.59	20.23	0.01	
			Average	**0.31**		**603.25**		**20.20**		
			St Dev	**0.03**		**69.45**		**0.03**		



Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
29	Diced	4.9	1	0.39	0.01	874.52	205.09	20.22	0.03	9.4
29	Diced	4.9	2a	0.30	0.02	303.39	124.98	20.34	0.05	10.9
29	Diced	4.9	3	0.33	0.01	384.03	17.53	20.30	0.01	11.3
			Average	**0.34**		**520.64**		**20.29**		
			St Dev	**0.04**		**309.11**		**0.06**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
29r	Diced	1.9	1	0.32	0.00	599.95	46.52	20.17	0.07	
29r	Diced	1.9	2	0.27	0.01	511.43	63.90	20.36	0.01	
29r	Diced	1.9	3	0.30	0.01	536.45	70.42	20.30	0.01	
			Average	**0.30**		**549.28**		**20.27**		
			St Dev	**0.02**		**45.63**		**0.09**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
30	Single Layer	3.3	1	0.55	0.01	1273.02	168.34	20.14	0.02	10.7
30	Single Layer	3.3	2	0.55	0.01	1121.21	48.03	20.14	0.01	10.4
30	Single Layer	3.3	3	0.56	0.01	1067.89	42.95	19.93	0.02	10.5
			Average	**0.55**		**1154.04**		**20.07**		
			St Dev	**0.00**		**106.43**		**0.12**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
30r	Single Layer	1.3	1	0.21	0.01	1678.51	136.92	20.34	0.01	
30r	Single Layer	1.3	2	0.21	0.00	1346.08	105.83	20.36	0.01	
30r	Single Layer	1.3	3	0.22	0.00	1128.52	85.04	20.36	0.00	
			Average	**0.21**		**1384.37**		**20.35**		
			St Dev	**0.00**		**276.99**		**0.01**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
31	Single Layer	9.8	1	1.49	0.04	1152.40	101.06	18.81	0.07	20.9
31	Single Layer	9.8	2	1.50	0.04	1336.86	96.68	18.80	0.07	20.7
31	Single Layer	9.8	3	1.46	0.05	1159.98	72.17	18.90	0.07	20.7
			Average	**1.48**		**1216.41**		**18.83**		
			St Dev	**0.02**		**104.38**		**0.05**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
31r	Single Layer	3.8	1	0.70	0.03	1392.24	89.93	19.74	0.03	
31r	Single Layer	3.8	2	0.73	0.02	1275.74	51.47	19.83	0.02	
31r	Single Layer	3.8	3	0.72	0.02	1391.03	64.92	19.72	0.03	
			Average	**0.71**		**1353.00**		**19.76**		
			St Dev	**0.01**		**66.91**		**0.06**		

Test Number	Cutting	Primary Air Flow	Replicate #	CO2 (%)	STD CO2	CO (PPM)	STD CO	O2 (%)	STD O2	Mass Loss
32	Single Layer	2.3	1	0.58	0.01	1742.89	140.83	19.94	0.02	10.3
32	Single Layer	2.3	2	0.59	0.01	1755.38	106.77	19.93	0.02	10.1
32	Single Layer	2.3	3	0.58	0.01	1772.89	89.49	19.92	0.02	10.2
			Average	**0.58**		**1757.06**		**19.93**		
			St Dev	**0.01**		**15.07**		**0.01**		