THE EFFECT OF ORIENTATION ON THE IGNITION OF SOLIDS

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ABSTRACT

The Effect of Orientation on the Ignition of Solids

David Morrisset

The ignition of a solid is an inherently complex phenomenon influenced by heat and mass transport mechanisms that are, even to this day, not understood in entirety. In order to use ignition data in meaningful engineering application, significant simplifications have been made to the theory of ignition. The most common way to classify ignition is the use of material specific parameters such as such as ignition temperature ($T_{ig}$) and the critical heat flux for ignition (CHF). These parameters are determined through standardized testing of solid materials – however, the results of these tests are generally used in applications different from the environments in which these parameters were actually determined. Generally, ignition temperature and critical heat flux are used as material properties and are presented readily in sources such as the SFPE Handbook [1]. However, these parameters are not truly material properties; each are inherently affected by the environment in which they are tested. Ignition parameters are therefore system dependent, tied to the conditions in which the parameters are determined.

Previous work has demonstrated that ignition parameters (such as $T_{ig}$ or CHF) for the same material can vary depending on whether the sample is tested in a vertical or horizontal orientation [2]. While the results are clear, the implications this may have on the use of ignition data remains uncertain. This work outlines the fundamental theory of ignition as well as a review of studies related to orientation.

The aim of this study it to analyze the influence of sample orientation on ignition parameters. All experimental work in this study was conducted using cast black polymethyl methacrylate (PMMA or commonly referred to as acrylic). This study explores ignition parameters for PMMA in various orientations and develops a methodology through which orientation can be incorporated into existing ignition theory. An additional study was also conducted to explore the statistical significance of current flammability test methodologies. Ultimately, this study outlines the problem of the system dependency of ignition and provides commentary on the use of ignition data in engineering applications.

Keywords: Ignition, Flammability, Orientation, Cone Calorimeter, Fire Science, Statistical Significance.
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“I have been enormously privileged to, through my work, in being able to contribute to our understanding of the universe. But it would be an empty universe indeed if it were not for the people I love, and who love me. Without them, the wonder of it all would be lost to me” - Stephen Hawking [3]

The longer I find myself in the field of fire safety, the more I find myself profoundly privileged to be working in a discipline in which our work directly influences the ability to protect life and property from fire. I have been blessed to have supporting friends, family, and mentors through the process of this master’s degree.

My exposure to the world of fire started back at a career fair on campus in October 2016 where I met Garner Palenske who introduced me to the world of fire protection engineering – I had no idea then what an impact that conversation would have on my life. My progression from that moment to now would not be possible without the help of various individuals at Cal Poly. I would like to thank Dr. Hans Mayer who had a profound influence on me as an undergraduate Mechanical Engineer. Both Dr. Fred Mowrer and Dr. Chris Pascual have been great mentors through my time at Cal Poly and I will forever be grateful for their efforts to start and maintain the FPE program at Cal Poly. A large milestone of this experimental work was developing a fume hood to be used on campus at Cal Poly, so I would like to thank Alex Schnorr, Cody Parker, and Kevin Williams who were pivotal in fabricating the hood. I am proud to see Cal Poly now able to conduct bench-scale fire testing on campus. Most of all, I owe so much to Dr. Rick Emberley who has taken me under his wing and brought me into the world of fire research. I now consider him a dear friend and a lifelong mentor.

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This field of fire safety has so many questions left to be answered, and I look forward to a future of pursing these questions and I hope to encourage the next generation to seek these answers with the same degree of passion I now feel.
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Chapter 1
INTRODUCTION

“The growth of man’s knowledge of fire is followed from Paleolithic times to the present… No men
without fire have ever been found” – H.W. Emmons, 1981 [4]

When considering the fundamental principles of fire safety science, the process of ignition is
essential in understanding the initiation of a fire event and subsequent fire spread. The study of ignition is a
mature field in the realm of fire safety [2-5] and ignition data for various materials is widely available in
references used throughout the industry [1],[6]. Practicing engineers often use ignition data to characterize
materials in terms of their relative flammability and at times will even use such data to predict material
behavior in real fire scenarios. Currently the industry understanding of ignition is virtually limited to results
of highly regimented, standardized testing. As the profession of fire protection engineering progresses
towards (or at least attempts to progress towards) performance-based design solutions, the use of ignition
data to predict material behavior in real fire scenarios will increase substantially. Hurley and Rosenbaum
warn of certain disadvantages to performance-based design, such as the reliance on expert competency and
the uncertainty of input data to performance-based analysis [9]. For use in both prescriptive design and
performance-based design, the process of ignition must be understood outside the framework of
standardized practice to adequately use ignition data in an appropriate context.

Flaming combustion is truly a gas phase phenomenon, occurring in a region in space in which
gaseous fuel and oxidizer meet. The reaction occurs in a thin sheet where the fuel and oxidizer meet in a
stoichiometric ratio [10]. All states of matter must first transition to the gas phase before flaming; liquids
(such as pool fires) will vaporize before igniting, solids may sublimate into a gas state, other solids may
melt and then gasify – regardless of the process required to get to the gas phase, flaming cannot occur in
any other state of matter. Smoldering and such oxidative processes can occur in the solid phase, but the
scope of this work is limited to flaming combustion.
Due to a gas phase dependency, the behavior of flame is fluid. This is illustrated on both the small scale, as seen in a simple candle flame, or on a larger scale such as a flaming ceiling jet establishing in the boundary layer outside of a compartment fire, both seen in Figure 1. The fundamentals of all fire science can be captured in the simple image of a candle. An initially solid fuel transitions to gaseous fuel by first melting and being transported up the wick to be turned into a gas; then the gas burns in a laminar diffusion flame. The heat from the flame continues to melt the candle and sustain the flaming. These fundamentals are captured in Michael Faraday’s *Chemical History of a Candle* given as a series of Christmas lectures at the Royal Institute of Great Britain (1848) [11].

![Image of a candle and a flaming jet](image1.png)

**Figure 1.** Examples of flame shape and behavior (Left: candle flame, Right: flaming jet leaving a compartment fire).

In the field of fire safety, practitioners are generally not concerned with candle flames. Perhaps they should, however – the same fundamental processes that occur with the simple candle flame also dictate the behavior of compartment-scale fire dynamics. The gas phase dependency of flaming combustion can be seen in Figure 1 as the flames out of a compartment establish on the boundary layer of the fluid leaving the compartment. Understanding this fluid behavior of flaming combustion is also critical to application of ignition data to predict material behavior in real fire scenarios. Fluid behavior around the surface of a material can greatly influence the ignition behavior of that material. This has been illustrated in the past particularly in the context of forced flows delaying the occurrence of ignition [6], [12], [13]. Therefore, there is a clear dependence on the system in which a material is burned when predicting ignition behavior.
Currently, ignition data is widely presented only in the context of material dependence. Information on ignition can be found in the back of a reference manual such as the SFPE Handbook [1]; an example of such a table can be seen in Figure 2. Engineers are taught to look for this information in such references as they would be taught to find material properties in the back of a fluid mechanics textbook – this creates a sense within the engineering discipline that the ignition “parameters” (e.g. Ignition temperature, Critical Heat Flux, etc.) presented in these resources can be taken as independent material properties.

Figure 2. An example of the ignition data that can be found in the back of a reference manual, in this case the SFPE Handbook [1]. Values seen for the critical heat flux (CHF) and the thermal response parameter (TRP).

1.1 Statement of Problem

Investigation into ignition literature reveals that other aspects of the ignition system (e.g. oxygen concentration, ambient pressure, flow field surrounding the material, material orientation, etc.) can greatly influence the behavior of ignition. A deeper understanding of the fundamental theory behind ignition illustrates that ignition is inherently a system dependent phenomenon. In other words, ignition data is “intimately related to the methodology used to extract it” [7].

Of all the system influences on the ignition of a material, the effect of sample orientation has not been adequately investigated by the field of fire safety science. This is particularly an area of interest in that standardized methodologies for determining ignition characteristics are generally limited to the horizontal
orientation (and in limited cases, the vertical orientation) – however the built environment is not limited to a single orientation. Currently ignition is understood almost exclusively in these two orientations and any application to other such arrangements of materials cannot be adequately assessed. Figure 2 illustrates that the provided information on ignition makes no mention to the orientation of the sample tested – one must then understand the standard in which it was tested to know that all of the values presented there are only in the horizontal orientation (in the case of the SFPE Handbook). From experience in the field of fire protection engineering, one can quickly see the instances in which ignition data is used, often being applied to all orientations.

If the future of the fire protection engineering profession is in fact moving to the use of performance-based design, then such a limited understanding of the effect of orientation on ignition will hinder engineers from understanding the true behavior of materials in a real fire. This limited understanding can also lead engineers to misunderstand the results of standardized testing, and make them unaware of the limitations of such results even in the context of prescriptive design.

1.2 Outline and Objectives

The objective of this work is to facilitate the following:

• To illustrate that the process of ignition is system dependent; as such, ignition parameters used in analysis are in fact system parameters not material properties
• To outline how the fundamental physics and comprehensive theories of solid ignition
• To give a brief history of solid ignition testing and how old testing procedures still influence material characterization
• To describe the standardized practices through which ignition is classified today and the limited orientations in which standardized procedures operate
• To quantify the influence of orientation on the ignition of solid materials and describe what implications this variation has to fire protection engineering
• To suggest ways to adequately capture the orientation dependency of ignition and to incorporate this dependency into how ignition parameters are presented
“The fire codes of the day specified various so called flammability tests as though flammability were a material property rather than a system property” – H.W. Emmons, 1984 [14]

The fire hazards within the built environment are generally dictated by the combustion of solids. While the process of combustion in the gas phase is relatively simple to characterize, the process by which solid fuel is degraded into said gaseous fuel is much more complex; Figure 3 illustrates the dominate processes of a solid being heated by an external heat flux. An accurate characterization of the flammability of solids is an essential part of designing for fire safety. If one is to look into resources such as the SFPE Handbook [1], or even the requirements of various building codes or NFPA standards, the flammability of solids is generally characterized by characteristics in the solid fuel (through the use of parameters such as Ignition Temperature, $T_{ig}$, or the Critical Heat Flux, CHF). Yet fundamentally, flaming combustion is dictated by phenomenon in the gas phase – which begs the question: is this characterization from CHF and $T_{ig}$ good enough? Or is there information that is lost when only looking at solid phase parameters for ignition? In order to investigate the current structure of classification, the understanding the process by which a solid transitions to the gas phase is crucial.

Figure 3. An illustration depicting the various processes occurring within a solid as it produces flammable pyrolzate, originally produced by Professor J.L. Torero in the SFPE Handbook [7].
2.1 Ignition of Solids

A solid can transition to a gas in a variety of ways. Solids can melt and then evaporate, solids can sublime, or solids can undergo a series of chemical and physical degradations known as pyrolysis. Most solids that are relevant in the study of fire safety science undergo pyrolysis to achieve a flammable mixture required for flaming. It is important to note that this discussion is limited to surface burning occurring from an external heat source and not spontaneous combustion within a solid or porous media.

Pyrolysis of a solid is required prior to ignition. When a solid is heated sufficiently, there will exist a region in-depth which will be raised to a temperature at which pyrolysis will occur. Pyrolysis can be described as a multi-stepped chemical process in which a solid material may undergo hundreds of steps in the degradation process. Furthermore, pyrolysis is strongly temperature dependent, and the process can also follow distinctly different chemical pathways depending on the heating conditions of the pyrolysis zone [7]. The rate at which pyrolysis gases are produced can be represented with the following:

\[ m''_p(0, t) = \int_0^L \chi(x, t) \left( Y_{F,s}(x, t) \sum_{i=1}^{N} \left[ A_i Y_o^{n_i}(x, t) Y_s^{n_i}(x, t) e^{-E_i/RT(x,t)} \right] \right) dx \]  

Equation 1

Where:

- \( m''_p \) – pyrolysis rate at the surface per unit area
- \( L \) – depth of the pyrolysis zone
- \( \chi \) – permeability of the solid between the pyrolysis zone and the heated surface
- \( Y_{F,s} \) – residual fuel that does not react within the solid
- \( Y_o \) – local oxygen concentration
- \( Y_s \) – local fuel concentration
- \( N \) – number of reactions in the pyrolysis process
- \( A_i \) – pre-exponential factor
- \( m_i, n_i \) – kinetics constants
- \( E_i \) – activation energy
- \( T \) – local temperature
- \( R \) – universal ideal gas constant

The various terms within Equation 1 are nontrivial to define – particularly the residual fuel concentration, local fuel concentrations, and permeability terms. These terms are further complicated when considering materials like timber that have porosity and a cellulosic structure to facilitate mass transfer through the material. Ultimately, pyrolysis can be modeled when combined or verified with experimental results; various pyrolysis models exist and are used frequently [12-13]. Modelling this complex process for every engineering application is, however, not practical. In order to do meaningful work with predicting
solid phase ignition, various ignition parameters were created to serve as a surrogate for pyrolysis and allow for solids to be characterized without modeling the minutiae of the degradation process. The process of pyrolysis is emphasized here, as this process is essential in understanding the benefits and limitations of defined ignition parameters in the solid phase.

As previously stated, pyrolysis is strongly temperature dependent. Most solids can be represented with a high activation energy to initiate pyrolysis [7]. In other words, one can generally assume that the pyrolysis process accelerates rapidly at a given temperature for a solid, as illustrated in Figure 4.

![Figure 4. Thermogravimetric Analysis data for PMMA which illustrates the rate of pyrolysis as a function of temperature [17]. Note at a given temperature the pyrolysis rate accelerates rapidly, in this case occurring at approximately 350-400 °C.]

A solid can undergo pyrolysis without actually initiating a combustion reaction. For example, flaming combustion requires sufficient oxygen while pyrolysis can occur in a non-oxidative environment such as nitrogen [18]. Pyrolysis does not indicate flaming combustion – the onset of flaming is determined by ignition. Initially the levels of pyrolyzate are too low (i.e. the mixture is too lean) to result in any ignition. As the material continues to pyrolyze, the pyrolyzate will eventually be within the flammable limits and allow for ignition to occur. Ignition occurs in one of two ways 1) piloted ignition, by which the combustion reaction is initiated by a sufficiently large source of energy such as a spark or flame, and 2) autoignition where the localized energy within the pyrolysis gases reach a level high enough to initiate combustion.
Entire volumes have been dedicated to the description of the mechanisms behind solid ignition; the description provided here is intended to cover enough of the theory to establish background for the analysis used through this project. For a much more detailed description of solid ignition, see Torero [7], Drysdale [2], or Quintiere [5] to list a few comprehensive sources.

Before presenting the governing equations through which solid ignition can be characterized, the following parameters and terms that are paramount to ignition will be first defined. Each will be defined from the perspective of how experimental conditions influence these parameters – particularly the effect of sample orientation.

2.1.1 Time to Ignition

A solid exposed to a sufficiently high irradiance will undergo pyrolysis. Ignition can then occur through either a pilot source or auto-ignition at a given time, $t_{ig}$ after exposure to external heat. The time to ignition, or ignition delay time, may be a simple quantity to define for a given experimental set-up; however, the term carries great significance. This measurement is the cornerstone of ignition experimentation and is arguably the most valuable piece of information in processing ignition data. The ignition delay time is a quantity that can be used to describe a variety of heating conditions. A time component to ignition describes the transience that is unavoidable in fire science. Generally, constant incident heat exposures are used to determine ignition characteristics. Ignition time delay can be used to link the thermal exposure from time variant sources, such as a real fire exposure, to the point of ignition of a solid. These data are important in characterizing the phenomenon of ignition but cannot be analyzed outside the context in which they were gathered.

The ignition delay time is sum of other characteristic times related to the phenomenon of ignition, as described by Long et. at as [19],

$$t_{ig} = t_p + t_m + t_i$$  \hspace{1cm} \text{Equation 2}

Where each term represents a different portion of the time leading up to ignition. Exposure to sufficient thermal radiation leads to pyrolysis in the solid. Based upon the thermal exposure, there is a time
at which pyrolysis will “begin”. Refer back to Figure 4 and note that the process of pyrolysis begins at a certain temperature (depending on the material) but then rapidly accelerates at what is referred to as the pyrolysis temperature, $T_p$. The pyrolysis time, $t_p$, is therefore defined as the time it takes to raise the solid from ambient to the pyrolysis temperature for a given thermal exposure. Once pyrolysis occurs, the gases then mix with the ambient oxygen in the air until a mixture exists in within the flammable limits. The time required for the pyrolysis gasses to sufficiently mix is known as the mixing time, $t_m$. The presence of a flammable mixture does not ensure ignition – the time between the mixing time and the actual initiation of flaming combustion is known as the induction time, $t_i$. In comparison to the pyrolysis time, the mixing time is generally assumed to be negligible. Providing a pilot source minimizes the induction time as well. The general assumption is the ignition delay time is equal to the pyrolysis time, or $t_{ig} = t_p$; this relationship has been shown to not be exact as, illustrated in Figure 5, but is assumed in order to use conventional ignition theory.

![Figure 5. The pyrolysis time compared to the experientially determined time to ignition; reproduced from the SFPE Handbook [7].](image)

Such a simplifying assumption may hold true for a controlled method of testing; however, variation in flow behavior around a sample may result in longer mixing times and auto-ignition conditions may result in longer induction times. The sensitivity of these individual terms will be further investigated, particularly in the context of orientation influence.
2.1.2 Critical Heat Flux for Ignition (CHF)

Assuming that an external radiant heat source is exposed to a solid to cause pyrolysis, there exists a minimum heat flux required to produce sufficient pyrolysis gasses to sustain ignition. Values for a material’s CHF is presented widely in a variety of sources and is widely accepted by the engineering community to represent a condition which can be applied in real fire scenarios. Using a critical heat flux for a given material is commonly found in engineering practice either within the framework of prescriptive requirements or for used in performance-based design – therefore, understanding the CHF is imperative for proper application of such data to engineering analysis. The critical heat flux for ignition is another term that seems trivial to define, but upon further investigation there is some complexity buried into it. Janssens describes it as “the critical irradiance below which piloted ignition under practical conditions no longer occurs” [20]. When described as such, the CHF seems to be a very simple and practical parameter. There essentially exists some threshold for external heat flux which defines a binary result of ignition or no ignition.

In an earlier paper, Janssens differentiates between the Critical Heat Flux for Ignition and the Minimum Heat Flux for ignition [21]; the MHF is defined as the heat flux level below which ignition cannot occur under practical conditions, while the CHF is theoretical threshold for ignition that is derived from correlating experimental data. In other words, the CHF is the theoretical boundary between the ignition and no ignition conditions which can never truly be attained, while the MHF is the best approximation of this threshold based upon experimental data. The theory through which a MHF is extrapolated will be discussed in detail later in this section. Past studies have illustrated the difference between the theoretical MHF and the experimentally determined CHF; Delichatsios suggested that the relationship between the minimum and critical heat flux can be approximated as \( \text{CHF} = 0.58 \times \text{MHF} \) [22]. However, the results detailed by Babrauskas [6] indicate that the ratio between CHF and MHF is not constant across all materials – this is illustrated in Table 1. In most applications today, the CHF reported in references actually refers to what Janssens defined as the MHF (i.e. the limit for ignition in practical conditions). This difference between the two concepts is not generally articulated in sources that produce ignition data, which can be misleading to the user. For the remainder of this work, the critical heat flux for
ignition will be defined as the practical limit for ignition within an experimental environment – as this is the concept that most engineers/scientists associate with the term CHF.

Table 1. The relationship between critical and minimum heat fluxes for a variety of materials [6].

<table>
<thead>
<tr>
<th>Material</th>
<th>MHF [kW/m²]</th>
<th>CHF [kW/m²]</th>
<th>CHF/MHF Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU</td>
<td>13</td>
<td>3.08</td>
<td>0.24</td>
</tr>
<tr>
<td>PMMA</td>
<td>8</td>
<td>3.33</td>
<td>0.42</td>
</tr>
<tr>
<td>WP</td>
<td>10</td>
<td>3.36</td>
<td>0.42</td>
</tr>
<tr>
<td>LD</td>
<td>8</td>
<td>5.44</td>
<td>0.68</td>
</tr>
<tr>
<td>PE</td>
<td>17.5</td>
<td>8.7</td>
<td>0.50</td>
</tr>
<tr>
<td>POM</td>
<td>11.5</td>
<td>2.2</td>
<td>0.19</td>
</tr>
<tr>
<td>PP</td>
<td>11.3</td>
<td>1.2</td>
<td>0.11</td>
</tr>
</tbody>
</table>

The critical heat flux is built on the idea that there exists a point at which a heated sample will reach thermal-equilibrium between the net energy into the sample and the heat losses. Therefore, the sample cannot produce a sufficient amount of pyrolysis gases for ignition. It is important to note that the concept of the CHF only defined for a constant irradiation. Using a CHF assumes that ignition is “path independent” with respect to time – in other words, whether a sample is exposed to a constant heat flux or a transient heat flux (as in the case of a real fire), the critical threshold for ignition will remain at the determined CHF. This assumption may not hold true for charring materials like timber. If a given incident heat flux acting on a charring solid was to ramp up, the solid would develop a char layer which may lead to varied results compared to the same sample exposed to a constant heat flux. The same critical threshold for ignition determined from a constant heat flux may not hold true in the case where a sample is ramped up to that same heat flux even in materials that do not char. A transient heat flux will result in different surface temperature-time histories for the solid which therefore influences the losses from the surface, effectively altering the process of pyrolysis and ultimately ignition. Current research suggests that the net energy that contributes to the degradation of a sample may yield a better ignition criterion then a critical external heat flux [23], [24]. Ultimately the concept of the CHF is useful in the classification of the ignitability of a solid, it is important however to remember that this concept is tied to a constant external irradiance which is not what a material will experience in a real fire.

Defining a CHF is limited to the experimental means by which it was determined – regardless of a transient or constant external heat flux. Other aspects of the experimental set-up can also greatly influence
the CHF (e.g. heating element, ambient conditions, orientation, etc.) – the present study will focus on the influence of orientation. Previous studies suggest that the critical heat flux varies in different orientations for the same material [25], however little has been done to account for this in existing ignition theory.

2.1.3 Ignition Temperature

The ignition temperature is a widely used ignition parameter in the field of fire safety. In principle, the ignition temperature represents a theoretical surface temperature at which ignition is assumed to occur. A more accurate perspective, however, is to view the ignition temperature as a threshold to generate a sufficient amount of pyrolysis gases to sustain ignition. When considering the process of pyrolysis seen in Figure 4, the concept of an ignition temperature is sound so long as pyrolysis can be assumed to “activate” at a given temperature (i.e. the pyrolysis temperature). This parameter can be determined in one of two ways: 1) calculated using the critical heat flux for ignition and a total heat transfer coefficient for the experimental set up, or 2) through direct measurements of the surface temperature during the experiment. For a given experimental set up (i.e. orientation and ambient conditions) the range of ±100°C has been historically accepted as the expected level of consistency between ignition temperatures [6]. Examples of ignition temperatures for various materials can be seen in Table 2.

Table 2. Example Ignition Temperatures presented in literature. Reproduced from Babrauskas [6], apart from the “woods” category taken from Drysdale [2].

<table>
<thead>
<tr>
<th>Category of Solid</th>
<th>Ignition Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Piloted</td>
</tr>
<tr>
<td>Thermoplastics</td>
<td>369 ± 73</td>
</tr>
<tr>
<td>Thermosetting Plastics</td>
<td>441 ± 100</td>
</tr>
<tr>
<td>Elastomers</td>
<td>318 ± 42</td>
</tr>
<tr>
<td>Halogenated Plastics</td>
<td>382 ± 70</td>
</tr>
<tr>
<td>“Woods”</td>
<td>350</td>
</tr>
</tbody>
</table>

As previously discussed in the time to ignition section (Section 2.1.1), a key assumption in the ignition temperature is that the mixing time and induction time are minimized such that the time to ignition is approximately the time to pyrolysis (i.e. the ignition temperature can be approximated as the pyrolysis temperature). This is achieved by testing materials in a well-controlled environment and with a pilot source to minimize the induction time. The concept of an autoignition temperature can be misleading as the
concept of an ignition temperature is truly only valid for the case of piloted ignition – the limitations of this will be discussed further in Section 2.5.

While the definition of an ignition temperature is useful in the context of establishing the relative flammability of a material, this concept is purely defined in the solid phase. Flaming combustion, however, is a gas phase phenomenon – the occurrence of ignition cannot be confidently tied to a given surface temperature in all scenarios. Factors such as flow over the sample and sample orientation can greatly influence the gas phase behavior above the sample, and therefore influence ignition. Ignition data presented in literature often reflect results from highly regimented and controlled standardized tests and must be considered from that perspective.

2.1.4 Mass Loss Rate at Ignition

Another criterion for ignition can be defined by a threshold burning rate sufficient to sustain ignition. While the most common criteria for ignition remains the solid phase critical heat flux and ignition temperature, using a threshold related to the burning rate (and consequently the pyrolysis rate) ties this criterion back to the gas phase where flaming combustion actually occurs. It is important to note that experiments record the mass loss rate using a load cell; however, the mass loss rate and the burning rate are not synonymous [5]. The mass loss rate includes moisture loss, char fall off, bubbling, and other sporadic behavior that is not associated with the rate of pyrolysis. As such, mass loss rate can only be used as a representation of the burning rate. Babrauskas presents tabulated data for the mass loss rate at ignition for various materials [6].

The criteria of mass loss rate at ignition is not, however, independent of flow conditions surrounding the sample either. For example, Cordova and Fernanadez-Pello illustrated that imposing a forced flow of 2.5 m/s over PMMA exposed to 35 kW/m² in the OSU Apparatus doubled the required mass flux at ignition compared to a sample without forced flow [13].

The benefit to using mass loss rate as a criterion is the ability to link ignition back to the gas phase. Popular methodologies for doing so incorporate “fire point theory” developed by Rasbash et al. [26] or the concept of Spalding’s B-Number [27]. Such models can be used to tie the mass loss rate of a burning
material to the point of possible ignition. Rich et al. used this theory to model the piloted ignition of PMMA to predict the influence of free stream oxygen concentration [12].

2.1.5 Thermal Inertia

Common ignition models (which will be discussed later in this section) generally incorporate a common group of material properties: thermal conductivity \(k\), density \(\rho\), and specific heat capacity \(c_p\) – together these properties are lumped to create a parameter known as the Thermal Inertia \((k\rho c_p)\). The thermal inertia can give a coarse understanding of generic material behavior; for example, the surface temperature of materials with low thermal inertia (such as polyurethane foam) will rise quickly when heated compared to materials with high thermal inertia (e.g. steel or oak) [2].

Thermal inertia is only comprised of fundamental material properties, so in theory this parameter should display a relative degree of similarity between experimental results. However, the underlying assumptions in ignition theory result in a perceived variation between results taken from experiments when compared to directly multiplying the three fundamental properties together – sometimes overestimating thermal inertia by a factor of four or more [28]. Mowrer elaborates stating that the thermal inertia determined experimentally can be viewed as “effective thermal properties” that are useful for comparative purposes but do not accurately model a solid’s behavior accounting for all the relevant boundary conditions [29]. Thermal inertia will be referenced throughout this work as a way to account for material dependency within the context of ignition theory, but the author acknowledges that experimental results will carry with it the uncertainty and assumptions of ignition theory.

2.2 Defining Ignition in the Solid Phase

Historically, ignition theory is primarily defined in the solid phase in order to develop useful models for engineering applications. Focusing on ignition in the gas phase could potentially allow researchers to couple the system dependency of ignition with theory; however, creating a meaningful model to define ignition in the gas phase is generally not practical for use in engineering applications.

While defining ignition in the solid phase does not lend insight directly to system dependency, almost all models for predicting ignition are defined by ignoring the fluid boundary conditions and the fire
chemistry, and instead focus only on the heat transfer of the reacting solid. In order to discuss existing ignition theory, a generic energy balance over a heated solid will be performed.

![Energy Balance Diagram]

Figure 6. The energy balance of a solid being heated by an external radiant heat flux. The shaded region illustrates the region within the solid undergoing pyrolysis.

As a solid is heated by an external radiant heat flux, \( \dot{q}_e \), the energy entering the solid is balanced by pyrolyzing solid material, \( \Delta H_p \dot{m}'_f \), heat losses from the surface through convection and radiation, \( \dot{q}_{\text{loss}} \), energy storage in the material, \( \frac{\partial \dot{q}''}{\partial t} \), and further conduction to virgin material, \( \dot{q}_{\text{cond}} \). The energy balance is illustrated in Figure 6, and outlined further in Equation 3.

\[
\dot{q}_e = \Delta H_p \dot{m}'_f + \dot{q}_{\text{loss}} + \frac{\partial \dot{q}''}{\partial t} - \dot{q}_{\text{cond}}
\]  

Equation 3

Through various assumptions and further simplifications, the following theories for solid ignition were developed from the simple energy balance seen above.

2.3 Comprehensive Theories of Ignition

Multiple comprehensive theories of ignition have been proposed over the years. However, the process of determining comprehensive ignition theory from first principles is complex to say the least; the number of parameters and inputs required to model the process of ignition is material and situationally dependent (i.e. depending on how it is heated). The most practical models that have been developed over the years involve a one-dimensional consideration of heat transfer from a single radiant heat source (see Equation 3). Most models also ignore the combustion chemistry and focus only on heat transfer.
One of the most important factors in considering a theoretical model for ignition is considering whether or not a solid can be treated as thermally thick or thermally thin. Defining a material as thermally thick or thin is tied to the Biot number which considers a dimensionless balance of the convective loses from a material to the ability to conduct heat in depth [30]. In the context of ignition, solids are also considered thick if they can be assumed to be semi-infinite for the time scales required for ignition. When exposed to a heat source at the front face, a solid will be semi-infinite so long as the thermal wave does not penetrate through the back face (i.e. the back face conditions are virtually unaffected by the heating of the front face). Most solid ignition theory is defined for thermally thick solids – as such, most of the following discussion will be limited to thick solids.

Lawson and Simms developed the first one-dimensional model that considers a solid heated by an external radiant heat flux that could be properly validated by experimental data [31]. This model incorporated an energy balance between the external heat flux acting on a sample and the net losses from the surface of the sample – the difference between the two was represented as stored energy that went towards increasing the material temperature to a theoretical ignition temperature. In order to develop an analytical model, the heat losses from the surface were linearized (illustrated in Equation 4). This simplification removes the fourth order dependency of the radiative losses on the sample surface temperature.

\[
h_T = h_c + h_r = h_c + \varepsilon \sigma (T_s^4 + T_\infty^4) (T_s + T_\infty)
\]

Equation 4

With the incorporation of a total heat transfer coefficient, a simple model can be expressed using Equation 5. This model incorporates a variety of assumptions such as the solid being inert until ignition occurs and that ignition occurs once the solid reaches a theoretical ignition temperature at the surface. The simplifications and assumptions built into the following derivation are laid out in detail by Torero [7] and Babrauskas [6]. The partial differential equation can then be solved for the solution seen in Equation 6.

\[
-k \frac{\partial T}{\partial x} = q_e'' - h_T (T_{ig} - T_o)
\]

Equation 5
\[ T_{ig} - T_\infty = \frac{q''_{ig}}{h_T} \left[ 1 - \exp(\tau) \text{erfc}(\sqrt{\tau}) \right] \quad \text{Equation 6} \]

Where \( \tau = h^2_T t_{ig} \alpha_s/kpc \) (often times assuming \( \alpha = 1 \)) which represents a nondimensional ignition time. This nondimensional ignition time expresses a ratio of the actual ignition time to a characteristic ignition time (\( t_c \)). When considering analytical solutions to Equation 5, the difficulty lies in dealing with the \( \tau \) term. In order to simplify the solution, ignition is generalized into two categories – long ignition times and short ignition times. Generalizing all ignition to these two conditions allows the user to assume that \( \tau \) either approaches zero or infinity.

For high heat fluxes, where the ignition delay time is appreciably less than the characteristic time (\( 1/\tau \)), a solution (Equation 7 or Equation 8) can be obtained from the first order Taylor Series Expansion for “short times” (assuming \( t_{ig}/t_c \rightarrow 0 \)):

\[ t_{ig} = \frac{\pi}{4} \frac{k_S \rho_S c_S (T_{ig} - T_\infty)^2}{q''_{ig}} \quad \text{Equation 7} \]

\[ \frac{1}{\sqrt{t_{ig}}} = \frac{2}{\sqrt{\pi k_S \rho_S c_S}} \frac{q''_{ig}}{q''_{ex}(T_{ig} - T_\infty)} \quad \text{Equation 8} \]

Results from ignition testing are generally presented in the form of \( t_{ig}^{-0.5} \) vs \( q''_{ex} \) so that the data ideally collapses onto a linear curve fit for the values which the short solution is valid. On the other hand, for low heat flux scenarios where the ignition delay time is much longer than the characteristic time (ie. \( t_{ig}/t_c \rightarrow \infty \)) the first order Taylor Series Expansion results for “long times” can be expressed as Equation 9.

\[ \frac{1}{\sqrt{t_{ig}}} = \frac{\sqrt{\pi h_T}}{\sqrt{k_S \rho_S c_S}} \left[ 1 - \frac{h_T (T_{ig} - T_\infty)}{q''_{ig}} \right] \quad \text{Equation 9} \]

Note that the “long time” solution incorporates the ambient temperature (\( T_\infty \)), opposed to the initial surface temperature (\( T_o \)). Assuming that the sample is initially at thermal-equilibrium with the environment prior to the start of the experiment, these two temperatures can be used interchangeably. The critical heat flux can also be related back to the ignition temperature through the following relationship:
\[
CHF = h_T (T_{ig} - T_o)
\]

Equation 10

Therefore, determining the ignition temperature is elementary if the critical heat flux and total heat transfer coefficients are well defined. While defining ignition in the solid state facilitates the ability to classify materials and assemblies in a meaningful way, the assumptions required to define these parameters do not account for various system components of the test such as orientation. Interpretation of ignition temperature and critical heat flux as pure material properties is a common mistake. In reality, both parameters are a function of the gas phase behavior which can be influenced by various aspects of the testing environment (e.g. orientation, extraction flow, ambient conditions, etc). Of course, the lack of a system component in ignition parameters does not negate its worth in application to design; however, it is critical to further classify such aspects that affect ignition.

Given the existing framework for ignition, the effect of orientation can be incorporated through quantifying the variation in total heat transfer coefficient, \(h_T\), as the sample orientation changes. Once \(h_T\), is well defined for a given testing condition, then ignition temperature can also be determined from the experimental critical heat flux.

The theory described so far is limited to solids that are sufficiently thick, or thermally thick. In order to evaluate a thermally thin solution, Equation 5 must be rewritten to incorporate a uniform thermal gradient through the material. Equation 11 replaces the conduction term with a storage term within the thin sample, which can be explicitly solved for Equation 12.

\[
2L \rho C \frac{\partial \theta}{\partial t} = q''_d - h_T (T_{ig} - T_o)
\]

Equation 11

\[
t_{ig} = \frac{2L \rho C}{h_T} \ln \left[ \frac{q''_d}{q''_d - h_T(T_{ig} - T_o)} \right]
\]

Equation 12

If one is to assume that the external radiation dominates over the convective heat transfer to the surface (i.e. \(h_T(T_{ig} - T_o) / q''_d \ll 1\)), then the solution for a thin solid can be expressed as Equation 13.
\[
t_{ig} = \frac{2L_p c}{q_e} (T_{ig} - T_o)
\]

**Equation 13**

### 2.4 Methodologies for Processing Ignition Data

For most practical applications, the thermally thick solutions to ignition theory are used. Other interpretations of the thermally thick solution have also been suggested by researchers over the years. The following sections outline the procedures of different researchers who developed their own procedures from processing ignition test data. Many procedures incorporate a CHF into the models through which the CHF does not need to be determined experimentally, but is instead extrapolated through processing time to ignition data. Past studies have demonstrated that there can be a large discrepancy between an experimentally determined CHF under practical conditions and the calculated CHF [6]. In general it is suggested that extrapolated values for the CHF below 15 kW/m² should be taken under scrutiny [32]. Data presented in sources like the SFPE Handbook [1] is presented without the context to indicate how the CHF was determined. The major difference in the approach of some methodologies is that the researcher did not view the CHF as data for practical application – instead this quantity was viewed as a value that is only theoretically useful [33]. Each of the following methodologies will be referenced in the experimental portions of this present work.

#### 2.4.1 Janssens [21]

Janssens followed a similar procedure to Lawson and Simms, however manipulated the resulting equation to try and capture the fourth-order radiation losses from the surface. This was achieved through a statistical approach and form fitting a modified theoretical model to a large set of data. The resulting equation Janssens suggested can be seen in Equation 14. While the model expressed by Janssens may fit data well, this was developed through a statistical approach to existing data opposed to firsts principles. Janssens also incorporated data from both the Cone Calorimeter and the LIFT apparatus, which incorporates results from tests in two different orientations. The benefit to this methodology is that data from an experiment can be processed as \( q''_e \) vs. \( t^{-0.55} \) from which the CHF and thermal inertia can be solved for without any further assumptions. This does, however, result in potentially small calculated CHF values as discussed previously in Section 2.1.2.
$$q_e'' = \text{CHF} \left[ 1 + 0.73 \left( \frac{k \rho C}{h_T t_{ig}} \right)^{0.55} \right] \quad \text{Equation 14}$$

2.4.2 Quintiere [34]

The methodology suggested by Quintiere is based around the use of the Lawson and Simm’s “short time” thermally thick solution (Equation 8) with no modification. The process requires a known convective heat transfer coefficient for the testing condition; Quintiere developed this procedure in the context of the LIFT apparatus and determined that a convective heat transfer coefficient of 15 W/m²-K was sufficient in most applications. The critical heat flux for ignition is then determined experimentally and using Equation 10 the ignition temperature can be found by simultaneously solving for the radiative losses as a function of surface temperature. This procedure only uses equations based on theory and does not extrapolate CHF values from time to ignition data.

2.4.3 Delichatsios [22]

The goal of Delichastsios’ work was to develop a model that could better predict the thermal inertia and critical heat flux using only the ignition delay time data. One modification was the inclusion of a radiation losses term in the derivation of a model. After a scaling analysis and a lengthy numerical solution (which is outlined in detail in Delichatsios work), two different solutions are proposed. Equation 15 is suggested for “high heat fluxes”, in a similar fashion to the “short time” equation presented by Lawson and Simms, and Equation 16 is suggested to be valid for conditions close to the critical heat flux (approximately \(q_e'' < (1.1) \text{CHF}\)).

$$\frac{1}{\sqrt{t_{ig}}} = \frac{2}{\sqrt{\pi} \sqrt{k \rho S \phi S}} \frac{q_e'' - 0.64 \text{CHF}}{(T_{ig} - T_0)} \quad \text{Equation 15}$$

$$\frac{1}{\sqrt{t_{ig}}} = \frac{\pi}{\sqrt{\pi} \sqrt{k \rho S \phi S}} \frac{q_e'' - \text{CHF}}{(T_{ig} - T_0)} \quad \text{Equation 16}$$
2.4.4 Tewarson [35]–[37]

Tewarson expanded on Delichastsios’ work by proposing that ignition data could be represented by Equation 17 which incorporates the CHF into the short time solution seen previously in Equation 7. If you assume that the ignition temperature of a material is a constant and assume that all experiments are conducted from the same relative ambient condition, then the numerator of Equation 17 can be rearranged to create a term known as the thermal response parameter, TRP, which allows for a simplified model seen in Equation 18. This theory was developed for use in the Fire Propagation Apparatus (FPA), which was the apparatus of choice for Tewarson and the process of finding the TRP and CHF through plotting time to ignition data is still common practice when using the FPA.

\[
t_{ig} = \frac{\pi}{4} \frac{k_{s}\rho_{s}c_{s}(T_{ig} - T_{o})^{2}}{(q''_{e} - CHF)^{2}}
\]

Equation 17

\[
t_{ig} = \frac{\pi}{4} \frac{TRP}{q''_{e} - CHF}^{2}
\]

Equation 18

2.5 Piloted Ignition vs. Autoignition

As previously described, ignition can occur either through the present of a pilot source or through autoignition. Pilot sources can come in many forms including sparks, flames, and hot wires [6]. Piloted ignition generally occurs faster than autoignition as the pilot source provides the minimum activation energy for ignition to occur. Providing the minimum activation energy promotes ignition once a sufficient quantity of pyrolysis gases has been generated; i.e. by lowering the induction time seen in Equation 2 to approximately zero. This low induction time justifies the assumption that the time to ignition is approximately the pyrolysis time, or more importantly that the pyrolysis temperature is approximately equal to the ignition temperature. Autoignition however is only achieved once a localized region in the pyrolysis gases reach a threshold temperature through the absorption of external radiation. The induction time for autoignition is non-negligible, which suggests that the time to ignition for autoignition does not correspond to the pyrolysis temperature directly. The series of events that lead to ignition are outlined in Figure 7.
The ignition temperature for piloted ignition can be reasonably approximated as the pyrolysis temperature and therefore the solid phase theory established in the previous sections is sound. In other words, the low induction time from introducing a pilot allows for the comprehensive theories described previously. These equations and models do not explicitly hold true for autoignition. The only reason the previously described theories would not apply for autoignition would be due to Equation 5 and Equation 6 breaking down as the solid is heated beyond the point at which piloted ignition is possible. One assumption within these two equations is that the surface losses can be linearized into a total heat transfer coefficient. This assumption becomes less valid at high surface temperatures due to the fourth order temperature dependency of radiation losses.

The most critical consideration is that the simple solid ignition model laid out by Lawson and Simms assumes that the surface temperature continuously increases until ignition (i.e. the surface temperature at ignition is equal to the pyrolysis temperature). The process of pyrolysis is a highly temperature dependent process. Considering only the case of piloted ignition requires no additional thought into what happens to the surface temperature after the pyrolysis temperature is reached at the point of ignition. If the pyrolysis temperature (within a certain range) acts as a phase change temperature, then there is a possibility for the surface temperature to remain at or within a small range of values of the pyrolysis
temperature. The delay between autoignition and piloted ignition is therefore not necessarily an increase in the surface temperature as much as a delay caused by the induction time associated with heating a localized region of pyrolysis gasses until the autoignition temperature (AIT) is reached. The gases are heated primarily through the absorption of external radiation which is strongly species dependent and is also strongly system dependent – Torero highlights that one of the greatest discrepancies in autoignition behavior is caused by varying orientation [7].

![Temperature vs Time Graph](Figure 8)

Figure 8. Experimental data and simulation results illustrating the surface temperature of a PMMA slab exposed to 30 kW/m² presented by Tsai [38]– autoignition achieved at a surface temperature of approximately 380 °C, which is similar to temperatures reported for piloted ignition.

Maintaining a constant surface temperature at the pyrolysis temperature may be a valid assumption of materials such as thermoplastics that burn with almost pool fire behavior but is not sound for charring solids like timber that can sustain solid phase combustion in the char layer at much higher temperatures than the pyrolysis temperature [18]. Past studies have led to suggest that the surface temperature at autoignition can correspond closely to the surface temperature at piloted ignition [38], [39], which can also be seen in Figure 8. The surface temperatures for materials such as timber, however, may greatly exceed the anticipated piloted ignition surface temperature at the point of autoignition [40].
The complexity of autoignition places a higher degree of uncertainty on the use of classical ignition theory. Autoignition takes an issue that can more or less be simplified into a solid phase heat transfer and reintroduces a gas phase dependency that can only be described in entirety by understanding a finely resolved temperature and mass distribution throughout the pyrolysis plume. While the assumptions of classical ignition theory break down for autoignition, no model currently exists to better characterize autoignition of solids. The fundamental theory developed for piloted ignition was used to characterize autoignition data in this study as the general trends in data behavior do match those expected in piloted ignition – using existing theory in this way must however include a degree of uncertainty in using this data in calculations of parameters such as the thermal inertia.

Comparing autoignition and piloted ignition data between varying orientations can, however, directly lend insight to the variation in approximate pyrolysis time and induction times for different orientations. For a simple polymer such as PMMA, the difference between the observed ignition times for autoignition and piloted ignition may serve as a metric for approximating the induction time of the gas phase and therefore illustrate orientation effects on the gas phase.
Chapter 3
A Brief History of Ignition Testing

“If I have seen further it is by standing on the shoulders of Giants”, Isaac Newton, 1675 [41]

The study of solid ignition set its roots centuries before the field of combustion science matured to a point at which the mechanisms of ignition could be properly classified – yet the current understanding and application of ignition theory have been separated from the original context in which they were derived. In order to understand the context of ignition theory and its current use in engineering design, one must look back on the history of ignition testing.

3.1 General History of Fire Engineering and Fire Science

Fire is a primordial phenomenon that has been inescapably intertwined with mankind. The very symbol of fire has grown to signify the idea of innovation and the inception of scientific progress. For as long as mankind has had fire, there has been a need to control it and understand it. Arguably the earliest form of a fire safety specialist was the fire tender who maintained the fire and ensured it would remain contained to its intended location. It is often said within the industry of Fire Safety that it is a “new industry” relative to other disciplines – the action of protecting life and property from the hazards of fire is as old as time; it is the scientific characterization of such phenomenon that is still fairly young as a discipline.

The earliest recorded studies on fire focus primarily on the chemical interaction flame has with the air. In the second century BCE, a Greek philosopher/writer named Philo of Byzantium began conducting experiments using a candle under a glass vessel and suggested that parts of the air were converted into the fundamental element “fire” [42]. Leonardo da Vinci ran similar experiments in the 15th century and suggested that only a portion of air is consumed by fire and suggested only a portion of air is similarly consumed in respiration [43]. English scientist John Mayow was one of the first to suggest that fire only consumed a part of the air, which he called “spiritus nitroaereus” [44]. His experiments were able to show
that if either a flame or a mouse were to be placed under a closed vessel both subjects would extinguish after displacing the same volume of air (determined by the displacement of water within the closed chamber). The work of Carl Wilhelm Scheele eventually linked the “spiritus nitroaereus”, which he instead called “fire air”, to a resulting byproduct of heating mercuric oxide [45] – therefore indicating that a portion of the air consumed by fire and respiration is a single element (the term oxygen was not introduced until later).

3.2 Fire Chemistry to Fire Safety Science

These initial experiments on air were conducted primarily by chemists who were looking into the theory out of curiosity as opposed to designing for safety. There ultimately came a shift towards research dedicated to fire safety opposed to fire chemistry. In the late 18th century and early 19th century, fires and explosions in coal mines were a prevalent issue in England. One gentleman, Sir Humphrey Davy, was enlisted to investigate the cause of such catastrophes and develop means to prevent them. His initial work focused on the gasses emitted from such mines, and the mixture of flammable vapors or dusts in the air [46].

Sir Humphrey Davy went on to make interesting observations such as a propagating flame from a gas explosion cannot pass through a tube of a very small diameter (inadvertently describing the effect of a quenching distance) [47]. He then incorporated small apertures acting as flame arresters into specialized lanterns he titled “safety lamps” to be placed in high risk areas such as mines. Starting in 1815, Davy produced a series of papers on the characterization of flames, particularly those that would pose a hazard in coal mine. One lasting impact Sir Humphrey Davy had on the field of combustion was the training of a young pupil named Michael Faraday who would later become a symbol for combustion chemistry.

The fire hazard related to coal mines continued to push the field of early fire research. In the mid-1880’s, a group of researchers from Harvard college were tasked with classifying the level of ignitability of various timber members from coal mines. The owners of the coal mines were concerned that the timber members had degraded in the mines and they wanted to know if such timber become more fire prone with time. In order to compare the ignitability of various timber members, small portions of each sample were heated in a rudimentary furnace until the point of ignition. The temperature at which the sample ignited was
recorded and then compared across the various timber members taken from the mine. The findings were published by two gentlemen by the name of Henry Hill and Arthur Comey in 1886, and this is (as far as the author is aware) the earliest reference to a systematic classification of the ignition temperature of a solid material for assessment towards the fire safety of a structure [48].

Table 3. The results presented by Hill and Comey from their 1886 research on the ignition temperature of timber [48]. The year indicates the age of the wood (i.e. how long the wood had been used in the mine).

<table>
<thead>
<tr>
<th></th>
<th>Pine</th>
<th>Hemlock</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sound</td>
<td>Sapwood</td>
</tr>
<tr>
<td>5 yr</td>
<td>285-300 °C</td>
<td>-</td>
</tr>
<tr>
<td>6 yr</td>
<td>318-330 °C</td>
<td>-</td>
</tr>
<tr>
<td>7 yr</td>
<td>230-238 °C</td>
<td>232-239 °C</td>
</tr>
<tr>
<td>8 yr</td>
<td>-</td>
<td>215-238 °C</td>
</tr>
<tr>
<td>9 yr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10 yr</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

It is interesting to note that Hill and Comey also observed the point of ignition changed with the heating rate they applied. If the temperature was slowly raised, then the pine would ignite between 405-417 °C, and if it was slowly heated it would ignite between 360-372 °C. The values seen in Table 3 illustrate trials in which samples were placed into a “bath” heated to a definite temperature (opposed to heating the sample in the chamber itself). Other interesting conclusions from the study include the fact that larger samples took longer to ignite than smaller samples due to greater heat losses.

This work sets the precedent for future studies to focus on the solid phase and develop a surface temperature at which ignition is achieved. However, the authors understood that different heating rates could change the results – they instead used their methodology as a metric of comparison. Their results were therefore a surrogate for performance in fire and not a direct way of predicting ignition in a real fire scenario.
Another notable early work in solid ignition was a thesis produced by Bixel in 1910 which investigated the effect of steam pipes on the ignition other materials [49]. The experimental apparatus used can be seen in Figure 9. The approach used by Bixel focused on the contact of materials with a heated steam pipe, however the results obtained from this experiment compare well to those obtained by Hill and Comey. The results of Bixel’s experiments can be seen in Table 4.

Table 4. Results from Bixel's study on ignition [49].

<table>
<thead>
<tr>
<th>Material</th>
<th>Ignition Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moist Charcoal</td>
<td>318 °F 159 °C</td>
</tr>
<tr>
<td>Georgia Pine</td>
<td>397 °F 203 °C</td>
</tr>
<tr>
<td>Dry Charcoal</td>
<td>420 °F 216 °C</td>
</tr>
<tr>
<td>Oily Waste</td>
<td>425 °F 218 °C</td>
</tr>
<tr>
<td>Paper</td>
<td>435 °F 224 °C</td>
</tr>
<tr>
<td>Maple Wood</td>
<td>450 °F 232 °C</td>
</tr>
<tr>
<td>Cypress</td>
<td>465 °F 241 °C</td>
</tr>
<tr>
<td>Chestnut</td>
<td>490 °F 254 °C</td>
</tr>
<tr>
<td>Oak</td>
<td>495 °F 257 °C</td>
</tr>
</tbody>
</table>

Numerous current methodologies for ignition testing incorporate a pilot flame to initiate combustion. In 1915 R.E. Prince conducted a series of experiments in which various woods were placed in a flow of constant temperature to find the point at which the wood ignites – however he also placed a pilot flame one-half inch above the surface of the timber samples [50]. Making this the earliest (as far as the author is aware of) documented study on piloted ignition. The results of this study are presented in Table 5.
Prince used a device he called the “inflammability apparatus” which used a quartz tube wrapped in nichrome wire. When an electric current is run through the wire, the air inside the quartz tube is heated to a known temperature and the sample within the quartz tube is then heated to the point of ignition. A schematic of the inflammability apparatus can be seen in Figure 10. This apparatus was modified over the years and was eventually incorporated into both British (BS 476, 1932) and American test standards (ASTM E136, 1958). Major contributions to altering the device itself were made by S.H Ingberg (1945) and N.P. Ketchkin (1949) [51] which ultimately lead to the development of the tube furnace used today to classify materials as combustible or non-combustible (i.e. ASTM E136).

Table 5. Results from Prince's study on piloted ignition [50].

<table>
<thead>
<tr>
<th>Exposure Temp (°C)</th>
<th>Long-Leaf</th>
<th>Red Oak</th>
<th>Tamarack</th>
<th>Western Larch</th>
<th>Noble Fir</th>
<th>Eastern Hemlock</th>
<th>Redwood</th>
<th>Sitka Spruce</th>
<th>Basswood</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>14.3</td>
<td>20.0</td>
<td>29.9</td>
<td>30.8</td>
<td>-</td>
<td>13.3</td>
<td>18.5</td>
<td>19.6</td>
<td>14.5</td>
</tr>
<tr>
<td>200</td>
<td>11.8</td>
<td>13.3</td>
<td>14.5</td>
<td>25.0</td>
<td>-</td>
<td>13.3</td>
<td>18.5</td>
<td>19.6</td>
<td>14.5</td>
</tr>
<tr>
<td>225</td>
<td>8.7</td>
<td>8.1</td>
<td>9.0</td>
<td>17.0</td>
<td>15.8</td>
<td>7.2</td>
<td>10.4</td>
<td>8.3</td>
<td>9.6</td>
</tr>
<tr>
<td>250</td>
<td>6.0</td>
<td>4.7</td>
<td>6.0</td>
<td>9.5</td>
<td>9.3</td>
<td>4.0</td>
<td>6.0</td>
<td>5.3</td>
<td>6.0</td>
</tr>
<tr>
<td>300</td>
<td>2.3</td>
<td>1.6</td>
<td>2.3</td>
<td>3.5</td>
<td>2.3</td>
<td>2.2</td>
<td>1.9</td>
<td>2.1</td>
<td>1.6</td>
</tr>
<tr>
<td>350</td>
<td>1.4</td>
<td>1.2</td>
<td>0.8</td>
<td>1.5</td>
<td>1.2</td>
<td>1.2</td>
<td>0.8</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>430</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>0.70</td>
<td>0.68</td>
<td>0.6</td>
<td>0.48</td>
<td>0.46</td>
<td>0.38</td>
<td>0.35</td>
<td>0.34</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Figure 10. Prince's schematic of the inflammability apparatus [50].
Figure 11. The results from Prince's study on piloted ignition [50]. Note that the pseudo-exponential growth seen when plotting ignition time vs. external heat flux can be observed in the data.

The results reported by Prince show interesting similarities with the general trends seen in current ignition testing. While most ignition testing presented today would show ignition time with respect to an external heat flux, the data generally follows the same “pseudo-exponential” growth leading up the critical threshold at which ignition is not possible (Figure 11). Early researchers such as Prince, Hill, and Comey understood that the heat transfer and mass transport phenomenon that controlled ignition were not entirely accounted for in their analysis. They explicitly state this understanding in their work and instead view this work as a means to compare the relative flammability of materials – not to predict ignition in engineering analysis in a real fire event. Research up to the early 1900’s made great strides in demonstrating solid ignition, however there lacked an analytical model to describe solid ignition accurately.
In the mid 1900’s, researchers began to experiment with providing an external radiant heat flux to samples to facilitate ignition. The Fire Research Station in the United Kingdom published work that used a gas-fired radiant panel to provide radiant heat fluxes for both ignition and flame spread testing in the early 1950’s [53], [54]. Radiant panels were used in the UK as early as 1946 as outlined in the Post-war Building Study No. 20 – Fire Grading of Buildings [55] (see Figure 12). In addition to radiant panels, experiments were conducted at the Fire Research Station using a tungsten lamp concentrated on a 2 cm² area through the use of an ellipsoidal mirror used to determine the time to ignition; an image of the device can be seen in Figure 13 showing Margaret Law conducted an experiment.

![Figure 12. A rendering of an early radiant panel used in the UK in the mid 1940's [52].](image)

In the mid 1900’s, researchers began to experiment with providing an external radiant heat flux to samples to facilitate ignition. The Fire Research Station in the United Kingdom published work that used a gas-fired radiant panel to provide radiant heat fluxes for both ignition and flame spread testing in the early 1950’s [53], [54]. Radiant panels were used in the UK as early as 1946 as outlined in the Post-war Building Study No. 20 – Fire Grading of Buildings [55] (see Figure 12). In addition to radiant panels, experiments were conducted at the Fire Research Station using a tungsten lamp concentrated on a 2 cm² area through the use of an ellipsoidal mirror used to determine the time to ignition; an image of the device can be seen in Figure 13 showing Margaret Law conducted an experiment.

![Figure 13. Margaret Law conducting ignition experiments using a tungsten lamp and an ellipsoidal mirror.](image)

This image was featured on the cover of the 1952 Fire Research Station Annual Report.
The use of a heat source to provide external irradiance also led to a breakthrough in solid ignition theory. In 1952, Lawson and Simms of the Fire Research Station introduced the analytical approach to solid ignition (described previously in Section 2) which assumes one-sided heating from an external radiant heat flux. Lawson and Simms used a coal gas/air fired radiant panel and with experimental data they developed a technique of plotting the results as the negative reciprocal of the ignition time vs. the external heat flux, in which case all of the ignition data collapses into a linear curve [31]. This marked the first model for predicting ignition based on an external heat flux which would lead to the development of further theory and standardized testing procedures.

Researchers continued to use a single radiant heat flux as the boundary condition for experimentation and there soon came rapid development in standardized testing for ignitability. In the mid-1950’s A.F. Robertson ran extensive experiments with gas-fired radiant panels and eventually developed the first ASTM standard to use a radiant panel (ASTM E162) [56]. In the late 1960’s, Professor Edwin Smith at Ohio State University developed the first bench-scale heat release calorimeter known as the OSU Calorimeter [32]. This device uses a thermopile method to approximate the heat released from burning an item in the testing apparatus which is heated by a silicon carbide rod heater [57]. While the OSU calorimeter was being developed, Archibad Tewarson at FM Global (known at the time as the Factory Mutual Research Corporation) developed the predecessor to the Fire Propagation Apparatus [32]. Similarly, Vytenis Babrauskas at the National Institute of Standards and Technology (NIST) developed the Cone Calorimeter in the 80’s [58]. Over a 40-year period, the process of quantifying the ignitability of a material was now dictated through various regimented standardized testing procedures.

The transition from the work done at the Fire Research Station in the 1950’s to the development of various standardized procedures for ignition that came to be at the end of the 1980’s is of significance when looking at the phenomenon of ignition and how engineers apply it in practice today. The researchers of the early 1900’s understood that their experiments did not in fact account for all aspects of reality. The work of the Fire Research Station was groundbreaking and began to unravel the complexities of solid ignition, while there were still very limiting assumptions embedded in this theory. It was understood that results from ignition tests that would later be interpreted as ignition temperatures or CHF were inherently
mathematical quantities dependent on both the testing procedure used and the limitations of the existing theory. There then came confusion amongst engineers and scientists about the practicality of a parameters such as the CHF; R.H. Whiteley describes in a short communication in the Fire Safety Journal in 1993 that the CHF results from standardized tests are of little relevance in engineering applications “if ignitability is considered to be a significant parameter in the assessment of the fire hazard…” [33]. In other words, the CHF is a useful comparative tool but the system dependency of this parameter makes it difficult to use this parameter directly in realistic analysis.

Since the late 1800’s, fire safety researchers have made great strides in characterizing the phenomenon of ignition and providing equipment to demonstrate the relative ignitability of a material (a summary of significant events can be found in Table 6). However, the origin of ignition theory started with an understanding that the resulting ignition parameters are mathematical principles that do not consider all aspects of reality. As the years pass between the original work done by researchers at organizations such as the Fire Research Station, the line became blurred between an ignition parameter useful as a mathematical quantity and an input that can be used to accurately predict ignition in a real fire event. This confusion remains to this day which is evident in codes and regulations around the world.
Table 6. Historical timeline of the development of ignition theory including other major developments in the field of Fire Safety and particular experiments on orientation and ignition (see Chapter 6).

<table>
<thead>
<tr>
<th>Fire Safety Science</th>
<th>Ignition Testing</th>
<th>Orientation Effects on Ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1815: Sir Humphry Davy develops first flame arrestor</td>
<td>-1886: Hill and Comey Investigate Ignition of Timber from coal mines</td>
<td></td>
</tr>
<tr>
<td>-1848: Michael Faraday’s Christmas Lecture</td>
<td>-1910: Bixel and Moore; steam pipe ignition testing</td>
<td></td>
</tr>
<tr>
<td>-1891: First “Fire Resistance” Type testing in Germany</td>
<td>-1915: R.E. Prince; first piloted ignition study</td>
<td></td>
</tr>
<tr>
<td>-1944: AJ Steiner develops the tunnel test for flammability</td>
<td>-1972: E. Smith develops OSU apparatus</td>
<td>-1993: Shields et al. conduct study on orientation (horizontal and vertical)</td>
</tr>
<tr>
<td>-1958: Kawagoe publishes the seminal work on ventilation factors and flashover</td>
<td>-1976: A. Tewarson develops predecessor of the FPA</td>
<td>-2009: Tsai conducts study on orientation (horizontal and vertical)</td>
</tr>
<tr>
<td>-1980: Huggett outlines process of oxygen consumption calorimetry</td>
<td>-1982: Quintiere develops theory that would turn into the LIFT</td>
<td>-2015: Peng et al. conduct study in orientations (beyond horz. &amp; vert.)</td>
</tr>
<tr>
<td>-1986: First Symposium for the International Association of Fire Safety Science (IAFSS)</td>
<td>-1982: Babrauskas develops the Cone Calorimeter</td>
<td>-2020: Current Study</td>
</tr>
<tr>
<td></td>
<td>-1991: Janssens publishes his ignition theory</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-2003: Babrauskas publishes the Ignition Handbook</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 4
USE OF IGNITION CHARACTERISTICS IN ENGINEERING APPLICATIONS

“Measurement and quantification are fundamental to any proper engineering design. It is sad so many people are reluctant to measure things: presumably that might cast doubts on what they know to be right” – Margaret Law, 1990 [59]

The current framework of Fire Protection Engineering incorporates ignition parameters such as the CHF and ignition temperature into engineering practice in different ways depending the governing regulatory structure. In the United States, the majority of the regulation used in the built environment is dictated by the International Building Code (IBC) or various NFPA Codes and Standards (e.g. NFPA 5000). Specifications within these codes are laid out to regulate the flammability of certain elements in a compliant building. The California Building Code (the IBC with state-dependent amendments, or CBC) states in §1403.5 that materials used in exterior wall assemblies must produce a peak heat release rate of less than 150 kW/m² as determined through ASTM E1354 (which will be discussed further below) and achieve a flame spread index of less than 25 as determined through ASTM E84. In this context, the results of regimented standardized tests are used as pass/fail criteria for building material use. Particularly in the context of ignition, bench-scale ignition testing is used to determine if a material should be permitted for a specific use or to validate whether a material can be considered “non-combustible” or “limited combustibility” in the eyes of the regulatory code. The results of these standardized tests do not provide further insight to the behavior of a material in a real fire scenario.

The application of ignition data can however be different where regulatory codes are not only based on a prescriptive compliance system. The Building Code of Australia (BCA), for example, allows for Fire Engineers to provide a “Performance Solution” to justify aspects of the design outside the regimented requirements of the building code itself. This allows engineers to deviate from the code (known in the BCA as a “departure”) so long as analysis can verify that the intent of the code is still met. The BCA is structured to allow these performance-based design solutions and often times engineers will use experimental or testing data as the basis of their performance solution. While it is not used as frequently, this same logical
process can be used in North American codes when developing design fire scenarios as outlined in NFPA 92 for smoke control applications. When developing a likely fire scenario (or “design fire scenario”), the structure of these regulations allows the engineer to dictate the degree to which the fire will grow based upon available fuel in the specified compartment. An engineer can then use provided data on the CHF for a given material and determine if it is likely to ignite in a reasonable design fire scenario (i.e. whether additional items will ignite). Performance-based design solutions allow engineers to use first principles to dictate building design; this however places a high degree of responsibility on the competency of the engineer and the validity of their analysis. The use of ignition parameters to predict real fire scenarios is currently in practice where performance solutions are allowed – as performance-based design solutions become more frequent around the world, such as the United States, the validity of using ignition parameters in this context must be discussed before engineers apply values without properly considering the context in which they were determined.

The following sections will first discuss the aspects of prescriptive regulation that incorporates ignition parameters as well as how this information is incorporated into performance-based design.

4.1 Standardized Testing (Prescriptive Design)

Solid materials are often classified in terms of relative ignitability. There are two approaches to testing the ignition of solids; 1) to simulate a specified fire scenario or 2) to utilize a highly controlled thermal environment with well-defined boundary conditions. The first offers more realistic scenarios which can mimic the behavior of actual fire conditions. These include the ASTM D2859 “Methenamine Pill Test” and the UL 94 Test Series. The results of specified fire exposure can lend insight into material flammability; however, the results are confined only to the scenario in which it is tested. For many testing procedures, the result is generally a binary pass/fail criterion and any information beyond that cannot be used as an input to fundamental theory to gain more information on a material. In other words, passing the Methenamine Pill Test lends no insight into what sort of thermal condition defines the threshold for ignition, only whether or not the material passes the test.

Another approach to ignition testing is to use a high degree of control over the thermal exposure, to a sample, generally in the form of a uniform, constant external heat flux. This highly controlled process
allows the results of these tests to gain insight into the controlling mechanisms of ignition and applying scientific theory to back out fundamental parameters. Other standardized methodologies use a small-scale furnace to determine the ignition temperature of a solid (which is accepted in regulation such as the IBC), however it is difficult to apply solid ignition theory to such test methodologies. The use of radiant heaters allows researchers to vary the external heat flux acting on the surface of a heated material which can lend insight into ignition, burning rate, and products of combustion produced at various external irradiances. A heated convective flow can also be used to ignite a material in a controlled environment, but for most practical applications ignition testing incorporates a radiative heat flux to the sample material. The use of a single external heat flux also allows for the theoretical calculations outlined in Section 2 in which material characteristics and ignition parameters can be determined through a regimented testing procedure. Therefore, the use of a single external heat flux is the standard way to characterize ignition parameters from standardized testing.

The three most popular methods of supplying a radiant heat flux include the use of a conical electrical heater (as seen in the ASTM E1354 Cone Calorimeter [60]), tungsten lamps (as seen in the ASTM E2058 Fire Propagation Apparatus, FPA [61]), or a gas-fired radiant panel array (as seen in the ASTM E1321 Lateral Ignition and Flame Spread Test, LIFT [62]) – examples of each element can be seen in Figure 14. Each of these heating elements are specifically associated with various testing procedures which provide similar metrics to classify the relative flammability of a given material (through ignition parameters, CHF and T_{ig}, for example) but can also be used outside the context of standardized testing to conduct experimental procedures beyond the regimented testing process.

Figure 14. Examples of various radiant heat sources. Left: a conical cone heater; middle: the tungsten lamps of the FPA; right: a propane-powered radiant panel array. Each photo was taken by the author.
4.1.1 Conical Electric Heaters (Cone Heaters)

One commonly used external heat source is a conical coil of Incoloy tube that emits thermal radiation when a current is passed through it [63]. Just as any resistor releases heat as current passes through it, the coils climb in temperature depending on the current passing through them and can reach temperatures sufficient to emit a heat flux to a sample upwards of 100 kW/m$^2$. The use of a conical heater became popularized in the 1980’s by Vytenis Babrauskas at the National Institute for Standards and Technology (NIST) [8].

The conical shape is designed to promote a uniform heat flux at the designated testing area (approximately 25 mm from the cone surface). This achieves a relatively uniform heat flux due to the hemispherical nature of radiation – if a flat plate was to be used, a region in the center of the sample would be exposed to a higher heat flux than the outermost parts of the sample. By effectively pulling the center of the radiating surface away from the sample, a more uniform heat flux can be provided. The design also includes an opening directly above the sample to allow for products of combustion to flow upwards from the sample unimpeded. The design of the heating element can be seen in Figure 15.

![Figure 15. A schematic representation of the conical heater [63].](image)

An electric cone heater can be used on its own or in a variety of apparatuses used in fire testing. The most common use of the cone heater is in the ASTM E1354 Cone Calorimeter [60]. This apparatus pairs the conical heating element with a gas analysis system to determine the Heat Release Rate (HRR) of a sample through oxygen consumption calorimetry [64], [65]. However, the cone can also be used without
the calorimetry equipment for use in ignition studies and to measure the burning rate (mass loss rate) of a sample at a given exposed heat flux.

### 4.1.2 Tungsten Lamps (FPA)

Another popular form of radiant heat source is through the use of high powered tungsten lamps, as seen in the FPA (ASTM E2058 [61]). The FPA was pioneered by Archibald Tewarson at FM Global in the 1960-1970’s [36], [66] – the apparatus Tewarson used can be seen in Figure 16. The benefit the FPA offers is that the testing apparatus incorporates a quartz cylinder which isolates the sample from the ambient environment. By changing the flow of oxygen or nitrogen into the testing area, the concentration of oxygen can be controlled while still providing a radiant heat flux from the tungsten lamps. The standard procedure for ignition is limited to the horizontal orientation, while past experimental studies have used the FPA to ignite samples in a vertical orientation [67].

![FPA Diagram](image)

**Figure 16.** One of Tewarson's original representations of the FPA [68]

### 4.1.3 Radiant Panel Arrays (RPA)

Many forms of standardized fire testing or experimental studies utilize gas-fire radiant panel arrays to provide an external heat flux. The most prominent procedure that uses radiant panels is the ASTM E1321 Lateral Ignition and Flame Spread Test (LIFT) [62] which determines ignition parameters for materials in the vertical orientation. The LIFT was developed by Quintiere in the 80’s; an early schematic of his work can be seen in Figure 17.
4.1.4 A Comparison of the Various Standardized Tests

Each heating element and the associated standardized tests described previously are used to develop bench-scale ignitability or flammability properties. Each standardized procedure uses a different heating element to expose a sample to a given heat flux – theoretically, similar ranges of radiant heat fluxes can be applied to a sample with each device which should result in similar material response. Studies have shown that the same material can produce different ignition characteristics when tested with two different apparatus. Figure 18 compares the ignition results presented for the same material exposed to an external heat flux from a cone heater, the LIFT apparatus, and the tungsten lamps of the FPA.

Figure 18. A comparison of black PMMA ignited in the LIFT apparatus [34], an electrical cone heater [69], and FPA lamps [37].
The difference in resulting ignition times stems from a variety of factors including the geometry of the apparatus itself, the size and geometry of the samples used in the testing apparatus, and the spectral difference between the radiation emitted from each heating element. Both the FPA and Cone test samples in the horizontal orientation, however the LIFT is used to test samples in the vertical orientation. Results from the LIFT have been found to differ from the horizontal orientation used in the cone, for example [70]. Such variations though may result from numerous factors including sample size and the use of a radiant panel compared to a conical heater. Even with samples of similar size in the same orientation, substantial differences can be seen when comparing data from the cone and the FPA (see Figure 18). A comprehensive review of ignition data for PMMA was conducted by Bal and Rein which demonstrates the scatter that exists in reported ignition data [71] – an example of their work can be seen in Figure 19. Regardless of the differences in results, the ignition parameters determined from each respective test are often published and reproduced without any context to indicate how they were determined.

Figure 19. An illustration of the scatter seen in past experiments with black PMMA using various heating sources; originally produced by Bal and Rein [71].

4.2 Predicting Real Fire Behavior (Performance-based Design)

The process of performance-based design for fire safety is rooted in an engineer’s ability to understand how one aspect of building design (such as material choice and geometry) influences the overall behavior of fire and how this behavior may lead to hazardous conditions for the building and occupants.
Currently in the United States, there are limited situations in which performance-based design can be incorporated for fire safety, but such solutions are expected to become more prevalent in years to come.

One aspect in which engineers are allowed flexibility to deviate from the prescriptive code in the US is through providing “engineering judgment” to justify a given deviation from the code. This is can be used, for example, to allow for a rated wall construction of a known composition that has not actually been approved by a standardized fire test. It is up to the engineer to evaluate whether or not the assembly in question would perform in the same fashion when compared to an identical assembly (generally from another manufacturer) which has undergone approved fire testing.

Fire Protection Engineers in the US are often given the most responsibility from the perspective of performance-based design when developing design fire scenarios to be used in approved design aspects such as smoke control design as dictated by NFPA 92. Chapter 5 of NFPA 92, Smoke Management Calculation Procedures, is one of the most well-defined sources for developing a design fire in North American codes and standards. This chapter is sometimes used to develop design fires even outside of the context of smoke control. NFPA 92 Chapter 5 outlines the general behavior of compartment fires and illustrates ways to account for a growth phase, steady burning phase, or decay phase of a fire. In discussing the development of a reasonable design fire growth phase, NFPA 92 §5.2.5 states “the design fire shall be increased if other combustibles are within the separation distance, \( R \), as determined from Equation 5.2.5.3”.

The equation defined in this section can be seen below (Equation 19), where \( Q_r \) is the radiative portion of the fire heat release rate and \( q_e \) is the “incident radiant heat flux required for piloted ignition”.

\[
R = \left( \frac{Q_r}{4\pi q_e} \right)^{1/2}
\]  

Equation 19

NFPA 92 gives authority to engineers to alter design fire scenarios based upon the assumed ignition of additional fuel packages. The only requirement from the engineer is to justify their analysis with available “test data” – this terminology is used throughout Chapter 5 of NFPA 92 and offers little clarity into what data should be used. The wording throughout the code suggests that the “required heat flux from piloted ignition” is an accurate representation of predicting ignition of additional items in a real fire scenario. The use of a pilot also implies that the inputs to this equation are to come from standardized
testing. Annex B goes on to suggest that ignition parameters are derived from “calorimetry tests, and LIFT apparatus, and other tests” (§B.6.2) but does not highlight differences between these testing procedures or what implications that may have to the analysis. At this point, an engineer would then open a resource such as the SFPE handbook [1] and find a CHF value presented for a given material and then apply this to their design. The underlying assumption is that the CHF value determined from experimentation can actually be used to predict the ignition of an item based only the items material without any consideration of orientation, scale, size of the target item, or conditions around the target item (not to mention Equation 19 also assumes that a fire will radiate uniformly as a point source). There is also a general lack of understanding that the CHF determined from these test methods can vary between test methods and how this variation may translate to behavior in a real fire event. This is a method of design that is currently implemented in the United States and will likely increase in frequency in the coming years.

The direct use of ignition parameters such as the CHF in engineering applications begs the question of whether or not such a parameter actually represents reality. Using experimentally determined ignition parameters in any engineering capacity requires a high degree of engineering judgment. This analysis also requires a high degree of technical competency in the approval authorities who in many cases should not be expected to understand the intricacies and variation within fire testing. Previous publications indicate that there has been confusion in the applicability of parameters such as the CHF in engineering analysis [33]. The researchers who originally developed the concepts of ignition testing understood the limitations of applying the mathematical quantities that are determined through such testing. The concept of a parameter such as the CHF was never intended to be directly applied to analysis of a real fire scenario – using these parameters in such a context places a high degree of uncertainty on the CHF. Applying these values in engineering analysis requires some form of a safety factor to ensure an adequate margin of safety which is not currently considered in existing analysis.

Previous studies clearly indicate variation in ignition testing between orientations and testing apparatus; if any “test data” can be accepted for use in analysis then engineers and approval authorities must understand these possible variations. Variation in ignition results is of no concern if little variation is observed, however the SFPE handbook cites a CHF for PMMA in a range between 6-23 kW/m² [1] –
leaving a large window of values to be used in analysis (all of which would be fully compliant from the perspective of NFPA 92). There currently exists no better way to consider ignition of fuel packages then by using ignition parameters. However, if ignition parameters such as the critical heat flux or ignition temperature can be applied directly in engineering applications, engineers must consider the uncertainty in these parameters. Experimental ignition data cannot be taken at face value. One of the most critical aspects of this uncertainty is the system dependency. Quantifying the influence of different system influence, namely the influence of orientation, allows for a better understanding of the applicability and limitations of using such ignition parameters.

A performance-based design solution cannot use simply pass/fail criterion developed from a highly regimented series of standardized tests – instead the designer must have a degree of confidence in how materials will behave in a realistic fire scenario. There is currently a confusion between the mathematical quantities that result from standardized testing and the ability to predict ignition for practical applications. The process of ignition is also inherently system dependent, one of the most critical aspects of which being the orientation of the material – therefore, if engineers are ever going to be able to characterize ignition for use in performance-based design, understanding the effects of orientation on ignition is critical.
Chapter 5
MASS AND HEAT TRANSPORT CONSIDERATIONS FOR VARYING ORIENTATIONS

The question of how orientation influences the process of ignition boils down to the fundamental fluid mechanics and heat transfer relating to a sample in various orientations. It has been established that ignition occurs in the gas phase – it is then no surprise that the flow field surrounding a sample can greatly influence the process of ignition. In the simple case of a forced flow over a sample surface, forced air flow can lead to enhanced mixing but can also lead to diluting the pyrolysis in the reaction zone, creating a mixture too lean to ignite. Air flow can also lead to heat transfer to or away from the sample (depending on the temperature of the flow) which could either aid or impinge on pyrolysis. Many studies have been conducted on the influence of forced flow on ignition [6], [12], [13] – this study will focus on the influence of orientation on the fluid mechanics and heat transfer involved in a solid at the point of ignition.

5.1 Orientation Influence on Fluid Mechanics

Once ignited, the resulting flame sheet anchored above the sample surface will behave differently depending on the orientation of the sample. As seen in Figure 20, a horizontal sample will produce a conical flame (assuming the heated surface is approximately a square) while a sample in the vertical orientation will display a flame that is anchored in the boundary layer that forms on the heated face. The fluid behavior of the flame in each orientation can lend some insight to the behavior of the flow fields around the sample surface prior to ignition.

![Figure 20](image)

Figure 20. The two traditional orientations for testing ignition, the horizontal orientation (left) and the vertical orientation (right).
As a material undergoes pyrolysis, the resulting pyrolysis gases flow from the sample surface and are driven away from the sample due to buoyancy (i.e. the pyrolysis gases are hotter and less dense than ambient air). The movement of pyrolysis gases induces fluid flow over the sample surface. In the horizontal case, air flows over the sides of the sample and then up to form a conical shape. The vertical condition creates a boundary layer over the sample surface – both of these conditions can be seen in Figure 21. The pyrolysis gases emitted from the sample surface meets oxygen in the ambient air, creating a gradient of fuel richness from the ambient air. The gradient of fuel to air seen in the horizontal orientation decreases as the gases move away from the surface. Fuel being emitted from a vertical sample on the other hand creates a boundary layer in which fuel is injected into the boundary flow along the height of the boundary layer. This results in a higher degree of mixing and a much less uniform distribution of fuel to air throughout the boundary layer. This effect is one of the contributing factors to the observation of delayed ignition times in the vertical orientation when compared to the horizontal orientation.

Figure 21. A comparison of the gas-phase conditions above the fuel surface in the vertical and horizontal orientations
The buoyancy of the pyrolysis gases in the horizontal orientation is enhanced by a forced flow condition; this flow effectively increases the height at which the stochiometric mixture is located above the sample. The same effect would be seen if the pyrolysis rate was to increase in the horizontal orientation, resulting in a higher mass flow rate out of the surface and a stochiometric location higher off the surface [6]. Forced flow acting over a vertical sample would yield a different result – the boundary flow would effectively push the boundary layer (approximately at which lower flammable limit is achieved) towards the heated surface. An increase in pyrolysis rate would however push the stoichiometric distance away from the sample surface as in the horizontal case. A previous study simulated the distribution of fuel and oxygen around a sample in the Cone Calorimeter [38] – some results of which can be found in Figure 22.

Figure 22. A numerical model developed by Tsai [38] that demonstrates the temperature and species distribution of a horizontal sample in the Cone Calorimeter. Sample simulated at an exposure of 35 kW/m², shown 184 seconds into the simulation (at the instant just before ignition).

The vertical case follows the approximate behavior of a flat vertical plate. Due to the relatively small characteristic length of samples used in bench-scale fire testing, it is unlikely that the forced flow over the sample surface will be great enough to establish a turbulent boundary layer assuming that a
turbulent boundary layer is not tripped at the base of the sample. An approximately laminar flow can be observed using Schlieren imagine of a vertical sample heated by an external radiant source. Figure 23 highlights the boundary layer that is formed over a vertical timber sample being heated by a cone heater.

![Figure 23. Schlieren Images of a timber sample being burned in the vertical orientation using the conical heater, cone heater of the Cone Calorimeter. The red dashed line highlights an approximately laminar boundary layer that forms over the heated face of the sample. Photo taken by author.](image)

Predicting boundary layer flows become more complicated when considering orientations between vertical and horizontal. For any inclined plate, the buoyant plume continues to induce flow vertically from the sample surface. In cases that are much less than 45° off horizontal, the pyrolysis plume behaves similarly to that of a horizontal sample; air can be entrained into the plume from all directions and the flame sheet is more or less conical (see the image in Figure 23 showing a sample at 22° off horizontal). For samples that are inclined much more than 45° but not quite vertical, the flame sheet will likely attach to the sample surface as seen in the vertical case. For samples at 45° off horizontal, the angle beings to have a notable influence on the shape and behavior of the pyrolysis plume. Figure 22 illustrates the results of a numerical simulation conducted by Nakamura and Kashiwagi [72] which show the approximate plume shape for an angled sample ignited by a CO₂ laser; the contours seen in the figure represent the concentration of fuel gasses emitted from the surface. At 45° the simulation predicts that air can continue to be entrained from the top and bottom of the sample. However, once the sample is tilted much further there
will come a point at which the pyrolysis plume will attach to the sample surface and behave similarly to a vertically oriented sample.

Figure 24. Renderings from a numerical simulation conducted by Nakamura and Kashiwagi that demonstrated the approximate flow behavior for a solid heated by a CO$_2$ laser source [72]. Left: 45° off horizontal. Right: 22° off horizontal. The black dot indicates the predicted autoignition point.

The orientation of a heated sample clearly influences the mass transport and fluid mechanics process around the sample surface. The connection between the variation in fluid behavior and ignition is achieved through the concept of the Damkohler Number (Da). Pyrolysis gases must then mix with air to create a flammable mixture, which is dictated by the flow field around the sample. If a mixture exists within the flammable limits and if there is a pilot source that can access that particular flammable region, then piloted ignition occurs. In the absence of a pilot a localized region of gases much reach the autoignition temperature through the absorption of external radiation. Either in the case of piloted or autoignition, ignition must initiate while the pyrolysis gases are in what will be referred to as the reaction zone. There is no chance of ignition once the gases have left the reaction zone. The Damkohler Number is a dimensionless ratio between the residence time of combustible gasses within the reaction zone and the chemical time associated with the reaction [73], [74] – see Figure 26. Therefore, the ratio of the residence time and reaction time can suggest whether or not ignition is possible. This ratio can also be used to predict other fire phenomena such as flame spread; Figure 25 illustrates variation in flame spread rates from forced flow conditions and demonstrates a fairly steady buoyant regime at low velocities and then a flow
dominated regime that results in eventual blow off and extinction. The transition between these regimes of flame spread can be quantified through the Damkohler number. The Damkohler number as traditionally defined can be seen in Equation 20.

\[
Da = \frac{\tau_{res}}{\tau_{chem}} = \frac{\left(\frac{A}{u_{\infty}}\right)}{\left(\frac{1}{\rho a \alpha e / RT_f}\right)} = \frac{\rho a \alpha e / RT_f}{A / u_{\infty}}
\]

Equation 20

Where \(A, E,\) and \(R\) are Arrhenius constants for the reacting fuel, \(\alpha\) represents the thermal diffusivity of the air, and \(u_{\infty}\) is the freestream velocity. The use of the Damkohler number does not, however, consider the induction time associated with autoignition. For autoignition to occur, the pyrolysis gases must absorb enough energy to reach the autoignition temperature before leaving the reaction zone. A modified form of the Da was defined to compare the residence time to what will be defined as the absorption time. This absorption time is closely related to the induction time defined in Chapter 2 which is

Figure 25. Results from flame spread experiments in forced flow environment; originally produced by Fernandez-Pello and Hirano [75].
defined as the time required to initiate combustion in the gas phase. When analyzing piloted ignition, the induction time is assumed to be negligible; therefore, the induction time for autoignition can be approximated as the absorption time defined here. The absorption time will be defined as the approximate time required to raise a differential unit of pyrolysis gases to the autoignition temperature (AIT). The absorption time can be expressed as the ratio of the energy required to reach the AIT and the total heat transfer to the pyrolysis gases.

Figure 26. A schematic showing the location of the reaction zone in the vertical orientation. Autoignition cannot occur if the residence time within the reaction zone is less than the time required to reach the AIT.

Figure 26 illustrates a sample heated in the vertical orientation and outlines the reaction zone indicated by a characteristic length ($l_{ch}$). The energy required for autoignition is approximated as the mass of pyrolysis gasses entering the reaction zone ($m''_p$) multiplied by the specific heat of the pyrolysis gases and the temperature rise to reach the AIT. Pyrolysis gases leave the surface of the sample at a temperature no less than the pyrolysis temperature – therefore, the temperature rise to autoignition will be assumed to be the difference between the AIT of the gas and the pyrolysis temperature of the solid. The net energy into the pyrolysis gases includes the total absorbed energy from the external heat flux and the total absorbed radiation from the sample surface to the pyrolysis gases. Additional considerations for the total heat transfer rate of the pyrolysis gases should include convective heat transfer from the gases to the surface (as the gases will be at a temperature greater than the pyrolysis temperature) and diffusion of ambient air into
the pyrolysis plume through entrainment that cools the pyrolysis plume. Quantifying the exact heat transfer rate into the pyrolysis gases would require additional assumptions to create a simple analytical form, so for this analysis the term will remain as \( q''_{in} \) - a first approximation of this term would ideally ignore the convection losses and entrainment of air which cool the gases to account for only heat into the gases and therefore determining the lower limit of the adsorption time. The residence time within the reaction zone will be modified from the original Damkohler number and will be defined as the characteristic length of the reaction zone \( l_{ch} \) divided by the free stream velocity \( (u_\infty) \) which captures the upper bound of the time in which a particle of pyrolysis gas can remain in the reaction zone. A modified form of the Damkohler number can be found in Equation 26.

\[
t_{abs} = \frac{\text{Energy required to reach AIT}}{\text{Total heat transfer to gases}} = \frac{m_p \rho_c (T_{Alg} - T_P)}{q''_{in}} \tag{Equation 21}
\]

\[
Da_{abs} = \frac{t_{res}}{t_{abs}} = \frac{(l_{ch}/u_\infty)}{\left( \frac{m_p \rho_c (T_{Alg} - T_P)}{q''_{in}} \right)} = \frac{(q''_{in} l_{ch})}{m_p \rho_c (T_{Alg} - T_P) u_\infty} \tag{Equation 22}
\]

The modified Damkohler number lends insight to the likelihood of pyrolysis gases reaching the AIT while still in the reaction zone. The pyrolysis gases may reach the AIT but without a sufficient oxidizer ignition will not occur. Therefore, the characteristic length of the reaction zone \( l_{ch} \) is not necessarily limited to the length over which external radiation is applied. Incorporating the external heat flux into the total heat transfer to the pyrolysis gases \( q''_{in} \) is relatively simple in the case of the vertical orientation; in any other orientation, the pyrolysis gasses are moving towards the heating element due to buoyancy and therefore the external heat flux is effectively increasing as the gasses leave the reaction zone.

The modified Damkohler number can ideally be used to correlate ignition data in various orientations through relating both factors of the system (namely the freestream velocity which should be predominantly a function of orientation) and the testing condition (namely the external heat flux). Applying this dimensionless parameter would however require further information into the absorptivity of pyrolysis gases in different orientations, velocity fields over heated samples in different orientations, and the effect of increasing heat flux as the gases move towards the heat source – this section outlines the fundamental
theory for using such a relationship, however additional studies are required before the modified Damkohler number can be used to correlated ignition data.

5.2 Convective Heat Transfer in Different Orientations

The changing flow conditions of each orientation ultimately influence the convective heat transfer from the heated surface of a tested sample. Understanding the variation in convective heat transfer for different orientations can lend insight into varying ignition results between orientations. In an effort to quantify the variation of convective heat transfer at different orientations, the following correlations will be used to approximate the orientation dependent variations in convective heat transfer.

The convective heat transfer coefficient is generally linked to the Nusselt number which can be defined at different orientations through empirical correlations [76]. The two values are related through the following relationships,

\[ \overline{h} = \frac{\overline{N_u L}}{k_{air}} \]  
Equation 23

Where \( L \) is the characteristic length associated with the Nusselt number and \( k_{air} \) is the thermal conductivity of air. For a flat plate in the horizontal orientation (\( \theta = 0° \)) the following correlation can be used,

\[ \overline{N_u L} = 0.54 \left( Ra L^{1/4} \right) \quad 10^5 < Ra < 10^7 \]  
Equation 24

For a flat plate in the vertical (\( \theta = 90° \)),

\[ \overline{N_u L} = \left[ 0.825 + \frac{0.387 Ra L^{1/6}}{1 + \left( \frac{0.492}{Pr} \right)^{9/16}} \right]^2 \]  
Equation 25

All other orientations (\( 0° < \theta < 90° \)) [77],

\[ \overline{N_u L} = 1 + \frac{0.635}{1 + \left( \frac{0.618}{Pr} \right)^{9/25}} \left( Ra L \cos \theta \right)^{1/4} \quad 5 \times 10^4 \leq Ra < 10^8 \]  
Equation 26
Where the Grashof and Rayleigh numbers are determined through the following,

\[
\frac{Gr_L}{\nu^2} = \frac{g\beta(T_s - T_\infty)L^3}{v^2} \quad \text{Equation 27}
\]

\[
Ra_c = Gr_L Pr = \frac{g\beta(T_s - T_\infty)L^3}{\nu \alpha} \quad \text{Equation 28}
\]

All properties were evaluated at the film temperature \((T_f = 0.5(T_s + T_\infty))\) [76]. All properties of air used throughout this work were taken from the reference found here [30]. Calculating the Nusselt number in this fashion determines the average convective heat transfer coefficient, \(\bar{h}_c\), which will be taken to be the representative convective heat transfer coefficient for calculation purposes (i.e. \(\bar{h}_c = h_c\)).

Convection alone is not the only source of heat losses for a sample. Radiation from the sample surface is dictated by the Stefan-Boltzmann model and has a fourth order dependency on surface temperature [30]. Ignition theory has been traditionally derived through the use of a linearized radiation loss term (as outlined in Chapter 2 along with various sources [2], [5], [7]). The total heat transfer coefficient, \(h_T\), will be defined as seen in Equation 29 [19].

\[
h_T = h_c + h_r = h_c + \varepsilon \sigma (T_s^2 + T_\infty^2) (T_s + T_\infty) \quad \text{Equation 29}
\]

Variation in the convective portion of the heat transfer coefficient is dependent on the sample orientation and the flow fields associated with each orientation. The radiative portion of the heat transfer coefficient is, however, only dependent on the surface temperature of the material. Approximate values for both the convective and radiative heat transfer coefficients for different orientations were calculated for a range of surface temperatures (300-500° C) and are presented in Table 7.

Table 7. Convective and radiative heat transfer coefficients calculated for a range of surface temperatures.

<table>
<thead>
<tr>
<th>Surface Temperature ((T_s))</th>
<th>300° C</th>
<th>400° C</th>
<th>500° C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(h_c) - Horizontal</td>
<td>7.7</td>
<td>13.1</td>
<td>13.7</td>
</tr>
<tr>
<td>(h_c) - 45°</td>
<td>7.4</td>
<td>12.1</td>
<td>12.6</td>
</tr>
<tr>
<td>(h_c) - Vertical</td>
<td>7.4</td>
<td>12.6</td>
<td>13.1</td>
</tr>
<tr>
<td>(h_r)</td>
<td>20.3</td>
<td>29.5</td>
<td>41.3</td>
</tr>
</tbody>
</table>

All values presented in W/m²-K.
The correlations presented for the Nusselt number are derived for flat plates of a uniform surface temperature – real ignition tests are conducted in very specified testing apparatuses and the sample is exposed to an external radiant heat flux that may or may not produce a uniform surface temperature. Some correlations have been produced in previous studies to relate the convective heat transfer anticipated for an ignition experiment to an external heat flux. Past studies commonly assumed a constant convective heat transfer coefficient of 13 W/m²-K regardless of orientation or testing apparatus [6]. The ASTM E1321 standard for the LIFT method recommends a convective heat transfer coefficient of 15 W/m²-K [62]. However, convective heat transfer in ignition testing is not the same for all exposure conditions – an increase in the external radiation can alter the flow conditions at the surface and/or increase the surface temperature of the specimen resulting in heat transfer dependent on the experimental conditions. Deintenberger suggested two different correlations for the convective heat transfer coefficient, one for the LIFT as seen in Equation 40 and one for the Cone Calorimeter seen in Equation 31 [70]. The correlation for the LIFT is a function of the location on the sample (x) and the external heat flux measured at 50 mm down the length of the sample (\( q_{50}^* \)). The LIFT correlation predicts an \( h_{c,LIFT} \) of 29.5 W/m²-K at 25 kW/m² and 35.1 W/m²-K at 50 kW/m².

\[
h_{c,LIFT} = (0.0139 - 0.0138x)(q_{50}^*)^{1/4} \quad \text{Equation 30}
\]

\[
h_{c,Cone} = 0.01433 + 1.33 \times 10^{-4} q_{ex}^* \quad \text{Equation 31}
\]

Another series of correlations originally suggested by Janssens are presented for the Cone Calorimeter and can be seen in Equation 32 and Equation 33. These correlations suggest that the change in convective heat transfer coefficient is different for heat fluxes greater than 50 kW/m² compared to lower heat fluxes.

\[
h_c = 0.0118 + 3.4 \times 10^{-4} q_{ex}^* \quad q_{ex}^* < 50 \text{ kW/m}^2 \quad \text{Equation 32}
\]

\[
h_c = 0.0255 + 6.5 \times 10^{-5} q_{ex}^* \quad q_{ex}^* \geq 50 \text{ kW/m}^2 \quad \text{Equation 33}
\]
A more recent study by Staggs commented on the fact that convective heat transfer is dominated by the surface temperature, not explicitly the external radiation [78]. As such, the study suggested that the Nusselt number and convective heat transfer coefficient can be calculated as seen in Equation 34 and Equation 35.

\[
\overline{N_u} = 0.222 \, Ra_L^{0.348} \quad 4.8 \times 10^6 < Ra_L < 7.1 \times 10^6 \quad \text{Equation 34}
\]

\[
h_c = 8.91 + 0.50(T - 293)^{0.54} \quad 400 \, K \leq T \leq 930 \, K \quad \text{Equation 35}
\]
5.3 Orientation Considerations for Heat and Mass Transport

The orientation of a heated solid influences the fluid behavior around the sample surface and the heat transfer mechanics to and from the surface. This chapter outlined the behavior of the resulting pyrolysis plume from a surface based on the orientation of the sample. The shape and direction of the pyrolysis gases relative to the sample surface dictate the location at which a stochiometric mix will be achieved (i.e. where ignition can occur). When compared to the vertical orientation, a horizontally oriented sample is more likely to achieve ignition conditions all else being equal. The location of the pyrolysis plume also influences the attenuation of radiation to a heated sample – suggesting that the same external heat flux exposure for a given orientation may not produce the same incident absorbed radiation at the surface due to the differences in the pyrolysis plume. Such complications in the gas phase behavior around the sample surface also indicate the dependence of the location of a pilot source on the results of a piloted ignition study. This dependency makes piloted ignition in an experimental study sensitive to sample orientation.

This chapter outlines various approximations of heat transfer coefficients in the context of solid ignition. Flat plate theory has been used to approximate convective heat transfer from the surface of a heated sample, however the user must appreciate the complexities not accounted for in this approximation including the fact the sample surface is emitting pyrolysis gases and that the surface temperature is changing in time. Additional correlations were presented related specifically to experimental apparatuses used in ignition testing and experimentation which suggest higher convective heat transfer values should be used in the context of solid ignition.
“...we want researchers to be viewing each problem as if it were fresh. Practitioners and regulators may feel comfortable with old rules but researchers should not”, Margaret Law and Paula Beever, 1995 [79].

The existing body of literature relating to ignition in various orientations is limited. Few studies investigate the use of the traditional horizontal and vertical orientations, and even fewer studies investigate orientations in between.

6.1 Shields et. al (1993) [25]

One of the earliest and most comprehensive studies on the influence of orientation on ignition was conducted by T.J. Shields, G.W Silcock, and J.J. Murray from the University of Ulster published in 1993. Experiments were conducted on three different cellulosic materials using both the Cone Calorimeter and ISO Ignitability Apparatus in three different orientations. The Cone Calorimeter was used to conduct experiments in the horizontal and vertical orientation, and the ISO Ignitability Apparatus was used to conduct experiments in the horizontal configuration but exposing samples in both the floor and ceiling configurations (i.e. heating from both above and below the sample).

The materials used included 20 mm Sitka Spruce softwood, 12 mm Gaboon plywood, and 15 mm chipboard (particleboard). Cone samples were approximately 100 mm x 100 mm and the ISO Ignitability samples were approximately 165 mm x 165 mm. Experiments in the cone used three modes of ignition (spark, flame, and auto-ignition) and experiments conducted with the ISO Ignitability Apparatus used both a flaming pilot and auto-ignition. The results from these experiments are extensive and thoroughly reported by Shields et. al. An example of the results is reproduced in Table 8. See the full paper for other materials and orientations; only a portion of the data is reproduced here.
Table 8. Reproduced results for experiments conducted using plywood in the Cone Calorimeter by Shields et. al [25].

<table>
<thead>
<tr>
<th>Heat Flux (kW/m²)</th>
<th>Ignition Delay Time (seconds)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spark Vert</td>
<td>135 ± 66</td>
<td>Spark Horz</td>
<td>366 ± 35</td>
<td>Gas Flame Vert</td>
</tr>
<tr>
<td>20</td>
<td>374 ± 71</td>
<td>135 ± 66</td>
<td>366 ± 35</td>
<td>120 ± 13</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>102 ± 11</td>
<td>53 ± 5</td>
<td>93 ± 17</td>
<td>48 ± 5</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>44 ± 6</td>
<td>32 ± 2</td>
<td>40 ± 4</td>
<td>32 ± 3</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>27 ± 2</td>
<td>22 ± 2</td>
<td>19 ± 4</td>
<td>19 ± 3</td>
<td>58 ± 24</td>
</tr>
<tr>
<td>60</td>
<td>19 ± 2</td>
<td>15 ± 2</td>
<td>16 ± 3</td>
<td>15 ± 3</td>
<td>27 ± 3</td>
</tr>
<tr>
<td>70</td>
<td>11 ± 2</td>
<td>11 ± 2</td>
<td>10 ± 2</td>
<td>9 ± 1</td>
<td>18 ± 2</td>
</tr>
</tbody>
</table>

Figure 29. An illustration of the influence of pilot source on ignition delay time. Note that using a flame as a pilot results in consistently faster ignition times compared to using a spark. Data reproduced from Shields et. al [25].

The general trend across all results indicate the ignition is more readily achieved in the horizontal orientation than in the vertical orientation (not considering the ceiling orientation). The use of a pilot also resulted in consistently faster ignition times when compared to auto-ignition, which is no surprise as a
piloted ignition case allows for ideal conditions for ignition while auto-ignition requires substantially larger exposure times to raise the local gas temperature to a point of ignition. It is also worth noting that the choice of pilot source appears to have an influence on the resulting ignition delay times. A gas flame pilot consistently resulted in faster ignition compared to a spark pilot. This is also to be expected when considering the gas flame results in a physically larger pilot element, therefore increasing the probability of contacting a portion of gas above the sample which is in the right stoichiometric conditions to ignite. The gas pilot flame also supplies free radicals that aid in the initiation of the gas phase reaction since the flame itself is undergoing a combustion reaction while the spark is not.

When considering ISO Ignitability Apparatus, results consistently showed that ignition occurred much more readily in the floor orientation than the ceiling orientation. The ceiling orientation adds complexity to the experiment as the fluid dynamics in the ceiling orientation are different than any other orientation. Ignition depends on the residence time of fuel in the reaction zone outside a sample. Due to buoyancy, the pyrolysis gasses emerging from a sample in the ceiling orientation are pushed along the face of the sample to the edges opposed to being lifted from the sample as seen in virtually all other orientations. This effect dramatically influences the residence time and as a result ignition is hard to achieve even with a pilot in the ceiling orientation.

Table 9. Reproduced results from Shields et. al using plywood in the ISO Ignitability apparatus; “normal” orientation indicates a typical horizontal orientation (i.e. floor arrangement) while “inverted” indicates a ceiling orientation [25].

<table>
<thead>
<tr>
<th>Heat Flux (kW/m²)</th>
<th>Ignition Delay Time (seconds)</th>
<th>Gas Flame</th>
<th>Auto-ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nor.</td>
<td>Inv.</td>
<td>Nor.</td>
</tr>
<tr>
<td>20</td>
<td>228</td>
<td>-</td>
<td>585</td>
</tr>
<tr>
<td>30</td>
<td>71</td>
<td>-</td>
<td>211</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>-</td>
<td>80</td>
</tr>
<tr>
<td>50</td>
<td>25</td>
<td>74</td>
<td>42</td>
</tr>
<tr>
<td>60</td>
<td>22</td>
<td>46</td>
<td>29</td>
</tr>
<tr>
<td>70</td>
<td>15</td>
<td>51</td>
<td>19</td>
</tr>
</tbody>
</table>
The earliest study on orientation effects on ignition was conducted by Kashiwagi at the National Bureau of standards in 1982, though the results were not as extensive as the study presented by Shields et al. Kashiwagi’s study primarily focused on the use of a CO₂ laser as an external radiation source in the horizontal and vertical orientation at various levels of irradiance. Experiments were conducted using PMMA and read oak. A small series of experiments were however conducted using gas-fired radiant panels at a single irradiance of approximately 60 kW/m². The results concluded that ignition was more readily achieved in the horizontal orientation. One of the more notable observations from the study was a measurement of the attenuation of the radiation through the pyrolysis plume measured using a heat flux gauge mounted in the sample, as seen in Figure 30. The attenuation of external radiation increased with the intensity of external radiation and attenuation increased rapidly at early times and leveled off later into the experiment. Lower degrees of attenuation were measured in the vertical orientation than the horizontal orientation for a given heat flux. The study also concluded that the attenuation of radiation is strongly dependent on the spectrum of radiation. While no data was presented in this study for the attenuation for other radiant sources, a previous study by Kashiwagi [81] suggests a similar qualitative behavior in attenuation for samples that were exposed to external radiation from an electrical heater used as a grey body radiator.

Figure 30. Attenuation from experiments using a CO₂ laser for PMMA. Originally by Kashiwagi [80].
6.2 Atreya et al. (1986) [82]

Atreya, Carpentier, and Harkleroad presented a study at the first international symposium of the international association of fire safety science (IAFSS) on the effect of sample orientation on ignition and flame spread. The emphasis of the work was primarily on the study of flame spread, however ignition trials were conducted as well. The study explicitly states that a radiant panel was used to expose samples in the vertical orientation but did not specify the heat source for the horizontal orientation (presumably also a radiant panel). The size of the sample, location of the pilot, and pilot source varied between the experiments conducted in the horizontal and vertical orientation (and possible used different heating elements between the orientations) – therefore the results include experimental variation beyond just orientation. The study concluded that the approximate CHF for wood corresponded to 13.2 kW/m² and 15.0 kW/m² for the horizontal and vertical orientations, respectively. The authors then suggest that regardless of the systematic trend in shorter ignition times in the horizontal orientation, that the results “did not show any significant difference between the horizontal and vertical mode”.


The *Ignition Handbook* written by Babrauskas is a very comprehensive body of work on the process of ignition and is referenced frequently throughout this present work. Babrauskas’ work describes various aspects of ignition and dedicates a small section to the influence of orientation. In this section he describes various studies that compare ignition in the horizontal and vertical orientations. It is proposed that the ignition time between the horizontal and vertical orientations can be related with a factor of 1.2 (this is hypothesis that will be thoroughly discussed later in the present study). There is a brief mention to ignition in orientations other than horizontal and vertical, however there is no suggestion of how or why ignition is affected.

6.4 Tsai (2009) [83]

Tsai published a study comparing Cone Calorimeter results from various materials that were conducted in both the horizontal and vertical orientation. The key conclusions from this study include that the time to ignition was consistently longer in the vertical orientation (approximately 1.2 times longer as
established by Babrauskas [6]) and that the CHF was found to be higher for the vertical orientation for all materials (approximated as 1.15 times higher or 15% greater).

6.5 Thomson and Drysdale (1990) [84]

The work conducted by Thomson and Drysdale is a scarce instance in which the researchers actually ran experiments in different orientations besides the horizontal and vertical orientations. The work was inspired by the King’s Cross Station fire in London, after which researchers realized the lack of understanding of how material flammability varies outside of the horizontal and vertical orientations. A modified electrical cone coil was placed on a movable A-frame in which a sample could be tested in numerous orientations (from horizontal to vertical), as illustrated in Figure 31.

![Figure 31. The apparatus Thomson and Drysdale used to test samples in different orientations [84].](image)

This work illustrated that ignition was more readily achieved in the horizontal orientation compared to the vertical orientation (as others had shown previously) – however the study also presented ignition data for three orientations between vertical and horizontal (30°, 45°, and 60°). Time to ignition was reported for two different heat fluxes (17 kW/m² and 31 kW/m²) and it was determined that the fastest time to ignition occurred at 30° from horizontal. The surface temperature at the time of ignition was also recorded. The results from the study are illustrated in Table 10 and Figure 32.

While the work done by Thomson and Drysdale demonstrated ignition behavior beyond the classical horizontal and vertical orientation, the work presents data for a limited trials of external heat flux. There is also no direct incorporation of the orientation effect into existing solid ignition theory.
Table 10. Results from Thomson and Drysdale [84]. Note that horizontal is an angle of 0° and vertical is at an angle of 90°.

<table>
<thead>
<tr>
<th>Orientation (θ)</th>
<th>0°</th>
<th>30°</th>
<th>45°</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>17 kW/m²</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire Point Temp [°C]</td>
<td>294</td>
<td>314</td>
<td>324</td>
<td>325</td>
<td>332</td>
</tr>
<tr>
<td>Ignition Time [s]</td>
<td>268</td>
<td>232</td>
<td>301</td>
<td>344</td>
<td>384</td>
</tr>
<tr>
<td><strong>31 kW/m²</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire Point Temp [°C]</td>
<td>300</td>
<td>308</td>
<td>314</td>
<td>315</td>
<td>325</td>
</tr>
<tr>
<td>Ignition Time [s]</td>
<td>60</td>
<td>55</td>
<td>58</td>
<td>67</td>
<td>73</td>
</tr>
</tbody>
</table>

Figure 32. The results presented by Thomson and Drysdale, indicating that ignition is more readily achieved in an orientation between horizontal and vertical [84]. Note that horizontal is an angle of 0° and vertical is at an angle of 90°.

6.6 Peng et al. (2015) [85]

Peng et. al. ran a series of experiments using PMMA in various orientations and found that in addition to ignition being more readily achieved in the horizontal orientation, ignition was the easiest to achieve at an angle between 15-30° off horizontal. However, the experimental apparatus used was unable to achieve heat fluxes higher than 45 kW/m² which is in the range of irradiance needed for autoignition of
PMMA. This work also used the ignition delay time data to extrapolate the critical heat flux for ignition opposed to verifying the CHF experimentally, resulting in very low CHF values.

6.7 Literature Review Conclusions

The study of radiative ignition of solids dates back over 130 years, however the investigation of orientation effects on ignition is less than exhaustive. Many studies have focused primarily on the vertical and horizontal orientations with only two studies that explored orientations in between (Thomas and Drysdale as well as Peng et. al) – one of which was only conducted using two external heat fluxes and the other used an experimental apparatus that could not exceed irradiances of 45 kW/m² and reported extrapolated CHF values. From these studies, it has been concluded that ignition occurs more readily in the horizontal orientation when compared to the vertical orientation; however, when considering angles between horizontal and vertical, ignition is achieved even more readily at angles between 15-45°. The most conclusive way to predict the orientation effects on ignition has been through the use of a single, constant parameter of approximately 1.2 that theoretically relates the ignition times observed between the horizontal and vertical orientations (meaning the ignition time in the vertical orientation is predicted to be 1.2 times greater than the horizontal orientation for a given heat flux). No study has yet modified existing ignition theory to incorporate a means to account for sample orientation.

The aim of the current study is to develop an understanding of the variation in ignition parameters such as the critical heat flux for ignition between various orientations and to ultimately develop a methodology of data processing to account for orientation effects in ignition data. Most significantly, no previous work has outlined implications of orientation effects on engineering applications of ignition data. Therefore, this work will also serve to discuss how the system dependency of ignition must be considered in engineering applications.
As outlined in the previous chapters, solid phase ignition is a phenomenon that has been well classified with various assumptions and has historical roots in assessing fire safety. For as long as researchers have been investigating and classifying ignition, experiments have been primarily conducted in limited orientations. Standardized ignition tests are virtually limited to the horizontal and vertical orientations. This section outlines the preliminary study conducted to investigate the effect of orientation on ignition.

Ignition can either be tested using a pilot source or through autoignition. In the case of piloted ignition, the location of the pilot is critical in the observed results between orientations. As such, a pilot was not used and all experiments were conducted to observe autoignition.

The experiments were conducted in the Cal Poly Combustion Lab using an ASTM E1354 Cone Calorimeter. Samples were of black cast polymethyl methacrylate (PMMA) with a heated area of 95 x 95 mm and a thickness of 12.5 mm (approximately 1/2 inch). Experiments were conducted in three orientations – vertical, horizontal, and at an angle of 45° off horizontal as seen in Figure 33. For each orientation, samples were exposed to heat fluxes ranging from 30-70 kW/m². A total of three trials were conducted at each orientation and heat flux as specified in ASTM E1354. If a sample was to ignite at a given heat flux, another series of samples would be tested at a heat flux 10 kW/m² less than previously used. When the samples no longer ignited at a given heat flux, the heating element was adjusted in increments of 1 kW/m² until the critical heat flux for ignition was determined. Any sample that exceeded 10 minutes without ignition was considered a “no ignition” case.
Experiments were conducted using standard ASTM E1354 sample holders and the back face and sides of each sample were insulated using ceramic wool. The sample holders were approximately 111 mm x 111 mm with a thickness of 54 mm and a heated area of 95 mm x 95 mm [63]. A Schmidt-Boelter heat flux gauge was used to calibrate the heat flux prior to each trial. The intensity of the cone was adjusted so that the heat flux gauge would read within 1% of the desired heat flux. At a given heat flux, data was recorded over 30 seconds to ensure the average heat flux over that duration remained within 1% of the desired value. The sensitivity of the heat flux gauge was assumed to be approximately 3% of the measured value per the manufacture’s documentation.

7.1 General Results & Determining a Critical Heat Flux (CHF)

Experiments conducted in the horizontal and vertical orientations resulted in critical heat fluxes of 34 kW/m² and 43 kW/m², respectively. As observed in past studies on ignition, there was a distinct variation between the CHF for PMMA in the horizontal and vertical orientations as seen in Figure 34. While a difference in the CHF was expected, the resulting values varied by over 25%. Such a large difference is due in part to the fact that this is considering auto-ignition and not piloted ignition.

Experiments conducted at 45° off horizontal were found to ignite even faster than in the horizontal orientation for the same external heat flux. The critical heat flux at 45° was determined to be 32 kW/m² compared to 34 kW/m² found at horizontal. Such a difference in CHF is arguably negligible given the
sensitivity of the heat flux gauge, however the consistently lower ignition delay times indicated in Table 11 suggest that this observation is a systematic trend.

Figure 34. Results for the auto-ignition of PMMA at horizontal, vertical, and at 45° off horizontal. The results are also displayed in Table 11. CHF for autoignition correspond to 34, 43, and 32 kW/m², respectively.

Table 11. Ignition delay times measured for the auto-ignition of PMMA in various orientations.

<table>
<thead>
<tr>
<th>Heat Flux [kW/m²]</th>
<th>Vertical t_{ig} [s]</th>
<th>Horizontal t_{ig} [s]</th>
<th>45° t_{ig} [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>24</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>60</td>
<td>44</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>50</td>
<td>68</td>
<td>48</td>
<td>37</td>
</tr>
<tr>
<td>45</td>
<td>153</td>
<td>56</td>
<td>50</td>
</tr>
<tr>
<td>44</td>
<td>537</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>43</td>
<td>*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>-</td>
<td>89</td>
<td>118</td>
</tr>
<tr>
<td>35</td>
<td>-</td>
<td>365</td>
<td>191</td>
</tr>
<tr>
<td>34</td>
<td>-</td>
<td>*</td>
<td>-</td>
</tr>
<tr>
<td>33</td>
<td>-</td>
<td>-</td>
<td>614</td>
</tr>
<tr>
<td>32</td>
<td>-</td>
<td>-</td>
<td>*</td>
</tr>
</tbody>
</table>

'-' indicates trials not conducted in a given orientation

'**' indicates the CHF at the given orientation
7.2 Ignition Temperature & Heat Transfer Coefficients

This analysis was conducted following the methodology developed by Quintiere and outlined in Section 2.4.2. The following analysis assumes that a linearized heat transfer coefficient can be used to describe the surface loses until the point of autoignition and assumes that the surface temperature will continue to exceed the pyrolysis temperature until autoignition occurs. Assuming that the surface temperature can exceed the pyrolysis temperature is likely invalid – however this preliminary analysis will illustrate the standard procedure for calculating the ignition temperature using time to ignition data which is currently used to predict autoignition temperature values reported in literature. The analysis will then be compared to a methodology in which the surface temperature is assumed to remain at the pyrolysis temperature.

Assuming the total heat transfer coefficient can be approximated for a given orientation, the ignition temperature can be determined through the critical heat flux using the relationship $CHF = h_f(T_{ig} - T_o)$. The convective heat transfer coefficient will be calculated for each orientation using the correlations for flat plates outlined in Chapter 5. The total heat transfer coefficient is also composed of a radiative portion which can be evaluated if the surface temperature is known. The total heat transfer coefficient is assumed to vary linearly surface temperature while in reality the radiative portion has a fourth-order dependence on the surface temperature. The linearization of the total heat transfer coefficient becomes less accurate at higher surface temperatures [29]; this error will be mitigated by only using the heat transfer coefficient at the point of ignition (i.e. making no assumption about the heat transfer coefficients varying with time and only use the values based on the surface temperature at the point of ignition).

Both the convective and radiative heat transfer coefficients can be expressed as a function of surface temperature. When considering the relationship $CHF = h_f(T_{ig} - T_o)$ the total heat transfer coefficient can then be represented as a function of surface temperature where the convective portion will vary depending on the orientation (as defined in Chapter 5) and the radiative potion is only a function of the surface temperature. By expressing both $h_c$ and $h_r$ as functions of temperature, the experimental CHF can be used to solve for the ignition temperature, $T_{ig}$.  

69
Table 12. The various heat transfer coefficients, critical heat flux, and ignition temperature determined at each orientation.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>$\bar{h}_c$</th>
<th>$\bar{h}_r$</th>
<th>$\bar{h}_r$</th>
<th>$CHF$</th>
<th>$T_{ig}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>13.6 ± 0.1 [W/m²-K]</td>
<td>49.5 ± 7.5 [W/m²-K]</td>
<td>63.1 ± 7.6 [W/m²-K]</td>
<td>34 ± 1 [kW/m²]</td>
<td>558 ± 81 °C</td>
</tr>
<tr>
<td>45°</td>
<td>12.5 ± 0.1 [W/m²-K]</td>
<td>48.1 ± 7.4 [W/m²-K]</td>
<td>60.6 ± 7.5 [W/m²-K]</td>
<td>32 ± 1 [kW/m²]</td>
<td>548 ± 82 °C</td>
</tr>
<tr>
<td>Vertical</td>
<td>13.0 ± 0.1 [W/m²-K]</td>
<td>59.0 ± 8.5 [W/m²-K]</td>
<td>72.0 ± 8.6 [W/m²-K]</td>
<td>43 ± 1 [kW/m²]</td>
<td>617 ± 86 °C</td>
</tr>
</tbody>
</table>

Previous studies cite an auto-ignition temperature for plastics similar to PMMA of approximately 500 ± 100 °C [6]; note the discussion in Chapter 2, however, suggests the concept of an autoignition temperature may not apply in cases such as PMMA. The ignition temperature observed for the vertical orientation is outside the expected range from literature, which is of little surprise as the past studies for similar conditions (i.e. the Cone Calorimeter) were likely conducted in the horizontal orientation and not the vertical orientation.

The radiative portion of the total heat transfer coefficient was dominant compared to the convective portion in all three cases. The convective heat transfer coefficient varied little between each orientation, while the radiative portion was 3.6-4.5 times greater than the convective portion. This is due to the high surface temperatures achieved when considering auto-ignition opposed to piloted ignition and the fact that the radiative heat transfer coefficient has a third-order dependence on surface temperature. If one was to consider average reported ignition temperatures of approximately 300 °C, then the radiative heat transfer coefficient would be on the order of ~20W/m²K compared to the values seen in Table 12.

### 7.3 Ignition Temperature – Constant Surface Temperature

The analysis presented in the previous section assumes that the sample surface temperature continues to rise above the pyrolysis temperature before autoignition occurs. As outlined in Chapter 2, the process of pyrolysis for materials such as PMMA is so highly temperature dependent that the pyrolysis temperature likely serves to regulate the surface temperature to a value close to the pyrolysis temperature. The induction time was previously defined as the time required to initiate combustion in the gas phase once
the pyrolysis time had been reached. Traditionally, the induction time is considered negligible for piloted ignition which allows for the assumption that the pyrolysis time is equal to ignition time. The induction time is non-negligible in the case of autoignition, however, and is primarily associated with the absorption time (discussed in Chapter 5), or the time required for a localized region of pyrolysis gases to reach the autoignition temperature. Therefore, the induction time for autoignition will be approximated in this analysis as the difference between the time at which the surface temperature reaches the pyrolysis temperature (generally defined as the ignition temperature for piloted ignition) and the time at which autoignition occurs. This analysis will be conducted using both a numerical model of the surface temperature and through reported data for piloted ignition.

The time history of the surface temperature was predicted using Equation 6 to approximate the time at which the surface reaches the pyrolysis temperature; Figure 35 illustrates the time histories of the sample surface temperature exposed to heat fluxes ranging from 20-60 kW/m². While past studies have assumed a constant total heat transfer coefficient for such calculations [39], the total heat transfer coefficient for this simulation was calculated in the same way as seen in Section 7.2 by allowing the total heat transfer coefficient to vary with temperature. A wide range of ignition temperatures have been reported for PMMA [2], [5], [6], [38] but generally center around approximately 300°C. The simulated surface temperatures will be capped at an assumed pyrolysis temperature of 300°C which will also be assumed to be the piloted ignition temperature.

A characteristic time must be defined in order to use Equation 6; the characteristic time can be approximated through using the thermal inertia and the total heat transfer coefficient, however this method is very sensitive to the uncertainty in both these terms, and as previously discussed, the apparent thermal inertia as determined by bench-scale testing can vary greatly for a given material [29]. Instead the characteristic time used in this analysis was determined by a linear curve fit through previously published PMMA ignition data – the process through which the characteristic time is isolated will be discussed in detail in Chapter 8. PMMA data suggests an approximate characteristic time of 1111 s (taken from Figure 53 in Chapter 8) which was used throughout the following analysis. Note that the characteristic time associated with processing autoignition data was not used to calculate the surface temperature time
histories. This is because in the derivation of Equation 6 ignition is assumed to be achieved through piloted ignition. The significantly longer induction time seen in autoignition therefore does not provide a characteristic time that is truly representative of the surface temperature time history.

Figure 35. The time history of the sample surface temperature exposed to various heat fluxes calculated using Equation 6. The diamonds at the end of each curve indicate the point at which piloted ignition is assumed to have occurred.

Figure 35 predicts the approximate time to piloted ignition for PMMA under a variety of heating conditions. As mentioned previously, the occurrence of piloted ignition indicates sufficient pyrolysis gases to initiate flaming combustion and therefore the difference between the time to piloted ignition and the time to autoignition reflects the induction time (i.e. approximately the time required for the pyrolysis gases to reach the AIT). Therefore the surface temperatures calculated using Equation 6 can then be compared to the experimentally determined times to autoignition in order to approximate the induction time ($t_i$). The time history solutions presented in Figure 35 were modified to maintain the pyrolysis temperature at the surface until the experimentally determined time to autoignition – the results of which can be found in Figure 36. The difference between the predicted piloted ignition times and the experimentally determined autoignition times serve to indicate the approximate induction time for each external heat flux tested.
Figure 36. Time histories of the sample surface temperature assuming that in the absence of a pilot source the surface temperature will remain constant at the pyrolysis temperature until autoignition. All autoignition times were recorded in the horizontal orientation.

Table 13 presents the time to piloted ignition predicted from using Equation 6 along with experimentally determined piloted ignition times presented in a study conducted by Babrauskas and Wetterlund for black PMMA in the Cone Calorimeter [87]. The experimentally determined time to piloted ignition matches the predicted ignition time closely at high heat fluxes but begins to deviate as the heat flux decreases. The reported time to autoignition in this study at 60 kW/m² exceeds the predictive model and exceeds the recorded time to piloted ignition; previous studies suggest that the time to piloted ignition and autoignition converge at high heat fluxes (on the order of 60 kW/m² or higher) [6], [25] and therefore similar ignition times are expected looking at the data presented at 60 kW/m². The autoignition data would ideally be compared to piloted ignition data using the same batch of material with the same testing
procedure. In the absence of such experimental data, some discrepancy between the results seen Table 13 at high heat fluxes is to be expected. Table 13 also outlines the approximate induction time comparing the autoignition time to the results from Equation 6 ($t_{i,\text{Eq 6}}$) and to the piloted data presented by Babrauskas and Wetterlund ($t_{i,\text{Exp}}$). While the tabulated induction times between the predicted ignition times and the experimental results from the piloted study differ at each heat flux, Figure 37 illustrates that the trend in the induction time is similar between the two calculation methods. At approximately 40 kW/m$^2$ there is a significant increase in the induction time, suggesting that the gas phase behavior is most significant for heat fluxes less than 40 kW/m$^2$.

Table 13. A comparison of the approximate time to piloted ignition as calculated by Equation 6, the experimental piloted ignition results presented by Babrauskas and Wetterlund, and the autoignition times determined in this study. All data presented for the horizontal orientation.

<table>
<thead>
<tr>
<th>Heat Flux [kW/m$^2$]</th>
<th>$t_{i,\text{Piloted}}$ Equation 6 [s]</th>
<th>$t_{i,\text{Piloted Experimental}}$ [s]</th>
<th>$t_{i,\text{Auto This Study}}$ [s]</th>
<th>$t_{i,\text{Eq 6}}$ [s]</th>
<th>$t_{i,\text{Exp}}$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>27</td>
<td>24</td>
<td>21</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>41</td>
<td>27</td>
<td>48</td>
<td>7</td>
<td>21</td>
</tr>
<tr>
<td>45</td>
<td>52</td>
<td>35</td>
<td>56</td>
<td>4</td>
<td>21</td>
</tr>
<tr>
<td>40</td>
<td>71</td>
<td>43</td>
<td>89</td>
<td>18</td>
<td>46</td>
</tr>
<tr>
<td>35</td>
<td>100</td>
<td>51</td>
<td>365</td>
<td>265</td>
<td>314</td>
</tr>
</tbody>
</table>

Figure 37. The induction time required for autoignition compared to both the ignition time predicted by Equation 6 and from the data presented by Babrauskas and Wetterlund [87].
Understanding the variation in the induction time for autoignition provides insight into the gas phase dependency for a given heat flux. The approximate induction time, as seen in Table 13 and Figure 37, quantifies the degree to which the occurrence of ignition becomes dominated by gas phase behavior. In the case of the horizontal orientation, the induction time increases significantly for heat fluxes less than 40 kW/m² – this transition corresponds to the approximate point at which the recorded ignition times begin to asymptote to infinity as the heat flux approaches the CHF.

### 7.4 Ignition Time Ratio (ITR)

When looking just at the horizontal and vertical orientations, previous studies have made an attempt to correlate the ignition time delay between the two orientations [6], [83], [85]. This correlation has generally be assumed to be a linear relationship expressed in the form \( t_{ig, \text{vertical}} = F \left( t_{ig, \text{horizontal}} \right) \). The linear coefficient \( F \) will be referred to as the Ignition Time Ratio (ITR).

The results of two Cone Calorimeter round robin test series reported by Babrauskas suggested an ITR of 1.20 which was determined to be independent of the level of irradiance [6]. Tsai reported an ignition time ratio of 1.16 for multiple wood products and plastic polymers using the Cone Calorimeter [83]. The results presented by Sheilds et. al indicate an ITR of approximately 1.45 when considering the results from tests conducted with plywood, chipboard, and solid timber together [25]. While the ignition delay time is accelerated when using the pilot flame opposed to the spark, little variation exists in the ratio of ignition times between the two pilot sources (an ITR of 1.46 and 1.43 for spark and flame igniters, respectively). The results for the ITR appears to be dependent on sample material. Figure 38 illustrates that each material exhibits a different ITR. If the data set from solid spruce samples were to be considered on its own, the data would result in an ITR of approximately 1.13. However, if the results from the plywood were to be considered individually, the results would indicate an ITR of 1.66.

Figure 38 compares the ITR found for piloted ignition and autoignition. When considering both the autoignition data from the current experimental study and the autoignition results from the study conducted by Shields et. al, the ITR results in a value of 1.64 – a value approximately 25-40% higher than values for the ITR reported by Babrauskas and Tsai (1.15-1.2) and within the spread of the data reported by Shields et. al. Such results suggest that a single ratio to compare the orientation effect on the ignition of a
sample is not valid. Material selection and the mode of ignition are aspects that need to be considered when looking at orientation effects.

Figure 38. Both the results of this experimental study and the results presented by Shields et. al [25] shown to compare ignition delay times in the horizontal and vertical orientation. The data for piloted ignition is based on both the data for spark and flame pilots tested at heat fluxes ranging from 30-60 kW/m$^2$. The data presented for autoignition include results from chipboard, plywood, spruce, and PMMA tested at heat fluxes ranging from 50-70 kW/m$^2$.

It is important to note that there is no theory to support a linear relationship between the time to ignition in the horizontal and vertical orientations – a roughly linear relationship may exist in some cases when correlating ignition times in the horizontal and vertical orientation, however no further information can be extrapolated from the results apart from the approximate ratio between the two times to ignition. The ITR varies appreciably between different materials and across different modes of ignition; as such, there is no single constant that can compare the orientation effects on ignition across all scenarios.
7.5 The Range of Validity for the Short-Time Solutions

There are only two cases which are generally used to process ignition data – the short time, high heat flux solution and the long time, low heat flux solution. Most ignition data is processed using a “short time” assumption which uses the approximation of ignition delay time approaching zero to simplify the Taylor Series expansion of the initial governing equations for ignition. The validity of this assumption is presumed to be sound for scenarios of high heat fluxes (i.e. much larger than the critical heat flux for ignition), however it loses validity as the incident heat flux used approaches the CHF. Various correlations used in fluid mechanics and heat transfer define a range over which the correlation or theory is valid over. Examples of this include using the Reynolds number to determine laminar or turbulent flow, or the use of a Nusselt number to define the range of validity for convective heat transfer correlations. A very coarse suggestion of three times the CHF was suggested in a previous study to validate the use of the short time solution [88], however there exists no equivalent range of values to quantify the transition between the two solutions to ignition theory.

![Graph showing short and long time solutions](image)

Figure 39. An illustration of the short and long time solutions to process ignition data. The diagonal dashed line follows the linear curve fit dictated by the shot time solution and the vertical line indicates the CHF. The data presented was taken from the results for PMMA in the vertical orientation which can be seen to follow the short-time solution for high heat fluxes, then deviate to the long-time solution as it approaches the CHF.
Looking at the results of the autoignition experiments with PMMA, each case fit the short time solution well at high heat fluxes, but then deviated as the experiments approached the CHF. An example can be seen in Figure 39, which illustrates the results from PMMA in the vertical orientation. The vertical results suggest a point of transition around 50 kW/m². If this transition point is then related to the critical heat flux, it is found that the transition from the short-time solution begins to deviate at a ratio of CHF to external heat flux (CHF/\(\dot{q}_e^\ast\)) of approximately 0.85 (for an external heat flux of 50 kW/m² and a critical heat flux of 43 kW/m²).

![Graph showing autoignition data for PMMA in various orientations as a function of 1-CHF/\(\dot{q}_e^\ast\).](image)

Figure 40. The auto-ignition data for PMMA in various orientations presented as a function of 1- CHF/\(\dot{q}_e^\ast\).

Top: indicating the ignition delay time. Bottom: indicating \(t_e^{1/2}\).
When all other cases were examined, the transition from the short solution consistently occurs around a CHF/\dot{q}_e ratio of approximately 0.85. This relationship is evident in Figure 40 which clearly shows the point of transition when plotting using the ratio of external heat flux to CHF for each orientation. Note that the figure uses 1-CHF/\dot{q}_e throughout only to maintain the familiar shape of Figure 40 where the ignition delay time increases asymptotically from the right to left.

Apart from determining the point of transition from the short-time solution, it is interesting to note that when using the ratio of CHF/\dot{q}_e (which will be formally defined in the following chapter) the ignition time delay results for all orientation collapse together in Figure 40. By incorporating the CHF, the ignition behavior can be compared across orientations as the influence of orientation is captured in the CHF.
Chapter 8  
ANALYSIS AND MODIFICATION OF EXISTING THEORY

“The conquest of nature is to be achieved through number and measure” – Decartes, 1619

Preliminary results from the autoignition experiments suggested that grouping the results to account for the CHF of a given orientation can collapse the results together. Such behavior suggests that the CHF may serve as a link to incorporating orientation into existing theory. In order to understand what the physical meaning of the collapsing data and to explain the slope seen in Figure 40, the equations used to describe ignition (outlined in Chapter 2) must first be rearranged to incorporate the CHF. The principle goal of this chapter is to develop a ratio of external heat flux to CHF which will in theory incorporate orientation effects into the analysis.

8.1 Modification to Existing Theory

If one begins with the classically defined “short” and “long” time solutions provided by Lawson and Simms,

\[
\frac{1}{\sqrt{t_{tg}}} = \frac{2}{\sqrt{\pi \sqrt{k_s \rho_p c_p} \overline{s} (T_{ig} - T_o)}}
\]

Equation 8

\[
\frac{1}{\sqrt{t_{tg}}} = \frac{\sqrt{\pi h_f}}{\sqrt{k_s \rho_p c_p} \overline{s} \overline{s}} \left[ 1 - \frac{h_f(T_{ig} - T_\infty)}{q_e''} \right]
\]

Equation 9

\[
CHF = h_f(T_{ig} - T_o)
\]

Equation 10

The “short” time solution will then be rearranged as follows:

\[
\frac{1}{\sqrt{t_{tg}}} = \frac{2}{\sqrt{\pi \sqrt{k_s \rho_p c_p} \overline{s} (T_{ig} - T_o)}} \left[ \frac{CHF}{q_e''} \right] = \frac{2}{\sqrt{\pi \sqrt{k_s \rho_p c_p} \overline{s} (T_{ig} - T_o)}} \frac{h_f(T_{ig} - T_\infty)}{CHF} = \frac{2 h_f}{\sqrt{\pi \sqrt{k_s \rho_p c_p} \overline{s} \overline{s}}} \left( \frac{q_e''}{CHF} \right)
\]

In order to simplify the modified short time solution seen above, additional terms will be defined. If the following relationships are defined,
\[
\frac{q_e''}{CHF} = \Psi \quad \text{Equation 36}
\]

\[
\frac{h_T}{\sqrt{k_S p_S e_S}} = \Lambda \quad \text{Equation 37}
\]

Then the short time solution reduces to what is seen in Equation 38. The resulting equation incorporates both the CHF through the parameter \(\Psi\), and also incorporates the term \(\Lambda\) that relates the heat losses from the sample \((h_T)\) and also incorporates the material properties captured in the thermal inertia. A similar parameter to \(\Psi\) can be found in previous work that processed ignition data as a ratio of surface losses to external heat flux \([89]\). \(\Lambda\) is also directly related to the characteristic time as defined by Torero \([7]\) – both terms serve as a surrogate for the ratio of heat lost from the surface to heat conducted into the solid that then contributes to pyrolysis and eventual ignition.

\[
\frac{1}{\sqrt{T_{ig}}} = \frac{2}{\sqrt{\pi}} \Lambda \Psi \quad \text{Equation 38}
\]

A similar process can be done using the “long time” solution seen originally in Equation 9,

\[
\frac{1}{\sqrt{T_{ig}}} = \frac{\sqrt{\pi h_T}}{\sqrt{k_S p_S e_S}} \left[ 1 - \frac{h_T(T_{ig} - T_{ref})}{q_e''} \right] = \frac{\sqrt{\pi h_T}}{\sqrt{k_S p_S e_S}} \left[ 1 - \frac{CHF}{q_e''} \right]
\]

Or,

\[
\frac{1}{\sqrt{T_{ig}}} = \sqrt{\pi} \Lambda \left[ 1 - \frac{1}{\Psi} \right] \quad \text{Equation 39}
\]

The modified equations exhibit the same general form as the traditionally defined equations in that ignition data can be plotted as \(1/\sqrt{T_{ig}}\) vs \(\Psi\) in the same way data is conventionally plotted as \(1/\sqrt{T_{ig}}\) vs \(q_e''\). The \(\Psi\) parameter incorporates the CHF for a given orientation which allows the experimental data in all orientations to collapse. The parameter \(\Lambda\) also captures both the losses from the surface (which should be system dependent and vary with orientation) as well as the thermal inertia of the material which should not be system dependent.

As a point of comparison, the original equations derived by Delichatsios were modified in a similar fashion to incorporate the \(\Psi\) parameter. The results of the modification can be found in Table 14. Both the model developed by Lawson and Simms and the model developed by Delichatsios will be used to
process the experimental data and investigate the possibility of incorporating a CHF/external heat flux ratio into existing ignition theory.

Table 14. The traditional and modified equations from existing ignition theory.

<table>
<thead>
<tr>
<th>Lawson and Simms</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Short Time</strong></td>
<td><strong>Long Time</strong></td>
</tr>
<tr>
<td>Traditional Equation</td>
<td>$\frac{1}{\sqrt{t_{ig}}} = \frac{2}{\sqrt{\pi}} \frac{\dot{q}''}{k_{s}r_{s}c_{s} (T_{ig} - T_{0})}$</td>
</tr>
<tr>
<td>Modified Equation</td>
<td>$\frac{1}{\sqrt{t_{ig}}} = \frac{2}{\sqrt{\pi}} \Lambda \Psi$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Delichatsios</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Short Time</strong></td>
</tr>
<tr>
<td>Traditional Equation</td>
</tr>
<tr>
<td>Modified Equation</td>
</tr>
</tbody>
</table>

8.2 Analysis of Autoignition Results

The modified equations presented in Table 14 will be used to process the experimental data for autoignition of black PMMA presented in Chapter 7. Figure 41 illustrates the ignition time data for all the orientations tested; when plotted as a function of external heat flux, the data from different orientations exhibit varying behavior in both their time to ignition and inverse ignition time data (i.e. $1/\sqrt{t_{ig}}$). Considering the fact that these experiments were conducted using auto ignition, and that the theory used assumes piloted ignition to reduce the induction time the theoretical models show a remarkably good prediction of the general trends and behavior of the data; suggesting that while a higher degree of uncertainty is associated with using this theory for autoignition, the overall trends are still captured.
Figure 41. Results for the auto-ignition of PMMA at horizontal, vertical, and at 45° off horizontal. Plots illustrate both the time to ignition data (left) and the inverse ignition time data (right) as a function of external heat flux.

Figure 42. Two regimes of ignition illustrated through plotting the inverse ignition time as a function of the heat flux ratio ($\Psi$): 1) a high irradiance regime that follows a relatively linear curve and 2) a low irradiance regime as the external heat flux approaches the CHF which results in a $1/x$ decay. The shaded region indicates a transition regime in which data may fit one, both, or neither of the theoretical models well.

Based on the results presented previously in Figure 40, using the CHF to normalize ignition data results in two distinct regimes. At high heat fluxes relative to the CHF, ignition data fit a linear curve when
plotted as the inverse ignition time (i.e. a High Irradiance Regime). As the external heat flux approaches the CHF, the inverse ignition time behavior becomes non-linear and behaves as a decaying $1/x$ function (i.e. a Low Irradiance Regime). Both of these regimes can be observed in all orientations when plotting the data as a function of the heat flux ratio $\Psi$ which inherently incorporates the orientation effects by accounting for the CHF. The transition between these two regimes occurs over a range that has not been previously defined. For the experimental data considered here, the transition between the two regimes occurs approximately between a $\Psi$ value of 1.15 to 1.25 (15-25% in excess of the CHF). The classical “long time” and “short time” equations were originally defined for two extreme conditions – one being an infinite time to ignition and the other being an approximately instantaneous ignition. Data within the transition interval may or may not fit the theoretical models of either regime. Having a region of transition opposed to a single point of transition can be seen in the transition of other phenomena such as the transition from laminar to turbulent flow in fluid mechanics [90] and therefore appears to be an appropriate means of defining the transition seen here.

For the experimental data considered in this analysis, only three data points fell within the transitional range (one for each orientation tested). For both the horizontal and vertical orientations, the point in the transitional range fit the linear relationship seen in Figure 42 and were included in the High Irradiance Regime analysis; the transitional point for the 45° orientation deviated greatly from the linear curve fit so it was not considered in the High Irradiance Regime analysis. None of the data points within the transitional region were considered in the Low Irradiance Regime.

### 8.2.1 Lawson and Simms

#### (i) High Irradiance Regime

As seen in Table 14, the “short time” solution from Lawson and Simms can be rearranged to incorporate the heat flux ratio $\Psi$. The results indicate that the data in the High Irradiance Regime can be fit to a linear curve through the origin when plotted as $1/\sqrt{t_0}$ vs $\Psi$. The slope of the resulting line is $\frac{2}{\sqrt{\pi}} \Lambda$, where $\Lambda$ represents the ratio of the total heat transfer coefficient to the square root of the thermal inertia.
Therefore, the slope of the linear curve fit lends insight to both a system dependent parameter in the form of the total heat transfer coefficient and a material parameter in the form of the thermal inertia.

Figure 43. Left: inverse time of ignition results plotted against external heat flux for all orientations tested using Lawson and Simm’s theory. Right: results plotted as a function of $\Psi$.

Plotting the data as a function of external heat flux results in three distinct linear curves with differing slopes for each orientation. These different slopes correspond to the variation in the value of 

$$\frac{2}{\sqrt{\pi}} \frac{1}{\sqrt{k \rho C_p s S (T_0 - T_a)}}$$

for each orientation; if the ignition temperature and thermal inertia were assumed to be material properties than the slope of each line should be constant for any one material. The variation in the resulting slopes seen in Figure 43 suggest that these values are in fact dependent on the system. The introduction of $\Psi$ results in a collapse of the three orientation onto a single line as indicated in both Figure 43 and Figure 44. A single slope corresponds to a single predicted value for $\Lambda$ for all orientations; the system dependence of the total heat transfer coefficient suggests that $h_T$ is not the same between different orientations while the thermal inertia should be in fact constant as a material dependent property. The single slope suggests that instead the ratio of the total heat transfer coefficient (i.e. the manifestation of total heat losses) to the perceived material thermal inertia is constant for all orientations – both values are likely to change between different orientations. The value of $\Lambda$ can be calculated from the slope presented in Figure 44; using Lawson and Simms’ theory, the resulting value for $\Lambda$ is approximately 0.101 s$^{-1/2}$ when considering the High Irradiance Regime data. From visual observation, the resulting curve fit does not follow the same line as a linear curve fit that is not forced through the origin. This results in an $R^2$ value of
approximately 0.9, and there is a clear delineation of the higher values of $\Psi$ being underpredicted by the curve fit and lower values of $\Psi$ being over predicted by the curve fit. This is likely to be a result of the break down in the Lawson and Simms theory which assumes a linearized heat loss term – an assumption that is likely not true at such high heat fluxes and when considering autoignition.

![Graph showing inverse time of ignition results plotted against $\Psi$ for the modified form of Lawson and Simm's equation; the use of $\Psi$ collapses the data into a relative constant linear function.](image)

**Figure 44.** Inverse time of ignition results plotted against $\Psi$ for the modified form of Lawson and Simm’s equation; the use of $\Psi$ collapses the data into a relative constant linear function.

**(ii) Low Irradiance Regime**

Based on the theory presented by Lawson and Simms, the “long time” solution can be rearranged such that the modified equation is a function of $1 - 1/\Psi$. Plotting the experimental data within the Low Irradiance Regime illustrates the anticipated $1/x$ behavior as seen in Figure 45. If only the values corresponding to $\Psi<1.15$ are considered, then the data can also be plotted as a function of $1 - 1/\Psi$ as seen in Figure 46. For the Low Irradiance Regime, plotting the data in such a way creates a linear curve fit through the origin, the slope of which being $\sqrt{\pi}A$. As seen in the analysis done for the High Irradiance Regime, processing the data in such a way should in theory collapse all of the data regardless of orientation. The data collected for the horizontal orientation unfortunately only includes one data point within the defined Low Irradiance Regime; however if a line is to be fit between the one point in consideration, then the slope of the curve fit is virtually identical to the curve for the vertical orientation (within 0.07%). The resulting slope from the trials at 45° does not however coincide with the same linear curve fit. The resulting slope differs by 51% when considering the two points within the Low Irradiance Regime.
Regime and up to 27\% if only the lowest value of $\Psi$ is considered. If average slope of the horizontal and vertical curve fits are taken as $1.833 \text{ s}^{-1/2}$, then by using the modified equation for the long time solution, $\Lambda$ is to be approximated as $1.03 \text{ s}^{-1/2}$. The predicted value of $\Lambda$ for the Low Irradiance Regime is approximately ten times higher than the predicted value for the High Irradiance Regime. This discrepancy could be due to a lack of data resolution at such low heat fluxes. The discrepancy may however indicate that the $\Lambda$ value expresses that the characteristic time behaves differently between the Low and High Irradiance regimes and that one value alone cannot describe $\Lambda$ for all values of $\Psi$.

Figure 45. Inverse time of ignition results plotted against $\Psi$. Note the values seen for $\Psi>1.15$ are shown for illustration only and will not be considered in the Low Irradiance Regime analysis.

Figure 46. Inverse time plotted against $1 - 1/\Psi$. 

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8.2.2 Delichatsios

(i) High Irradiance Regime

The modified equations presented in Table 14 can also be used to express Delichatsios’ theory. Similar to the analysis done with Lawson and Simms’ theory, the experimental results indicate that the data in the High Irradiance Regime can be fit to a linear curve through the origin when plotted as $1/\sqrt{t_{ig}}$ vs $\Psi - 0.64$. The difference between the two fundamental theories is that Lawson and Simms’ model must be forced through the origin while in Delichatsios model the intercept of the heat flux axis is the CHF. When plotted as a function of $\Psi - 0.64$ the experimental data collapses and creates a single curve through the origin. Plotting the data as a function of $\Psi$ would result in the similar results to that seen in Figure 43 but the curve would not pass through the origin for the Delichatsios model.

![Graphs](image)

Figure 47. Left: inverse time of ignition results plotted against external heat flux for all orientations tested using Delichatsios’ theory. Right: results plotted as a function of $\Psi - 0.64$.

As seen in Table 14 the slope of the modified theory of Lawson and Simms and of Delichatsios should be equal when plotted as they are presented in both Figure 44 and Figure 48. The slope presented in Figure 48 can be used to calculate the value of $\Lambda$. Using the modified Delichatsios’ theory results in a $\Lambda$ value of $0.163 \text{ s}^{-1/2}$ for the data in the High Irradiance Regime. This value differs from the predicted value from Lawson and Simms by 61%. The linear curve fit from the Delichatsios model does produce a better fit
to the experimental data which is captured in both a slight improvement in the $R^2$ value and in the fact that the overpredicting and underpredicting trend seen in Figure 44 is not present.

![Graph](image)

Figure 48. Inverse time of ignition results plotted against $\Psi - 0.64$ for the modified form of Delichatsios’ equation; the use of $\Psi$ collapses the data into a relative constant linear function.

**(ii) Low Irradiance Regime**

![Graph](image)

Figure 49. Inverse time of ignition results plotted against $\Psi - 1$.

As seen in the case for the Lawson and Simms solution, the Low Irradiance Regime data produces more scatter in than seen in the High Irradiance Regime. Figure 49 illustrates the data plotted as a function of $\Psi - 1$ which should also produce a linear curve through the origin. The horizontal and vertical cases resulted in similar slopes (~1%) while the slope of the data at 45° differs by approximately 54% based upon
two data points or 27% when only the lowest value of $\Psi$ is considered. Using the modified equation for the “long time” solution and a slope of $1.77 \text{ s}^{1/2}$ (the average of the horizontal and vertical cases), $\Lambda$ can be approximated as $1.00 \text{ s}^{1/2}$. The predicted $\Lambda$ value is within 3% of the value predicted by the Lawson and Simms solution for the Low Irradiance Regime and is approximately ten times the value predicted by the modified Delichatsios High Irradiance Regime solution (as was the case for the Lawson and Simms solution). Again, the discrepancy between the predicted values of $\Lambda$ for the Low Irradiance Regime and High Irradiance Regime may be due to an insufficient amount of data or from the fact that the characteristic time that is captured by $\Lambda$ actually varies between the regimes.

8.3 Predicting Critical Heat Flux

One common aspect of ignition data processing is the using ignition time delay data to predict the critical heat flux for ignition. While there is validity in some approaches to predicting the CHF, this process carries with it great uncertainty depending on the data used and is a large proponent of the degree of scatter seen in CHF values reported throughout literature. Lawson and Simms’ original work predicted that when data is plotted as the external heat flux vs. $1/\sqrt{t_{1/2}}$ then the CHF for ignition would be determined at the intercept of the external heat flux axis [31]. However, this was ultimately not considered when using the “short time” solution and is generally not used with the “long time” solution in common practice. Predicting the CHF is however used commonly when considering the Delichatsios approach to ignition data processing.

The practice of experimentally determining the CHF, through a process referred to as bracketing, involves a very iterative process of trying heat fluxes close to the CHF until ignition no longer occurs. In principle the methodology is simple, however there are multiple often disregarded complications of this process. As the external heat flux approaches the CHF, the recorded ignition times increase dramatically – with the increase of ignition time comes an increase in statistical scatter within the results (statistical uncertainty in ignition time data is addressed in detail in Chapter 9). Additional trials are required at low heat fluxes to ensure that a truly representative value is used for the time to ignition. Therefore, the process of bracketing is both time consuming and requires a high number of available samples. Such a process may not be possible if the amount of a tested material is limited. Additionally, the “no ignition” condition is
defined by an arbitrary length of time over which ignition does not occur. For example, if the “no ignition”
condition is set to 10 minutes as was used by Shields et. al [25], then any the CHF is determined as the
lowest heat flux at which ignition does not occur within 10 minutes regardless if ignition would have
occurred one second past the 10 minute mark. The sensitivity to the length of time used to experimentally
determine the CHF adds additional uncertainty to the measured value.

Current methodologies result in a high degree of scatter in predicted CHF and determining the
CHF experimentally can be a time consuming, iterative process with a high degree of uncertainty as the
ignition times asymptote to infinity. A refined methodology for predicting the CHF from experimental
values without bracketing would be a benefit to ignition data processing. The following analysis illustrates
both the uncertainty of current methods to predict CHF and a possible solution to make more accurate
predictions.

8.3.1 High Irradiance Regime

Based on the equations presented in Table 14, the short time solution presented by Lawson and
Simms does not include the CHF. The theory presented by Delichatsios on the other hand indicates that the
CHF can be solved for using the experimentally determined ignition time data. The Delichatsios short time
solution is used to predict the CHF for a given material in past studies with varying degrees of accuracy –
using the equation to predict the CHF is one of the largest contributions to such a large discrepancy
between the MHF and CHF as described in Section 2.1.2 and demonstrated by Babrauskas [6].

Figure 47 illustrates the results of the short time solution for Delichatsios’ theory ($\Psi<1.15$); the
results plotted as a function or external heat flux can be rearranged to solve for the CHF which is simply
the intercept of the external heat flux axis. Solving for the intercept in Figure 47 results in the predicted
CHF; these results are presented in Table 15. The predicted CHF underestimates the CHF by up to 26%.
Such a calculation will always underpredict the CHF as a linear curve fit will not account for the
asymptotic decay of $1/\sqrt{\varphi}$ as the external heat flux approaches the CHF (see Figure 41).
Table 15. Predicted CHF values (MHF) compared to the experimentally determined CHF values.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Experimental [kW/m²]</th>
<th>Predicted [kW/m²]</th>
<th>Predicted/Experimental [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>34</td>
<td>26.00</td>
<td>0.76</td>
</tr>
<tr>
<td>45°</td>
<td>32</td>
<td>28.06</td>
<td>0.88</td>
</tr>
<tr>
<td>Vertical</td>
<td>43</td>
<td>33.04</td>
<td>0.77</td>
</tr>
</tbody>
</table>

8.3.2 Low Irradiance Regime

As illustrated previously in Figure 45 and Figure 49, ignition data for heat fluxes particularly close to the CHF are poorly represented by a linear curve fit. Lawson and Simms’ original theory suggests that the intercept of the heat flux axis is in fact an accurate representation of the theoretical critical heat flux for ignition – the trouble is, however, accurately modeling the approach to the axis as the heat flux approaches the CHF. A linear curve fit does not capture the true nature of the data because the long time solution suggested by Lawson and Simms is such that $1/\sqrt{\dot{q}_0}$ is a function of $1/\dot{q}_e''$. The long time solution can be represented in the form $y = m (1 - C/x)$, where $y$ is the ignition data plotted $1/\sqrt{\dot{q}_0}$, $m$ represents $\sqrt{\pi h_f/\sqrt{kpc}}$, $C$ represents the CHF, and $x$ is the external heat flux. When the solution is considered in this way, the value of $C$ corresponds to the intercept of the $x$ (or heat flux) axis, as seen in Figure 50. The slope of the function is fairly linear until the heat flux values approach the CHF.

![Figure 50. A graphical representation of the behavior of the long time solution by Lawson and Simms’](image)

$y = m \left(1 - \frac{C}{x}\right)$

$m = 1, C = 30$
The most accurate representation according to the theory would be to curve fit the ignition data to a function of \( m \left( 1 - \frac{C}{\chi} \right) \); however, fitting data to such a function is not ideal for simple data processing techniques. Simpler approximations can be used to predict the CHF with high resolution that add very little to data processing – the predicted CHF values for each of the following methods can be seen in Table 16. Simply plotting the Low Irradiance Regime data as \( \frac{1}{t_{ig}} \) vs \( \dot{q}_e'' \) leads to a poor linear curve fit and underestimated CHF predictions similar to those seen in Table 15. If the data is instead plotted as \( \frac{1}{t_{ig}} \) vs \( \dot{q}_e'^\prime \), i.e. \( y = \left[ m \left( 1 - \frac{C}{\chi} \right) \right]^2 \), then a much more accurate prediction of the CHF can be obtained. Using a simple linear curve fit for the \( \frac{1}{t_{ig}} \) vs \( \dot{q}_e'^\prime \) data can predict a CHF value within 3% of the experimentally determined CHF; using a second-order polynomial curve fit to the same data predicts the CHF within 1% of the experimental value. Both of these approaches approximate the CHF well within the uncertainty of an experimental measurement itself. Previous studies have suggested the use of plotting \( \frac{1}{t_{ig}} \) vs \( \dot{q}_e'^\prime \) to predict the CHF, however did not offer any physical insight into why such an approximation works [91], [92]; the validity of this approach will be discussed further here.

![Figure 51](image-url)

Figure 51. Reciprocal of ignition time plotted against the external heat flux for “long time” data where the CHF is the intercept of the heat flux axis; intercept found with both a linear curve fit (left) and a second order polynomial fit (right).
Table 16. Predicted CHF values using the “long time” ignition data compared to the experimentally
determined CHF.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Experimental $q''_{ex}$</th>
<th>Linear $q''_{ex}$</th>
<th>Quadratic $q''_{ex}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>[kW/m$^2$]</td>
<td>[kW/m$^2$]</td>
<td>[kW/m$^2$]</td>
</tr>
<tr>
<td>34</td>
<td>26.1</td>
<td>33.6</td>
<td>33.7</td>
</tr>
<tr>
<td>45°</td>
<td>32</td>
<td>28.0</td>
<td>31.1</td>
</tr>
<tr>
<td>Vertical</td>
<td>43</td>
<td>39.4</td>
<td>42.1</td>
</tr>
</tbody>
</table>

The process of squaring the original solution and plotting the data as a function of $1/t_{ig}$ vs $q''_{e}$ is only an approximation but allows for a more accurate linear curve fit through the heat flux axis. Figure 52 illustrates that by squaring the $m \left( 1 - C/X \right)$ function, the resulting curve can be much better approximated with a linear curve. Using this approach still approximates a curve that is not entirely linear, but this assumption is found to produce results that suggest this to be a valid assumption. Considering a polynomial curve fit seems to better fit the general trend in the plotted data. Fitting the data to a polynomial curve fit would only be accurate if the resulting curve exhibits the same general trends to be expected of the $m \left( 1 - C/X \right)$ curve – in particular, the curve must at the least be a parabolic function with a negative concavity with real roots to ensure that a real intercept of the heat flux axis exists. However, using a polynomial curve fit to $1/t_{ig}$ adds no physical insight from the theoretical models and offers marginal benefit to a simple linear curve fit.

Figure 52. A comparison of a linear approximation when plotting $1/\sqrt{t_{ig}}$ vs $q''_{e}$ (left) and $1/t_{ig}$ vs $q''_{e}$ (right); using a $1/t_{ig}$ relationship significantly increases the accuracy of a linear curve fit.
Theoretically, fitting the data to a function in the form of \( m \left( 1 - \frac{c}{x} \right) \) would yield the most accurate result; to do so would be cumbersome with in the current structure of ignition data processing. The predominantly used processing methodology used already incorporates data processed as \( \frac{1}{\sqrt[4]{t_{ig}}} \) vs \( \dot{q}_e'' \), so introducing a \( \frac{1}{t_{ig}} \) vs \( \dot{q}_e'' \) relationship adds little marginal effort compared to form fitting a multiplicative inverse function. The use of a linear curve fit through data presented as \( \frac{1}{t_{ig}} \) vs \( \dot{q}_e'' \) adequately predict the same CHF as would be determined experimentally considering this particular data set.

The practical benefit of this proposed prediction methodology is only realized if the user does not have to bracket heat fluxes experimentally and therefore commit time and resources to the iterative process. Using the relationship of \( \frac{1}{t_{ig}} \) vs \( \dot{q}_e'' \) to predict the CHF as seen in Figure 51 requires at least three data points spread over \( \Psi \) values of approximately 1.05 – 1.30. Higher accuracy in the predicted CHF results from at least two of the points laying between the CHF and \( \Psi =1.15 \). If the data points corresponding to the lowest heat flux tested were removed, the predicted results from a linear curve using \( \frac{1}{\sqrt[4]{t_{ig}}} \) vs \( \dot{q}_e'' \) still predicts the CHF for the vertical orientation within 3%, but the predicted values for the horizontal and 45° orientations differ from the experimental values by 9% and 20%, respectively. This process is therefore not effective if data is not taken sufficiently close to the CHF – this can be mitigated through the use of the \( \Psi \) parameter but becomes complicated as the \( \Psi \) parameter is inherently dependent on the actual CHF value (therefore requires a rough approximation of a predicted CHF). If a consistent procedure was to be developed using this approach, researchers who are limited in time or resources could potentially predict the CHF without bracketing and risking an unknown amount of iterations that may not actually result in determining the CHF. Therefore, this procedure has merit but requires further experimentation and validation across other materials and other modes of ignition (namely a piloted study).

8.4 Modified Theory Applied to Previous Studies

A high degree of scatter exists between previously published ignition data for the same material. As discussed previously, this variation can be attributed to many factors such as the apparatus used and the orientation of the sample. This chapter has already demonstrated that by incorporating the CHF into existing ignition theory, through the use of the parameter \( \Psi \), results can be collapsed into a single curve
regardless of orientation (i.e. the CHF incorporates the orientation effects). This same concept can also be applied to previous studies that exhibit differing results for ignition.

Black PMMA has been studied extensively in previous ignition studies [34], [37], [69], [83], [87], [93], [94]. Different studies conducting experiments on the same material often yield different results – this is captured clearly looking at PMMA in particular in work by Bal and Rein [71]. While PMMA is one of the most, if not the most, studied material in bench-scale fire testing, ignition time results for a given external heat flux and reported CHF values vary between studies. The scatter in reported CHF values for PMMA is also reflected in a reported range of 6-23 kW/m² in the appendix of the SFPE Handbook [1].

Figure 53. Piloted ignition data for black PMMA from various sources over 27 years of experiment.

Incorporating $\Psi$ (bottom figure) reduces the variation between experimental studies, even between results from differing experimental apparatus.
Figure 53 illustrates the scatter in ignition data presented in the form of $1/\sqrt{t_{ig}}$ vs $q''_e$; the data presented spans 27 years of experiments and includes data from the Cone Calorimeter (Rhodes [69], Luche [93], and Babrauskas [87]), the LIFT apparatus (Quintiere [34]), the Fire Propagation Apparatus (Tewarson [37]), and the ISO Ignitability Apparatus (Thomson [94]). The scatter observed is not only caused by orientation of the tested sample, as is observed by the FPA and cone results (both in the horizontal orientation) having both the steepest and shallowest curves, with the LIFT data (vertical orientation) falling between the two. Using this data to calculate the slope of a linear curve fit would result in slopes ranging from 0.0026 to 0.0054 (i.e. ±35%) resulting in a high degree of uncertainty for calculated parameters from the slope.

If the data is to instead be normalized by the reported CHF and instead be plotted $1/\sqrt{t_{ig}}$ vs $\Psi$, then the data from each experiment collapses onto a single curve. The incorporation of an experimentally determined CHF therefore accounts for more than just the orientation of a sample; variations due to the use of different heating elements, uncertainty in heat flux measurements, and other factors such as flow conditions around the surface at ignition are all captured by the experimentally determined CHF (and therefore considered in the use of $\Psi$). Note that where an experimentally determined CHF was not provided in the referenced study, one was approximated from the asymptotic behavior of the ignition data.

The range of $\Psi$ observed for piloted ignition is much larger than seen in Figure 42 for the autoignition data; this is to be expected due to the simple fact that experimental heat fluxes are relatively limited for the Cone Calorimeter and that the experimental CHF for piloted ignition can be 3 to 5 times less than autoignition CHF values. Therefore, the data from piloted ignition studies are not expected to collapse in the same manner as autoignition data when plotted as a function of $\Psi$. Figure 54 illustrates the different behavior between piloted and autoignition data when plotted as $1/\sqrt{t_{ig}}$ vs $\Psi$. Such a variation in resulting curves is expected since the parameter $\Psi$ inherently incorporates different CHF values (for piloted, approximately 8-12 kW/m$^2$, or for autoignition, approximately 30-45 kW/m$^2$). The variation also implies that the range of $\Psi$ used to characterize the transition from the High Irradiance Regime to the Low Irradiance Regime for autoignition does not correspond to the same range of $\Psi$ for piloted ignition. The data presented from previous studies on piloted ignition do not provide enough resolution at heat fluxes that
transition between the two heating regimes. Further experimentation is required to determine the range of \( \Psi \) values over which the transition between heating regimes is to be expected for piloted ignition. With a higher resolution of data at low heat fluxes, a plot similar to Figure 42 can be created to illustrate the transition between the two regimes and define a transition interval as a range of \( \Psi \) values.

![Graph](image)

Figure 54. A comparison of the piloted ignition studies described in Figure 53 compared with the Autoignition data provided by this study as well as by Tsai [38] and Peng [85].

8.5 Discussion and Conclusions from Modified Theory

Ignition data conducted at various orientations collapse into a single curve through the use of \( \Psi \), which captures for the orientation dependency in the experimentally determined CHF. The results suggest that the slope of the data, \( \Lambda \), is constant regardless of orientation. In other words, the ratio of \( h_t / \sqrt{k_{sp}c_s} \) remains constant in all orientations. The rate of heat transfer from the surface is system dependent and will inherently change with orientation; thus, the fact that \( \Lambda \) remains constant suggests that the thermal inertia is dependent on orientation to account for variations in the heat transfer coefficient. The term defined as \( \Lambda \) in this work is closely related to the characteristic time as defined in other works [6], [7]. Therefore, the results of this study also suggest that the characteristic time remains constant with orientation for a given material. Current analysis in flame spread modelling and ignition modelling generally use the thermal inertia of a material as determined through a form of testing or experimentation. If the characteristic time remains constant for all orientation, suggesting that the thermal inertia in fact varies based upon the
orientation, then perhaps some form of the characteristic time (or \( \Lambda \)) as determined here may prove as a more useful input to modeling applications. Table 17 shows the tabulated values for \( \Lambda \) and the variation between irradiation regimes and mode of ignition.

Table 17. Calculated values for \( \Lambda \) for both the autoignition data presented in this study and the piloted ignition data from previous studies seen in Figure 53. Data presented for both the High Irradiance Regime (HIR) and Low Irradiance Regime (LIR) for autoignition.

<table>
<thead>
<tr>
<th></th>
<th>Autoignition</th>
<th></th>
<th>Piloted Ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HIR</td>
<td>LIR</td>
<td>HIR</td>
</tr>
<tr>
<td>( \Lambda [s^{1/2}] )</td>
<td>( \Lambda [s^{1/2}] )</td>
<td>( \Lambda [s^{1/2}] )</td>
<td></td>
</tr>
<tr>
<td>Lawson and Simms</td>
<td>0.101</td>
<td>1.03</td>
<td>0.032</td>
</tr>
<tr>
<td>Delichatsios</td>
<td>0.163</td>
<td>1.00</td>
<td>0.039</td>
</tr>
</tbody>
</table>

\( \Lambda \) was found to be constant for PMMA but varies between data for piloted ignition and autoignition. Further experimentation is required to understand how \( \Lambda \) varies between different materials. The use of \( \Psi \) can determine the approximate transition between the High Irradiance and Low Irradiance regimes. For the black PMMA used in these experiments at autoignition, the transition between the two regimes can be approximated between \( \Psi \) values of 1.15-1.25; additional experimentation is required to determine if this transition occurs for other materials under autoignition. Figure 54 indicates that the transition region for piloted ignition may not coincide with the transition region defined for autoignition and the transition for piloted ignition requires further investigation.

Extrapolating data from the High Irradiance Regime leads to a poor prediction of the CHF. Approximations of the CHF can be much more accurately made by using data in the Low Irradiance Regime. The best predictions were made using data plotted as \( \frac{1}{\bar{t}_{ig}} \) vs \( \dot{q}_e'' \) opposed to \( \frac{1}{\sqrt{\bar{t}_{ig}}} \) vs \( \dot{q}_e'' \) which has been traditionally used. The process of predicting the CHF described in this work does require data close to the CHF (at least three data points spread over \( \Psi \) values of approximately 1.05 – 1.30; at least two of the points laying between the CHF and \( \Psi=1.15 \)); therefore, the process of bracketing to determine the CHF experimentally remains the recommended approach for an accurate determination of the CHF.
Predicting the CHF in this manner does however offer benefit if, for example, if there is a limited amount of material to be tested and the user is not able to risk bracketing iteratively until the CHF is determined. Instead, the user can choose a series of heat fluxes so long as the relative magnitude of the CHF can be guessed initially. If the \(1/x\) decay as seen in Figure 45 is observed for at least three heat fluxes, then the CHF can be approximated to some degree through extrapolation. An extrapolation of this nature is not ideal but serves as a better approximation then by extrapolating from the High Irradiance Regime if data or material is limited.

The use of \(\Psi\) serves as a way to collapse ignition data compared across various orientations. However, Figure 53 also suggests that the use of the experimentally determined CHF can also collapse data that shows variation due to differences in experimental apparatuses or procedures. The piloted ignition data presented in Figure 53 collapses data taken from studies using the Cone Calorimeter, the FPA, and radiant panels (LIFT) – all of which have historically shown variation for the same material depending on the experimental apparatus. While the majority of the discussion in this study is focused on the ability to describe ignition behavior between different orientations, the same principle of using \(\Psi\) to plot ignition data can account for experimental variation associated with other factors and may even offer a way to compare experimental variations across equipment in different laboratories.
Chapter 9
STATISTICAL SIGNIFICANCE STUDY

Over the duration of the present master’s thesis, multiple additional projects were brought to light that required additional investigation of their own to contribute to the overall work. As a disclaimer, the initial plan of this dissertation project was to conduct an initial series of experiments (autoignition study), then conduct a sensitivity study to refine the methodology used, and ultimately conduct a final series of experiments (using piloted ignition). The interim sensitivity study was designed to investigate the influence of the number of trials on the results of ignition experiments. Due to the outbreak of the novel coronavirus (COVID 19) in late 2019, the final series of experiments (piloted ignition study) for this study was not conducted due to lab facility closures. The sensitivity study was still conducted; the results may seem out of context here to the reader as the final experiments were not conducted. The statistical significance study presented here does however serve as a starting point for future research and any expansion upon the core work conducted for this thesis.

9.1 Statistical Significance in Bench-scale Fire Testing

Bench-scale ignition testing is a well-defined process with requirements and procedures outlined in regimented standardized tests [60]–[62], [95]. Each standardized procedure dictates a particular number of trials to be conducted; the required trials for various standards can be seen in Table 18. The standardized testing procedure for ignition testing in the Cone Calorimeter (both ISO 5560 and ASTM E1354) only require three specimens to be tested. Ignition testing can, however, yield a high degree of experimental scatter in data such as the time to ignition, particularly at low heat fluxes. Past work has investigated the reproducibility of Cone Calorimeter data in round robin studies [96], [97] – yet there has been no regimented quantification of the confidence interval placed on the number of specimens tested.

Currently, ignition time data is presented with an uncertainty associated with the experimental spread in the data recorded. This does not however reflect the true statistical uncertainty of the measurement; instead the user is if anything discouraged from conducting more tests than needed since the spread of recorded times, and hence the ‘uncertainty’ as defined as the spread in experimental data, can only increase with more trials. True statistical uncertainty relates to the scatter predicted from an infinite
population of experimental results. The goal of this study is to provide an idea of the marginal reduction in statistical uncertainty gained from each additional trial (i.e. how much more confidence is gained with each additional trial) to guide researchers in choosing a number of trials for a given experimental condition based on the degree of confidence desired opposed to following a standard procedure.

Table 18. Required number of trials for different ASTM flammability tests [60]–[62], [98]–[101].

<table>
<thead>
<tr>
<th>Standardized Test</th>
<th>Minimum Number of Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cone Calorimeter ASTM E1354</td>
<td>3 Samples</td>
</tr>
<tr>
<td>Mass Loss Cone ASTM E2102</td>
<td>3 Samples</td>
</tr>
<tr>
<td>Lateral Ignition and Flame Spread (LIFT) ASTM E1321</td>
<td>3 Samples (Flame Spread)</td>
</tr>
<tr>
<td></td>
<td>6 Samples (Ignition)</td>
</tr>
<tr>
<td>Fire Propagation Apparatus (FPA) ASTM E2058</td>
<td>3 Samples</td>
</tr>
<tr>
<td>OSU Apparatus ASTM E906</td>
<td>3 Samples</td>
</tr>
<tr>
<td>Intermediate Scale Calorimeter (ICAL) ASTM E1623</td>
<td>3 Samples</td>
</tr>
<tr>
<td>Critical Radiant Flux of Floor-covering Systems using a Radiant Heat Energy Source ASTM E648</td>
<td>3 Samples</td>
</tr>
<tr>
<td>Surface Flammability of Materials Using a Radiant Heat Energy Source ASTM E162</td>
<td>4 Samples</td>
</tr>
</tbody>
</table>

In order to properly validate the chosen numbers of trials for bench scale ignition testing, an exploratory study was conducted in which a high number of experiments were conducted (n=100) to determine the marginal confidence gained from each additional trial. The sample material chosen was black PMMA 6 mm thick (heated area of 100 x 100 mm). An ASTM E1354 Cone Calorimeter was used to expose the samples to the desired irradiance and the samples were ignited with the spark ignitor per the ASTM standard. Each sample was placed in an ASTM E1354 standard sample holder (only the bottom half of the sample holder was used) and was wrapped in aluminum foil. A total of three heat fluxes were tested – 20 kW/m², 40 kW/m² and 60 kW/m². The Cone Calorimeter coils were calibrated using a Schmidt-Boelter heat flux gauge and were calibrated to within 1% of the desired heat flux. Heat flux readings were also taken at various times between trials to ensure the heat flux calibration remained with the desired 1% range. A total of 100 trials was conducted at each heat flux to examine the statistical significance of the
ignition time results. Trials were conducted in groups of approximately 20-25 trials in each day to minimize variation from calibration and set up. The Cone Calorimeter apparatus was also disassembled, cleaned, and serviced approximately every 100 trials conducted to prevent accumulation of combustion products that could affect gas analysis.

The time to ignition was recorded for each trial; ignition times were determined through visual observation during each trial and were reported within the nearest second. The assumed uncertainty in any given time to ignition will be assumed to be two seconds to account for user reaction time. Gas analysis and load cell measurements were also taken to determine the heat release rate (HRR) and mass loss rate (MLR) for each trial as well – these data will however not be discussed in detail in the current study and the focus will remain on ignition time data alone.

9.2 Ignition Results

Figure 55 illustrates the ignition time results for 100 trials conducted at 20, 40, and 60 kW/m². The "true average" ignition time was determined by removing any values two standard deviations from the total mean; these values are presented in Table 19. Scatter in the data around the mean was quantified through both the standard deviation of the data (σ) and a 95% confidence interval (i.e. variation from the mean value in which 95% of the data lie). As expected, the ignition results show a high time to ignition at low heat fluxes accompanied with higher scatter in the data. As the external heat fluxes increase, both the time to ignition and scatter in the data decrease. Both the 40 and 60 kW/m² cases begin to show discrete bands of ignition times which illustrates that the degree of scatter in the experimental data is similar to the resolution of the data rounded to the nearest second.

Table 19. The "true average" time to ignition for each heat flux tested. Values corresponding to two standard deviations from the mean and a 95% confidence interval are also presented.

<table>
<thead>
<tr>
<th>Heat Flux [kW]</th>
<th>t_ig [s]</th>
<th>2σ [s]</th>
<th>95% [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>169.56</td>
<td>18.00</td>
<td>17.64</td>
</tr>
<tr>
<td>40</td>
<td>43.18</td>
<td>4.23</td>
<td>4.14</td>
</tr>
<tr>
<td>60</td>
<td>21.04</td>
<td>2.63</td>
<td>2.58</td>
</tr>
</tbody>
</table>
Figure 55. Resulting ignition times for 20, 40, and 60 kW/m$^2$. Dashed lines indicate a 95% confidence interval. Histograms are provided to demonstrate approximately Gaussian behavior for each set of data.

The associated histograms, as seen in Figure 55, suggest that the results at each heat flux are unimodal in the approximate center of the data range and asymptotic as to zero as the values approach zero or infinity on either side. This behavior suggests that the population of data can be reasonably treated as Gaussian distributions (particularly at 20 and 40 kW/m$^2$). Assuming a normal distribution, the mean of the
trials conducted for each heat flux will also be assumed to be the population mean; this is justified generally for sample sizes over 30-60 [102], and therefore the assumption is likely sound for the 100 trials.

9.3 Statistical Analysis

The goal of this work is to establish the following at each heat flux tested:

1) The statistical uncertainty in the resulting time to ignition if only n-trials had been conducted (i.e. the uncertainty as a function of n)

2) The marginal improvement in statistical variation with each additional experiment conducted (i.e. how much more certainty is gained by conducting n + 1 instead of n trials)

Both of these goals can only be determined if the results from the 100 trials conducted can be assumed to represent every possible outcome of the experiment at a given heat flux and that the distribution of the 100 results represents the distribution of any possible number of experiments conducted at a given heat flux. Each assumption is sound based on the relatively normal distribution of the ignition data. The uncertainty will be quantified through Gaussian statistics and then verified through a Monte Carlo simulation as outlined in Figure 56.

Figure 56. Flow chart outlining the goals and process of the following analysis.
9.3.1 Gaussian Statistics

The field of Gaussian statistics is used to predict statistical behavior of a sample of data if the overall behavior of the population can be quantified through parameters such as the standard deviation. A Gaussian distribution is defined as a unimodal distribution that is centered on the mean value and the probability density of the resulting values decay asymptotically as the predicted values approach zero or infinity, as demonstrated in Figure 57. The standard deviation of the data is used to capture the probability density at a given value from the mean – in particular, one standard deviation in either direction of the mean captures 68.26% of the resulting values from a data set. In other words a normal distribution allows for the user to predict the probability of choosing a certain value within the range of possible data based on the distribution of the data – quantifying uncertainty within a measurement is achieved through determining the range of possible values captured within an acceptable probability or a desired degree of confidence (e.g. predicting a value with 95% confidence).

Figure 57. A typical Gaussian distribution. The table illustrates how the t-statistic varies with the degrees of freedom \((n - 1)\) for a 95% confidence interval.

<table>
<thead>
<tr>
<th>Degrees of Freedom</th>
<th>t-Statistic (95% Conf.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n-1)</td>
<td>(t)</td>
</tr>
<tr>
<td>1</td>
<td>12.71</td>
</tr>
<tr>
<td>2</td>
<td>4.30</td>
</tr>
<tr>
<td>3</td>
<td>3.18</td>
</tr>
<tr>
<td>4</td>
<td>2.78</td>
</tr>
<tr>
<td>5</td>
<td>2.57</td>
</tr>
<tr>
<td>10</td>
<td>2.23</td>
</tr>
<tr>
<td>25</td>
<td>2.06</td>
</tr>
<tr>
<td>100</td>
<td>1.98</td>
</tr>
<tr>
<td>z</td>
<td>1.96</td>
</tr>
</tbody>
</table>

By assuming a normal distribution, the population mean of the experimental data can be predicted given a sample of \(n\)-trials using Equation 1, where \(s\) is the standard deviation of the trials selected (i.e. the standard deviation of the sample of \(n\)-trials) and \(t\) is the tabulated t-statistic which is a function of the desired confidence interval and the number of trials.

\[
\mu = \bar{x} \pm \frac{t \cdot s}{\sqrt{n}}
\]  

Equation 40
The statistical uncertainty in predicting the mean is captured in the plus or minus term seen in Equation 40. Understanding how the statistical uncertainty chances with each additional trial can be used to quantify the marginal benefit of that trial. The value of t is constant for a given confidence interval and number of trials in a sample, however the standard deviation for each sample of trials is not trivial. Depending on the trials chosen, the standard deviation can vary greatly so one cannot easily choose a value to be used in this equation. While the sample standard deviation may complicate the calculation of the statistical uncertainty, and hence quantifying the marginal benefit of an additional trial, Equation 40 suggests that the uncertainty will behave with a $1 / \sqrt{n}$ relationship. As the sample size reported becomes high enough to approximate the population of the mean ($n$=30-60), then Equation 40 can be rewritten in the form seen in Equation 41, where $\sigma$ represents the standard deviation of the population and $z$ represents the $z$-statistic which is the value for the t-statistic as the number of trials approaches infinity (i.e. for statistically significant numbers of trials).

$$
\mu = \bar{x} \pm \frac{z \sigma}{\sqrt{n}} \tag{Equation 41}
$$

By incorporating the standard deviation of the population, $\sigma$, the potential variation in the sample standard deviation is removed for the sake of this analysis and the uncertainty of the population mean is simplified to be a function of $n$ alone. Therefore, the uncertainty term can be plotted for the number of trials in a given sample. Equation 41 can only be used for large samples (i.e. high values of $n$) and may not be valid for all sample sizes. Equation 41 could only be used for small sample sizes if the population standard deviation and the product of the $z$-statistic and the population standard deviation can accurately simulate the product of the t-statistic and sample standard deviation for all values of $n$ (i.e. $(z \sigma) = t s$). If this assumption is made, than Equation 41 can serve as an analytical solution to the uncertainty associated with any sample of n-trials based upon the assumed distribution of the population represented by the actual 100 trials conducted. Plotting the uncertainty in predicting the population mean as a function of the number of sample trials, representing the uncertainty associated with only conducting n-trials opposed to the whole data set, produces the curve seen in Figure 58; the curve represents the 95% confidence interval of predicting the mean for a given sample size. The results reflect the anticipated decaying behavior as the number of trials increases. The corresponding uncertainty at one trial corresponds to the 95% confidence
value previously presented in Table 19 which then decays to approximately a value of two seconds as the trials exceed 100.

![Graph showing 95% confidence interval (s) vs. Trials Averaged](image)

Figure 58. Equation 41 plotted as a function of sample trials (using $z = 1.96$ for 95% confidence and $\sigma = 9.0$ s).

In order for the curve detailed in Figure 58 to reflect the true uncertainty of the data set, Equation 41 must be valid for all values of $n$. This assumption may, however, not be valid when considering small sample sizes because the standard deviation for small sample sizes is prone to a high degree of variation. One way to investigate the validity of this assumption is to replicate the fundamental idea of Gaussian statistics – the uncertainty in the calculated mean for a given sample size reflects the range of possible values within a given probability density associated with an acceptable level of confidence (i.e. what is the scatter in the calculated averages if the sample average was calculated with an infinite data set). This same principle can be applied to determining the distribution of all possible outcomes of $n$-trials and then determining the standard deviation within those results and ultimately the uncertainty associated with a level of confidence. Therefore, a simulation was developed to replicate the anticipated scatter associated with the calculated average for a given sample size to validate the predictions from Gaussian statistical theory.
9.3.2 Monte Carlo Simulation

Monte Carlo simulations are often applied to quantify uncertainty in various forms of experimental data or in parametric studies – as such, a Monte Carlo simulation was used to investigate the uncertainty of the predicted population mean using an n-trial sample size. The principle of the simulation is based on the ability to predict every possible outcome for a given sample size (i.e. every possible outcome for a sample of n-trials) and from this information perform a statistical analysis on the uncertainty of predicting the average of a given sample of n-trials.

One way of visualizing this concept is through plotting the data seen in Figure 55 the case of 20 kW/m², but instead of plotting the ignition times as a scatter of all trials, Figure 59 shows the calculated average ignition time with each additional trial in the order in which the data was taken (i.e. n-trials averaged is equal to the average of the first n-trials in the order presented in Figure 55) – this will be referred to as the rolling average. The resulting data demonstrates anticipated fluctuation for low numbers of averaged trials and becomes fairly stable as more trials are averaged (the increase at the end is caused by a few high outliers in the data at the 88th and 91st trial). The high fluctuation is an indication of the higher uncertainty at small samples and a reduction in uncertainty at higher sample sizes.

Figure 59. The rolling average of ignition data for 20 kW/m² averaged in the order in which the data was taken.

If the 100 trials conducted can accurately represent the distribution of all outcomes of the experiment, then the order in which the data is taken can be re-arranged into different orders and the rolling average for any random order of 100 trials can be calculated. Figure 60 illustrates a total of 100 simulations
of calculating the rolling average from random rearrangements of the ignition data at 20 kW/m$^2$. The general behavior of the rolling averages validates that the results exhibit a high degree of uncertainty for small sample size and the scatter in values decays with larger sample size. For any sample size of n-trials, the standard deviation can be calculated across the simulations to produce the bottom plot in Figure 60. The standard deviation for each sample size decays with a $1/\sqrt{n}$ relationship as predicted by Equation 40 and Equation 41 and can be used to predict the uncertainty in predicting the mean for a given confidence interval. However, the results of running only 100 simulations will change if an additional 100 simulations are run and will affect the calculated uncertainty at each sample size of n-trials.

Figure 60. Results of rolling averages produced by rearranging the gathered ignition data in 100 random orders. The bottom plot displays one and two standard deviations from the mean value which illustrates the predicted decay in uncertainty with increasing trials being averaged.

Another way to visualize the uncertainty associated with the number of trials conducted is through predicting every possible combination of n-trials. Various standardized testing procedures, including the Cone Calorimeter, prescribe a total of three trials and the reported time to ignition is the average of those
three trials. The scatter seen in the data presented in Figure 55 may however lead to a calculated average ignition time that deviates far from the true value depending on the results of the three individual trials as seen in Figure 60. A MATLAB script was generated to calculate the average ignition time for every combination of three and five trials from the total 100 trials conducted at 20 kW/m².

Figure 61. A histogram of all the possible 3-trial combinations and all 5-trial combinations based on the 100 trials conducted at 20 kW/m²; a coarse box width is used on the bottom right to illustrate the probability of the calculated average lying within each four second window (i.e. a two second uncertainty).

Due to the high scatter seen at lower heat fluxes, the calculated average time to ignition between any three trials can range from approximately 155-195 seconds, with only 31% of the calculated averages falling within two seconds of the true average, or 76% falling within six seconds of the true average. The same process was also repeated for all possible combinations of five trials to simulate using a higher amount of trials. All possible combinations of any five trials instead results in a 38% chance of falling within two seconds of the true value or 86% chance of falling within six seconds of the true average – see Table 20 for more detail.
Table 20. The probability distribution from the coarse histogram seen in Figure 61.

<table>
<thead>
<tr>
<th>Range of Calculated $t_g$</th>
<th>3-Trials Probability (%)</th>
<th>5-Trials Probability (%)</th>
<th>Percent Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>156-160</td>
<td>0.8</td>
<td>-</td>
<td>8.0-5.6</td>
</tr>
<tr>
<td>160-164</td>
<td>7</td>
<td>3.1</td>
<td>5.6-3.3</td>
</tr>
<tr>
<td>164-168</td>
<td>21.8</td>
<td>20.9</td>
<td>3.3-0.9</td>
</tr>
<tr>
<td>168-172</td>
<td>31.1</td>
<td>38</td>
<td>0.9-1.4</td>
</tr>
<tr>
<td>172-176</td>
<td>23.3</td>
<td>27</td>
<td>1.4-3.8</td>
</tr>
<tr>
<td>176-180</td>
<td>11.1</td>
<td>8.6</td>
<td>3.8-6.2</td>
</tr>
<tr>
<td>180-184</td>
<td>3.9</td>
<td>1.4</td>
<td>6.2-8.5</td>
</tr>
<tr>
<td>184-188</td>
<td>0.9</td>
<td>-</td>
<td>8.5-10.9</td>
</tr>
<tr>
<td>188-192</td>
<td>0.1</td>
<td>-</td>
<td>10.9-13.2</td>
</tr>
</tbody>
</table>

All possible combinations of trials larger than five quickly becomes computationally expensive, as the possible combinations soon approach trillions. While computing each possible combination of outcomes serves an illustrative purpose, using this metric as the sole determination of the statistical uncertainty for a given sample on $n$-trials is misleading. In reality, the possible outcomes of running the experiment again are not limited to the possible arrangements of the existing 100 data points; i.e. limiting the statistical uncertainty to every possible combination does not consider the fact that values can possibly repeat themselves if the experiment was in fact conducted again. The influence of allowing trials to repeat when calculating the average ignition time for a sample of $n$-trials will be illustrated further on.

Understanding the spread of average values taken from all possible outcomes of $n$-trials would allow for the quantification of statistical uncertainty in that given number of trials (not necessarily the same as all possible combinations – all possible outcomes refers to a virtually infinite combination of a virtually infinite pool of experimental data). This can most simply be captured in the standard deviation of outcomes if the average value for a given sample size was calculated an infinite amount of times. Calculating each combination of $n$ trials for a given sample is not practical and each possible combination does not allow for values in the data set to repeat. An analytical prediction of the statistical uncertainty as presented in Figure 58 assumes that Equation 41 can be applied for all values of $n$ and should be supported.
by additional analysis to be validated. Therefore, a series of Monte Carlo simulations were conducted using MATLAB to predict the uncertainty for a given sample of n-trials.

The following Monte Carlo simulations in essence takes the 100 experimentally determined ignition times and simulates the experiments having been conducted again in random orders. In the purest form, a Monte Carlo simulation would create a set of random values based upon an assumed mean and standard deviation; the simulation used in this study instead simply pulls random values from the total pool of experimental values recorded due to the generally Gaussian behavior observed. From these random orders, data is averaged in samples of n-trials and the scatter in the calculated average ignition time for each set of n-trials is calculated. Each simulation chooses random trials from the full data set and averaged these values to determine a calculated ignition time average for that specific sample of n-trials. Simulations were then repeated \( i \) times, resulting in \( i \) predicted average ignition times for any n-trial size. As \( i \) approaches infinity, the simulation predicted the distribution of calculated ignition times for an approximately infinite population of values. This process therefore simulates the experiment which produced the data seen in Figure 55 being conducted \( i \) times; the results of which will illustrate the possible scatter in data from the approximate population mean associated with only conducting n-trials.

![Monte Carlo Simulation Flow Chart](image)

Figure 62. Flow chart outlining the process of the Monte Carlo Simulation.

In choosing the random trials to fill each slot of the n-trial sized sample, the simulation must operate under one of two conditions: 1) unique trials from the original data set can only be used once in
each simulation (i.e. the sample of n-trials is composed of a random permutation of the total data set of length n) or 2) allow unique values to be repeated within one simulation (i.e. each value used within the sample of n-trials is a value picked at random from the data set and can be repeated). Table 21 demonstrates an example of simulations with and without the repeating condition for choosing the trials to populate the sample of n-trials. As seen in the example, allowing samples to repeat does not indicate that each simulation will have repeat values; instead this condition only allows for the possibility of repeating values.

Each Monte Carlo simulation produces two results: 1) the average ignition time averaged across all i simulations conducted, and 2) the standard deviation of all i simulations conducted. This process can then be repeated for various values of n to simulate the uncertainty of various sample sizes. For low values of n the difference between the repeating and non-repeating conditions is negligible. However, at high sample sizes the limitation of preventing values from repeating creates less possible combinations and therefore an artificially low amount of scatter in the data. Both conditions of with and without repeating values were incorporated into the Monte Carlo simulation to compare the results of each methodology.

Table 21. An example comparing the process of choosing values to fill the sample of n-trials with and without repeating values. For this example, a total of 3 trials were selected for each sample (n = 3) and the simulation was iterated 5 times (i = 5).

<table>
<thead>
<tr>
<th>Data Set: [170 173 169 175 164 171]</th>
<th>Simulation w/o repeating (n = 3, i = 5)</th>
<th>Simulation with repeating (n = 3, i = 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[t₁, t₂, t₃, t₄, t₅, t₆]</td>
<td>Sim. 1) [173 164 170] - [t₂ t₅ t₁]</td>
<td>Sim. 1) [170 164 173] - [t₁ t₅ t₂]</td>
</tr>
<tr>
<td></td>
<td>Sim. 2) [170 169 175] - [t₁ t₃ t₄]</td>
<td>Sim. 2) [170 169 170] - [t₁ t₃ t₁]</td>
</tr>
<tr>
<td></td>
<td>Sim. 3) [170 173 171] - [t₁ t₂ t₆]</td>
<td>Sim. 3) [169 173 171] - [t₃ t₂ t₆]</td>
</tr>
<tr>
<td></td>
<td>Sim. 4) [171 169 173] - [t₆ t₃ t₂]</td>
<td>Sim. 4) [171 171 164] - [t₆ t₆ t₅]</td>
</tr>
<tr>
<td></td>
<td>Sim. 5) [164 173 171] - [t₅ t₂ t₆]</td>
<td>Sim. 5) [173 164 170] - [t₂ t₅ t₁]</td>
</tr>
<tr>
<td></td>
<td>MC Simulation Results:</td>
<td>MC Simulation Results:</td>
</tr>
<tr>
<td></td>
<td>t₁ₜ,AVG = AVG(Sim 1, ..., Sim 5)</td>
<td>t₁ₜ,AVG = AVG(Sim 1, ..., Sim 5)</td>
</tr>
<tr>
<td></td>
<td>= 170.40 s</td>
<td>= 169.47 s</td>
</tr>
<tr>
<td></td>
<td>σ₁ₜ = 1.14 s</td>
<td>σ₁ₜ = 0.93 s</td>
</tr>
</tbody>
</table>

Table 21. An example comparing the process of choosing values to fill the sample of n-trials with and without repeating values. For this example, a total of 3 trials were selected for each sample (n = 3) and the simulation was iterated 5 times (i = 5).
The number of iterations within each Monte Carlo simulation, \(i\), dictates the accuracy of the simulation’s ability to predict the statistical uncertainty for any value of \(n\). Theoretically, the statistical uncertainty is quantified for each set of \(n\)-trials as \(i\) approaches infinity. For application in a real simulation, a finite value of \(i\) must be chosen. As a criterion for choosing \(i\), the resolution of the uncertainty was limited to 0.01 s – therefore, any value of \(i\) that converges to a value within 0.01 s consistently can simulate all possible outcomes for the sake of this Monte Carlo simulation. For the experimental ignition data in question, a total of one million iterations was required to consistently produce a result consistent within 0.01 s; for the remaining analysis, \(i\) will always be of the value 1,000,000 iterations. Higher numbers of iterations only increase computational time and add no benefit in gaining additional accuracy in the calculated uncertainty.

### 9.4 Results & Discussion

The results of the Monte Carlo simulation for the data at 20 kW/m\(^2\) are illustrated in Figure 63 and Table 22 – the simulation results exhibit the \(\frac{1}{\sqrt{n}}\) relationship as anticipated from a Gaussian distribution. Simulations that allowed for values to be repeated predict uncertainties within 1% of the values predicted by Gaussian statistics for all values of \(n\). Non-repeating simulations, however, only fall within 10% of the theoretical values for values of \(n < 20\) and then continue to deviate further at high sample sizes. This behavior illustrates that simulations without repeating produce artificially low uncertainty, particularly at high sample sizes, and do not accurately portray the desired uncertainty. The Monte Carlo simulations conducted with repeating trials on the other hand serves to validate that Gaussian statistics are applicable for all values of \(n\).

At 20 kW/m\(^2\), the uncertainty in a single value representing the population mean is nearly 18 seconds and drops to 10 seconds if samples of three trials are taken. The uncertainty continues to decrease as the number of \(n\)-trials is increased, however the rate at which the uncertainty decreases with each additional trial diminishes. Using the uncertainty as a function of \(n\), as presented in Figure 64 as the only criterion for choosing a statistically sound number of trials may be misleading. Supposed it is desired to match the statistical uncertainty to the approximate experimental uncertainty of two seconds. Achieving a
statistical uncertainty of two seconds at 20 kW/m² would require approximately 80 trials which is not necessarily ideal or practical for an experimental series. Therefore, an additional parameter must be introduced to refine the process of choosing a statistically sound number of trials.

Figure 63. The results of the Monte Carlo (MC) simulations compared to Gaussian statistics (Equation 41) for all values of \( n \) at 20 kW/m²; both the repeating and non-repeating simulations converge for small sample sizes but diverge as the sample size increases.

Table 22. The results of the Monte Carlo simulations compared to Gaussian statistics (Equation 41) for all values of \( n \) at 20 kW/m². The repeating Monte Carlo simulation produces the same value as predicted by Equation 41 within 1%.

<table>
<thead>
<tr>
<th>Trials Averaged ( n )</th>
<th>Gaussian Statistics ( \mu ) [( s )]</th>
<th>Monte Carlo Repeating ( \sigma ) [( s )]</th>
<th>Monte Carlo w/o Repeating ( \sigma ) [( s )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>12.48</td>
<td>12.41</td>
<td>12.35</td>
</tr>
<tr>
<td>3</td>
<td>10.19</td>
<td>10.13</td>
<td>10.04</td>
</tr>
<tr>
<td>4</td>
<td>8.82</td>
<td>8.78</td>
<td>8.64</td>
</tr>
<tr>
<td>5</td>
<td>7.89</td>
<td>7.84</td>
<td>7.68</td>
</tr>
<tr>
<td>10</td>
<td>5.58</td>
<td>5.55</td>
<td>5.29</td>
</tr>
<tr>
<td>25</td>
<td>3.53</td>
<td>3.51</td>
<td>3.06</td>
</tr>
<tr>
<td>50</td>
<td>2.50</td>
<td>2.48</td>
<td>1.76</td>
</tr>
<tr>
<td>70</td>
<td>2.11</td>
<td>2.10</td>
<td>1.16</td>
</tr>
<tr>
<td>90</td>
<td>1.86</td>
<td>1.85</td>
<td>0.59</td>
</tr>
<tr>
<td>100</td>
<td>1.76</td>
<td>1.76</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Figure 64. Top: the uncertainty as a function of \( n \) for the data at 20 kW/m\(^2\); symbols indicate the Monte Carlo simulation results while the line represents the analytical solution from Gaussian statistics. Bottom: the marginal gain in uncertainty from the \( n \)-th trial conducted.

Figure 64 also shows the marginal gain in confidence from each additional trial (defined as the difference between the 95% confidence interval between \( n \) trials and \( n - 1 \) trials) which shows the sharp peak in marginal confidence gained at low values of \( n \). In the case of 20 kW/m\(^2\), the marginal confidence begins to decrease at an accelerated rate after \( n = 5 \); however even after five trials, each additional trial continues to gain 1 – 0.5 seconds marginally until approximately 10 trials. Both the 95% confidence interval and the marginal gain in uncertainty can be used together to optimize the information gained from the chosen number of trials conducted.

The Monte Carlo simulation was repeated for both the 40 and 60 kW/m\(^2\) ignition data which also verified that Equation 41 accurately described the uncertainty associated with predicting the mean with \( n \)-trials; the results of all three heat fluxes can be found in Table 23 and Figure 65. The uncertainty observed for any value of \( n \) was substantially lower for both the 40 and 60 kW/m\(^2\) cases when compared to the 20 kW/m\(^2\) data. In a similar fashion, the marginal gain was much higher when considering the 20 kW/m\(^2\) condition for all sample sizes.
Table 23. The 95% confidence interval and marginal gain in uncertainty for the data conducted at 20, 40, and 60 kW/m$^2$ determined using Equation 41.

<table>
<thead>
<tr>
<th>Trials Averaged (n)</th>
<th>20 kW/m$^2$</th>
<th>40 kW/m$^2$</th>
<th>60 kW/m$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[-]</td>
<td>[s]</td>
<td>[s]</td>
<td>[s]</td>
</tr>
<tr>
<td>2</td>
<td>12.48</td>
<td>5.17</td>
<td>2.93</td>
</tr>
<tr>
<td>3</td>
<td>10.19</td>
<td>2.29</td>
<td>2.39</td>
</tr>
<tr>
<td>4</td>
<td>8.82</td>
<td>1.36</td>
<td>2.07</td>
</tr>
<tr>
<td>5</td>
<td>7.89</td>
<td>0.93</td>
<td>1.85</td>
</tr>
<tr>
<td>10</td>
<td>5.58</td>
<td>0.30</td>
<td>1.31</td>
</tr>
<tr>
<td>15</td>
<td>4.56</td>
<td>0.16</td>
<td>1.07</td>
</tr>
<tr>
<td>25</td>
<td>3.53</td>
<td>0.08</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Figure 65. The uncertainty for each external heat flux tested plotted using Equation 41. A second plot showing only the 40 and 60 kW/m$^2$ cases is provided to show these cases in greater detail.
Figure 66. Left: the uncertainty as a function of $n$ for the data at 40 and 60 kW/m$^2$; symbols indicate the Monte Carlo simulation results while the line represents the analytical solution from Gaussian statistics. Right: the marginal gain in uncertainty from the $n$-th trial conducted.

All of the analysis presented here illustrates that for ignition testing the calculated time to ignition for any sample of $n$-trials can be subject to a high degree of uncertainty depending on the external heat flux and the trials conducted. The methodology outlined here suggests two different parameters to guide the choice of an appropriate value for $n$ – the uncertainty (quantified through a 95% confidence interval) lends insight to the overall scatter associated with a value of $n$ while the marginal gain illustrates how much more information was gained from conducting the $n$th trial. While the uncertainty in the calculated ignition time becomes minimal when considering 100 trials, such a large sample size is not practical for every experiment. The reduction in uncertainty with each additional trial diminishes as the value of $n$ increases and calculating the marginal gain can provide a criterion for quantifying at what point conducting additional trials is not worth the time and resources to do so. The marginal gain serves as a way to balance the desire for optimized results while also considering the practical limits of large sample sizes.
The calculated uncertainty was significantly lower when considering the 40 and 60 kW/m² case when compared to 20 kW/m² (approximately 75% and 85% lower, respectively, for all values of n). Figure 67 illustrates that the predicted uncertainty for any sample of n-trials is highly non-linear between the heat fluxes tested. For any value of n, the increase in uncertainty from 60 to 40 kW/m² is as low as 1 or 2 seconds; the increase in uncertainty from 40 to 20 kW/m² can be as high as 13.5 seconds (for n = 1). The calculated uncertainties for each heat flux suggest that 40 kW/m² serves as an approximate transition from a high degree of uncertainty to a lower degree of uncertainty. Further experimentation would be required to definitively quantify the behavior of heat fluxes between 20 and 40 kW/m², however the uncertainty is likely to follow the general trend indicated in Figure 67.

Further insight to the trends in uncertainty by presenting a normalized uncertainty for each heat flux (i.e. the uncertainty at a given value of n normalized by the true average ignition time for the given heat flux) which captures the ratio of the spread in data to the recorded ignition time. As seen in Table 24, the normalized uncertainty remains fairly constant for any value of n across all heat fluxes tested. These results suggest that the for any heat flux, the uncertainty of predicting the true average ignition time is 10-12% of the average time to ignition when considering a single trial. If the normalized uncertainty can truly be applied to all heat fluxes, then the analysis conducted can be potentially extrapolated to lend insight to potential uncertainty at other heat fluxes.
Table 24. The calculated uncertainty for each heat flux tested. The normalized uncertainty is the ratio of the calculated uncertainty at any value of n to the average time to ignition for each experimental heat flux.

<table>
<thead>
<tr>
<th>Trials Averaged (n)</th>
<th>20 kW/m²</th>
<th></th>
<th>40 kW/m²</th>
<th></th>
<th>60 kW/m²</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncertainty</td>
<td>Normalized</td>
<td>Uncertainty</td>
<td>Normalized</td>
<td>Uncertainty</td>
<td>Normalized</td>
</tr>
<tr>
<td>[-]</td>
<td>[s]</td>
<td>[%]</td>
<td>[s]</td>
<td>[%]</td>
<td>[s]</td>
<td>[%]</td>
</tr>
<tr>
<td>1</td>
<td>17.64</td>
<td>10%</td>
<td>4.15</td>
<td>10%</td>
<td>2.58</td>
<td>12%</td>
</tr>
<tr>
<td>2</td>
<td>12.48</td>
<td>7%</td>
<td>2.93</td>
<td>7%</td>
<td>1.82</td>
<td>9%</td>
</tr>
<tr>
<td>3</td>
<td>10.19</td>
<td>6%</td>
<td>2.39</td>
<td>6%</td>
<td>1.49</td>
<td>7%</td>
</tr>
<tr>
<td>4</td>
<td>8.82</td>
<td>5%</td>
<td>2.07</td>
<td>5%</td>
<td>1.29</td>
<td>6%</td>
</tr>
<tr>
<td>5</td>
<td>7.89</td>
<td>5%</td>
<td>1.85</td>
<td>4%</td>
<td>1.15</td>
<td>5%</td>
</tr>
<tr>
<td>10</td>
<td>5.58</td>
<td>3%</td>
<td>1.31</td>
<td>3%</td>
<td>0.81</td>
<td>4%</td>
</tr>
<tr>
<td>15</td>
<td>4.56</td>
<td>3%</td>
<td>1.07</td>
<td>2%</td>
<td>0.67</td>
<td>3%</td>
</tr>
<tr>
<td>25</td>
<td>3.53</td>
<td>2%</td>
<td>0.83</td>
<td>2%</td>
<td>0.52</td>
<td>2%</td>
</tr>
</tbody>
</table>

Plotting the uncertainty as a function of heat flux provides a visualization of the importance of sample size at particularly low heat fluxes. If the observed trend continues beyond 20 kW/m², then the uncertainty in measurements at heat fluxes below 20 kW/m² could be substantial. This behavior has serious implications to experiments conducted at low heat fluxes such as bracketing to determine the critical heat flux for a given material. When conducting experiments near the critical heat flux, experimental ignition times can be on the order of 600-1000 seconds. If the normalized uncertainty is truly constant for all heat fluxes, then the resulting uncertainty for ignition times on the order of 1000 seconds could be as high as 100-120 seconds if a single value was chosen and as high as 60-70 seconds if three trials were averaged. Such high potential uncertainties at low heat fluxes are non-trivial and can lead to unnecessarily high error when analyzing ignition data. Experimental validation of these results at low heat fluxes is required for a higher degree of certainty, however these results do suggest that care should be taken at low heat fluxes and a higher sample size may be required to mitigate inappropriate degrees of error.

9.4.1 Extrapolating Results

The analysis conducted suggests that the degree of statistical uncertainty for time to ignition results vary depending on the external heat flux used and that the ratio of statistical uncertainty to measured ignition time (normalized uncertainty) appears constant over all heat fluxes for any value of n. Therefore, the statistical uncertainty for other heat fluxes within the range tested over the experimental study can be
extrapolated. When plotted as the inverse time and external heat flux ($\sqrt{t_{\text{ig}}} \; \text{vs} \; q'_e$) time to ignition data collapse into a linear curve. The slope of the linear curve fit allows for an approximation of the ignition times at heat fluxes between conditions used in the experiment (20, 40, and 60 kW/m$^2$). Extrapolation beyond the experimental range is no valid as the equation used to predict ignition time as a function of heat flux is only valid over a range of heat fluxes and breaks down at low heat fluxes. The resulting linear curve fit carries uncertainty from the error bars of the uncertainty in the ignition time data – the uncertainty in the slope is approximately ±0.0002 or a 11.8% uncertainty in predicting the time to ignition in seconds.

Figure 68. Ignition data plotted as the inverse time. The table presents extrapolated values for ignition times. Predicted values presented do not considered the 11.8% error associated with extrapolation.

<table>
<thead>
<tr>
<th>Heat Flux [kW/m$^2$]</th>
<th>$t_{\text{ig}}$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>116.87</td>
</tr>
<tr>
<td>30</td>
<td>81.16</td>
</tr>
<tr>
<td>35</td>
<td>59.63</td>
</tr>
<tr>
<td>45</td>
<td>36.07</td>
</tr>
<tr>
<td>50</td>
<td>29.22</td>
</tr>
<tr>
<td>55</td>
<td>24.15</td>
</tr>
</tbody>
</table>

Once the ignition times are estimated for other heat fluxes, the statistical uncertainty can be predicted using the normalized uncertainty seen in Table 25. The normalized uncertainty remains relatively constant at all heat fluxes for any value of $n$. Slight increases in normalized uncertainty are seen as heat fluxes approach 20 kW/m$^2$ from increased variation at low heat fluxes and at 60 kW/m$^2$ from the statistical variation approaching the resolution of the measurement. These small variations are accounted for by extrapolating the normalized uncertainty for heat fluxes between 20, 40, and 60 kW/m$^2$. 
Table 25. Extrapolated uncertainty for ignition times within the range of heat fluxes tested.

<table>
<thead>
<tr>
<th>Trials (n)</th>
<th>Uncertainty (95% Confidence) - [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25 kW/m²</td>
</tr>
<tr>
<td>1</td>
<td>11.93</td>
</tr>
<tr>
<td>2</td>
<td>8.43</td>
</tr>
<tr>
<td>3</td>
<td>6.89</td>
</tr>
<tr>
<td>4</td>
<td>5.96</td>
</tr>
<tr>
<td>5</td>
<td>5.33</td>
</tr>
<tr>
<td>10</td>
<td>3.77</td>
</tr>
<tr>
<td>15</td>
<td>3.08</td>
</tr>
<tr>
<td>25</td>
<td>2.39</td>
</tr>
</tbody>
</table>

The extrapolated uncertainty for various heat fluxes can be found in Table 25. As seen when considering the heat fluxes tested experimentally, the uncertainty is much higher at lower heat fluxes for any value of $n$ and the marginal gain from additional trials diminishes at higher heat fluxes. For exploratory studies ASTM E1354 recommends that a heat flux of 35 kW/m² is used; in absence of other specified heat fluxes, the standard also recommends tests at 25, 35, and 50 kW/m². Currently as it stands, ASTM E1354 suggests a total of 3 trials for 25, 35, and 50 kW/m² which corresponds to predicted statistical uncertainty of approximately 6.9, 3.4, and 1.8 seconds, respectively.

9.4.2 Uncertainty in Calculations

Time to ignition data taken at various heat fluxes is used to calculate various material parameters as outlined in standards such as the Cone Calorimeter test and the Fire Propagation Apparatus test standards. Parameters such as the ignition temperature ($T_ig$), thermal inertia ($k_s\rho_c\epsilon_c$), thermal response parameter (TRP), and critical heat flux for ignition (CHF) can all be calculated using ignition time data – each of these parameters are readily found in resources such as the SFPE handbook [1] and are used to classify materials in terms of their relative ignitability. Since these values are determined through the ignition data, uncertainty in the time to ignition directly affects these parameters used throughout the industry.

Equation 42 represents a popular ignition model that is typically used to determine ignition parameters from time to ignition data. By quantifying the uncertainty in the ignition data, namely the time
to ignition reported, further insight can be gained on the resulting uncertainty of parameters calculated from time to ignition data.

\[ t_{ig} = \frac{\pi}{4} \left[ k_f \rho_f c_f (T_{ig} - T_o)^2 \right] \]

Equation 42

The statistical analysis presented previously determined the statistical uncertainty of the time to ignition data for a given heat flux; this value does not however capture the uncertainty in equipment used during the experiment. In order to adequately calculate the uncertainty of each parameter both the statistical uncertainty and the experimental uncertainty must be considered. Bench-scale ignition testing relies on two measured quantities: 1) the calibrated heat flux for a given exposure and 2) the time from the start of a test to sustained flaming ignition. The uncertainty in the heat flux calibration is limited to the accuracy of the heat flux gauge used, and the variation of the calibrated heat flux from the nominal value. The heat flux gauge used in these experiments is assumed to have a 3-4% error in accuracy. All trials were also calibrated within 1% of the desired nominal value, and therefore a total experimental uncertainty of the external heat flux will be assumed to be approximately 5%. Each ignition time was determined through visual observation – while the reaction time can vary greatly between the individual conducting the experiment, the experimental uncertainty of the ignition time will be approximately 1 second.

The total uncertainty in any measurement is defined by Equation 43; the total uncertainty is composed of both the statistical and experimental uncertainty for a given measurement. The degree to which the uncertainty in any one measurement influences a calculated parameter depends on the functional relationship between individual measurement and the parameter (i.e. the uncertainty in a calculated parameter resulting from uncertainty in a measurement depends on how the parameter is calculated). In order to calculate the total uncertainty in a given parameter determined from ignition data, the uncertainty must be propagated through the calculation procedure. The total uncertainty in one measurement is then propagated through the desired equation through the process laid out in literature [102], [103].
\[ U_{\text{total}} = U_{\text{statistical}} + U_{\text{Experimental}} \]  

Equation 43

The two ignition parameters represented in Equation 42 are the thermal inertia \((k_\rho c)_S\) and ignition temperature \((T_{ig})\) of the tested material. The thermal inertia is linearly related the ignition time and related to the square of the external heat flux \((k_\rho c)_S = f(t_{ig}, q_e'^2)\) while the ignition temperature is related to the square root of the ignition time and linearly related to external heat flux \((T_{ig} = f(\sqrt{t_{ig}}, q_e'))\).

The results from the uncertainty propagation analysis can be seen in Table 26. While the statistical uncertainty in the ignition time results decreases with increased trials, the 5% uncertainty in the external heat flux calibration does not change. Even at high trial numbers, the uncertainty in the heat flux calibration serves as a lower limit to the total propagated uncertainty.

Table 26. The propagated uncertainty in the ignition parameters calculated in Equation 42.

<table>
<thead>
<tr>
<th>Trials (n)</th>
<th>20 kW/m² [%]</th>
<th>40 kW/m² [%]</th>
<th>60 kW/m² [%]</th>
<th>Average [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Inertia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>13.1%</td>
<td>13.9%</td>
<td>18.4%</td>
<td>15.1%</td>
</tr>
<tr>
<td>2</td>
<td>10.6%</td>
<td>11.5%</td>
<td>15.2%</td>
<td>12.4%</td>
</tr>
<tr>
<td>3</td>
<td>9.7%</td>
<td>10.6%</td>
<td>13.8%</td>
<td>11.3%</td>
</tr>
<tr>
<td>4</td>
<td>9.1%</td>
<td>10.0%</td>
<td>13.0%</td>
<td>10.7%</td>
</tr>
<tr>
<td>5</td>
<td>8.8%</td>
<td>9.7%</td>
<td>12.4%</td>
<td>10.3%</td>
</tr>
<tr>
<td>10</td>
<td>8.1%</td>
<td>8.9%</td>
<td>11.2%</td>
<td>9.4%</td>
</tr>
<tr>
<td>15</td>
<td>7.8%</td>
<td>8.5%</td>
<td>10.6%</td>
<td>9.0%</td>
</tr>
<tr>
<td>25</td>
<td>7.6%</td>
<td>8.2%</td>
<td>10.1%</td>
<td>8.6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trials (n)</th>
<th>20 kW/m² [%]</th>
<th>40 kW/m² [%]</th>
<th>60 kW/m² [%]</th>
<th>Average [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>9.2%</td>
<td>9.8%</td>
<td>13.0%</td>
<td>10.7%</td>
</tr>
<tr>
<td>2</td>
<td>7.5%</td>
<td>8.2%</td>
<td>10.7%</td>
<td>8.8%</td>
</tr>
<tr>
<td>3</td>
<td>6.8%</td>
<td>7.5%</td>
<td>9.7%</td>
<td>8.0%</td>
</tr>
<tr>
<td>4</td>
<td>6.5%</td>
<td>7.1%</td>
<td>9.2%</td>
<td>7.6%</td>
</tr>
<tr>
<td>5</td>
<td>6.2%</td>
<td>6.8%</td>
<td>8.8%</td>
<td>7.3%</td>
</tr>
<tr>
<td>10</td>
<td>5.7%</td>
<td>6.3%</td>
<td>7.9%</td>
<td>6.6%</td>
</tr>
<tr>
<td>15</td>
<td>5.5%</td>
<td>6.0%</td>
<td>7.5%</td>
<td>6.4%</td>
</tr>
<tr>
<td>25</td>
<td>5.3%</td>
<td>5.8%</td>
<td>7.1%</td>
<td>6.1%</td>
</tr>
</tbody>
</table>

9.5 Conclusions

The presented methodology can be used to choose an ideal number of trials in order to optimize the statistical uncertainty within a practical limit. Both the statistical uncertainty and marginal gain at any
given value of \( n \) can be used together to choose a number of trials that minimizes uncertainty while still optimizing the amount of trials conducted. Additionally, the results presented here can help guide researchers to understand the variation of uncertainty in ignition data for a given number of trials at various external heat fluxes. The results of this analysis are only valid for the particular experimental conditions described here. PMMA is a particularly predictable material in the context of fire testing with no complications such as charring – thus the results for PMMA are characteristic of a likely minimum degree of uncertainty compared to other materials all things being equal. While the general trends can be used for insight into other conditions, further experimentation is required to determine if the same degree of uncertainty can be expected for any value of \( n \) when using another material such as timber, or even PMMA samples of greater thickness than those tested in these experiments.

Statistical uncertainty in ignition data is heavily linked to the external heat flux used during the experiment. Higher degrees of scatter are seen at low heat fluxes due to longer ignition times. The relationship of uncertainty to external heat flux is non-linear in a similar way that the time to ignition itself is not linearly related to external heat flux. These results suggest that a more robust analysis may require more trials at low heat fluxes than traditionally conducted in standardized testing. The non-linearity of the results also suggests that an optimized approach to ignition testing may incorporate variable sample sizes (i.e. vary \( n \)) at different heat fluxes.

The criteria for determining an appropriate degree of trials depends on the experiment conducted, the acceptable range of uncertainty, and the practical limit of time and resources that can be dedicated to the experimental series. Therefore, it is difficult to establish a single benchmark criterion for a ‘statistically significant amount of trials’ – instead this methodology can at least lend insight to the degree of statistical uncertainty in a measurement at ignition. The calculated uncertainty for a value of \( n \) can be used in combination with the marginal gain but no single combination of criteria can capture the best practice for all applications. The selection of a number of trials can be guided by this analysis but is ultimately dependent on the acceptable degree of uncertainty agreed upon by the researchers.

The predicted uncertainty and marginal gain may also be useful during an experimental series as well. Assuming all things being equal, the predicted uncertainty at any heat flux and sample of \( n \)-trials
should simulate the uncertainty of the experimental results to a similar degree. If a new series of experiments is to be conducted and the resulting standard deviation of n-trials is far less than the anticipated statistical uncertainty suggested by this study (for a given value of n at a given heat flux), then perhaps the trials conducted do not represent an accurate spread ignition times. In such a case, more trials are required to ensure that the n trial conducted approximate the distribution of all possible results. More trials can be conducted until the predicted statistical uncertainty matches the observed uncertainty within an acceptable degree. The initial intent to this study was to determine a number of trials that would be appropriate for a series of experiments with PMMA at heat fluxes from 60 kW/m² to the critical heat flux for this master’s thesis project. The testing matrix presented in Table 27 is to be adopted for following experiments within this project and is not necessarily a general guideline for all experimental procedures. The observed spread in the trials conducted will be compared to the anticipated statistical uncertainty and marginal gain for n trials and more repetitions will be conducted if the statistical spread far exceeds the spread in experimental data.

Table 27. Adopted testing matrix for ignition testing of PMMA in the Cone Calorimeter for this study.

<table>
<thead>
<tr>
<th>External Heat Flux (kW/m²)</th>
<th>Trials Conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 20</td>
<td>10 - 15</td>
</tr>
<tr>
<td>20-40</td>
<td>10</td>
</tr>
<tr>
<td>40-60</td>
<td>5</td>
</tr>
<tr>
<td>≥ 60</td>
<td>3</td>
</tr>
</tbody>
</table>

The methodology presented here provides a benchmark for determining a relevant trial size based on statistical analysis opposed to rules of thumb and tradition. Understanding the anticipated statistical uncertainty in ignition testing should guide the quantification of experimental error – the standard deviation of three trials does not necessarily capture the true uncertainty of that measurement. Similar statistical analysis may be required in other aspects of fire safety science. Often times theory, codes/standards, and other procedures are developed from a limited number of experiments and too often there is no discussion to the uncertainty of doing so. The ability to quantify statistical uncertainty is possible for all scales of fire testing and has not been adequately investigated to date. This does not suggest that all testing at all scales must be conducted in trials of 100 as this is an impractical use of time and resources. However, a better understanding of the uncertainty and limitations of experimental procedures in the field of fire safety is required to ensure the adequacy of the existing framework to protect life and property from the effects of fire.
“…a fire safety engineer must be tough enough to stand up to a good deal of questioning and in his turn to be able to push other people in the same way: justify what you are saying if you want to be taken seriously”

– Margaret Law, 1990 [59]

The process of ignition is inescapably intertwined with the system in which ignition is observed. Experimental results from this study have highlighted the fact that ignition parameters used in engineering applications, such as the CHF, are often reported as material properties but can significantly vary between different orientations. Most ignition data is presented in the horizontal orientation as is the case in the SFPE Handbook [1] – the built environment is not limited to any one orientation and therefore further characterization is required for an adequate understanding of using such parameters to predict real fire events. Only reporting the horizontal orientation could possibly be warranted if the horizontal orientation represented the lower limit for ignition parameters and therefore reported a conservative value. Experimental results have concluded that ignition at angles between horizontal and vertical can more readily achieve ignition, meaning that the horizontal orientation and the values presented in the SFPE handbook may not represent the lower limit. The CHF for the vertical orientation as determined in this study varied by over 25% from the horizontal orientation when considering autoignition; using data from horizontal testing to characterize the vertical orientation may be conservative compared to the vertical orientation, but there must come a point when a conservative analysis becomes an incorrect analysis. The history of ignition testing highlights that parameters like the CHF were assumed to be mathematical properties that were tied to the method through which they were determined – this context must be considered when applying such parameters in analysis.

10.1 Conclusions for Engineering Applications

The concept of ignition is incorporated into engineering practice in two primary ways: 1) standardized testing for material characterization and 2) performance-based design solutions. Fire Protection engineers must be aware of the variation in results from differing testing apparatuses and that
results are linked directly to the testing apparatus and the standardized testing procedure. A practicing engineer may also want to note the statistical significance of data reported in standardized testing and understand conducting three trials regardless of external heat flux may not capture an adequate degree of statistical uncertainty. Standardized testing procedures, such as the Cone Calorimeter standard, can be modified to account for various orientations. An ASMTE E1354 standard Cone Calorimeter was modified in this study to conduct experiments in the horizontal and vertical orientations as well as 45° off horizontal. Such a procedure can be incorporated into existing testing methodologies, if not developed into a standardized testing procedure of its own.

The two leading misconceptions with using ignition data as it is presented in the SFPE Handbook is the CHF is a material property and the time scales associated with the CHF. The concept of the CHF assumes ignition never occurs – however this concept is not always clear from simply looking at a table of CHF values. An engineer who may not be familiar with ignition data may take a CHF value to imply ignition is instantaneous once exposed to the CHF.

Table 28. A novel presentation of ignition data to account for both the orientation effects on ignition.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>CHF</th>
<th>$q_{1100}^*$</th>
<th>$q_{150}^*$</th>
<th>$q_{125}^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>34</td>
<td>39</td>
<td>44</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>32</td>
<td>38</td>
<td>40</td>
</tr>
<tr>
<td>Vertical</td>
<td>43</td>
<td>47</td>
<td>52</td>
<td>74</td>
</tr>
</tbody>
</table>

Table 28 demonstrates an example of a modified table through which ignition data can be presented from standardized testing. For a given material, ignition tests are to be conducted in at least three orientations, as done in Chapter 7, and the CHF in each orientation is to be reported. In addition to the CHF, additional heat fluxes are to be reported that suggest the approximate required irradiance to result in a known ignition time. For example, $q_{1100}^*$ indicates the external heat flux that corresponds to an ignition time of 100 seconds. The corresponding heat flux for a given time to ignition can be approximated by the $1/\sqrt{T_{100}}$ vs $q_e^\alpha$ relationship previously discussed; the results seen in Table 28 were determined using the $1/\sqrt{T_{100}}$ vs $q_e^\alpha$ curve for the High Irradiance Regime processed using the theory developed by Lawson and Simms. Providing information in this way removes the misconception of the CHF being a material
property, as it clearly changing with orientation, and also highlights the time dependency and the variation of time to ignition with external heat flux. Such a table can also be used for other system dependent factors such as forced flow conditions; however, orientation is a simple concept to apply since an engineer can easily understand how materials are oriented in a space. This approach lends practical insight to allow engineers to judge the response of a material in a fire event – the use of such information must, however, come with the understanding that ignition data is still fundamentally tied to a standardized testing procedure used and therefore will not necessarily behave the same way in a real fire event when exposed to transient heat fluxes. This presentation would serve to reinforce the temporal and system dependencies of ignition to the practicing engineer.

Current design methodologies such as the calculation procedures outlined in NFPA 92 allow for the use of ignition data to directly calculate the ignition of additional fuel packages within a space and therefore change the specified fire size in a given analysis. The approach implies the use of bench-scale ignition data to be extrapolated to predict the behavior of materials on a compartment fire scale. Calculations can predict the incident radiant heat flux a fire will project to another item, however it is unclear how an engineer should then interpret the time at which the secondary item will ignite. Ignition theory, as presented throughout this work, was defined with very limiting assumptions and was intended to be applied to bench-scale testing in a controlled environment. The use of parameters such as the CHF can be used as binary indicators of whether an item is likely to ignite, however using calculations to predict the exact time of ignition must be considered with a high degree of uncertainty. The traditional theory pioneered by Lawson and Simms only considers a constant external heat flux and linearizes surface loses into a total heat transfer coefficient; this simplification leads to variation even between various highly controlled testing environments, let alone in realistic engineering analysis. Simple calculations and the extrapolation of bench-scale data to compartment fire dynamics does not consider other factors such as the effect of smoke on the item, multi-directional heating, and convective cooling from air flow within the compartment – these effects are illustrated in Figure 69.
Figure 69. An illustration of the ignition of a secondary fuel package in a real fire scenario. The use of bench-scale ignition theory and ignition parameters should be used with uncertainty when considering compartment scale effects and the transient nature of fire.

With the current knowledge of the Fire Protection discipline, applying ignition parameters for engineering analysis should be considered as more of a qualitative analysis than an absolute, quantitative calculation. The process of ignition is inherently system dependent and this dependency must be considered in engineering analysis. Further research needs to be conducted to predict ignition of additional items with certainty. At this point, published ignition data can still lend insight to the relative flammability of a material in a given orientation. While data presented in Table 28 cannot be used to predict actual ignition times for real items in an absolute manner, knowing the CHF for a material can lead to the understanding of whether or not another item could possibly ignite in a fire event. The other heat fluxes associated with ignition times do not give exact ignition times but provide a sense of the order of magnitude of the time expected for a material to reach a point where ignition could be possible under ideal conditions. The confidence, if any, is primarily in the binary result of ignition or no ignition. Even with that being said, more care must be taken if this analysis is to suggest that ignition will not occur. The radiation calculation laid out in NFPA 92 does not account for compartment scale fire dynamics and other factors that may promote or hinder ignition; assuming a secondary will never ignite may have significant implications to the
life safety analysis being conducted and therefore these simple calculations must be considered with a margin of error. If the result from such calculations is that a secondary item will not ignite, then a sensitivity analysis should also be conducted assuming ignition may occur in order to explore if the possible consequences of secondary ignition negate the degree of confidence placed in such a simple calculation. Future research into ignition of items in a real fire scenario may lead to a better understanding of such calculations.

10.2 Conclusions for Fire Safety Science

This study has outlined the mass transport and heat transfer mechanisms that pertain to the ignition of solids in various orientations. Over 130 years have been dedicated to the study of solid ignition, yet the attempt to investigate orientation effects on ignition date not much further than the 1990’s. Results from the autoignition study determine that ignition occurred most readily at 45° between horizontal and vertical. The experimental results also verify that ignition occurs more readily in the horizontal orientation when compared to the vertical orientation. The occurrence of ignition in any orientation is fundamentally tied to both the presence of a flammable mixture and the required energy to initiate combustion. The horizontal orientation produces a gradient of fuel rich to lean mixtures as the gas moves away from the heated surface while the vertical orientation features a boundary layer flow that is likely to promote more mixing and more complicated behavior; such a difference in flows could help to explain the ease of ignition in the horizontal orientation compared to the vertical. When considering the samples at 45°, however, the flow structure changes because air entrained along the surface is not traveling in line with the buoyant plume upwards. Further investigation is required to quantify how these flow behaviors facilitate ignition when considering orientations at angles between horizontal and vertical.

The results presented here highlight the system dependency of ignition and develops a framework for incorporating orientation into exiting ignition theory. The use of an ignition time ratio (ITR) as a constant value does not capture the intricacies of orientation effects. The most effective way to incorporate orientation was through the use of a heat flux ratio defined as $\Psi$ (external heat flux/CHF) which collapses the data of all orientations into a single curve due to the orientation dependency of the experimentally determined CHF. The collapse of the data signifies the fact that $\Lambda$, or the ratio of heat transfer from the
surface to the apparent thermal inertia of the material, is constant irrespective of the orientation. Fluid behavior around a sample surface indisputably changes with orientation and therefore the heat transfer from the surface is dependent on the sample orientation. If $\Lambda$ is truly constant with orientation, and the heat transfer from the surface is dependent on orientation, then the apparent thermal inertia (assumed to be a material property) must also vary with orientation. Many applications in fire safety science rely on thermal inertia as an input (e.g. ignition predictions, flame spread models, pyrolysis models, etc.) which is generally determined from standardized testing and assumed to be more or less a material property. The results from this study suggests that perhaps a material parameter such as $\Lambda$ may prove to be a more consistent input compared to the thermal inertia when considering predictive calculations and modelling applications.

The use of $\Psi$ also illustrates the distinct transition between the Low Irradiance and High Irradiance Regimes and quantifies the transition which has not been as clearly defined in previous studies. The transition region of $\Psi$ values of 1.15 and 1.25 is only valid for the autoignition of PMMA and needs further validation and experimentation to apply to other materials and modes of ignition. Incorporating the CHF can also be used to remove some of the scatter historically seen in previous ignition studies (i.e. the CHF not only accounts for orientation, but variations in experimental set up, uncertainty in calibration, etc.).

A statistical analysis was conducted on a series of experiments with a high number of trials to explore the statistical uncertainty in ignition studies. Most standardized testing procedures only require 3-6 trials and do not consider how the statistical variation might change between the heat flux tested or the material used. This study serves to establish a methodology for quantifying the marginal benefit in statistical uncertainty from conducting additional trials. From this methodology, a researcher is able to optimize the number of trials to a desired degree of statistical uncertainty. The results presented here only apply to the material tested and the apparatus used in this study (black PMMA and the Cone Calorimeter), but the methodology can be used for various exploratory studies into ignition. This statistical study would ideally be repeated for various materials in different apparatuses which could develop a database from which researchers could develop their experimental matrix based upon the relative uncertainty expected from the material they wish to investigate. This study also suggests that while the statistical uncertainty is
strongly dependent on the external heat flux, the normalized uncertainty remains constant at all heat fluxes. If this trend is verified with additional studies into other materials and apparatuses, then researchers would be able to predict the statistical uncertainty for virtually all practical degrees of irradiation with testing only a few heat fluxes which would lend itself as a very powerful tool for the scientific community.

The results from the statistical study can also be tied to the larger work on orientation through the discussion involving the parameter Λ. This study suggests that Λ may serve as a useful property given that parameters such as the thermal inertia have shown a high degree of variation when determined experimentally. One source of that variation is likely due to orientation effects, and the use of Λ may serve to reduce that as previously discussed. However, the scatter observed in reported values of properties like the thermal inertia may also be linked to uncertainty in experimental results (i.e. statistical variation of the ignition time used to determine the thermal inertia). The statistical study can therefore be used to establish the uncertainty propagated to determined parameters (e.g. CHF, T_{ig}, thermal inertia, Λ, etc.) from the statistical uncertainty in the recorded time to ignition values. This analysis would contribute to the question of whether or not thermal inertia is influenced by orientation and would quantify the uncertainty in Λ for use in engineering applications.

10.3 Future Work

Further research can lend more insight into the system dependency of ignition and how these dependencies can be incorporated into engineering analysis. For the purposes of predicting ignition in a real fire scenario, further research must be dedicated to the ignition of secondary items to supplement the existing analysis structure that relies on bench-scale data that has not been verified to extrapolate to compartment scales. Standardized testing procedures can be modified to include the effects of orientation on ignition – in particular, the Cone Calorimeter lends itself to incorporate such testing with relative ease.

Analysis presented in this work used the CHF to modify existing theory and incorporate orientation. Further insight could be gained into the fluid behavior of pyrolysis gases in various orientation through a numerical investigation into a heated plated with pyrolysis gasses emitted from the heated surface. From this simulation, the velocity profiles and gradient of pyrolysis gases could be quantified for
various orientations and heating conditions. This simulation can then be combined with additional experimental work to further comment on the gas phase behavior of pyrolysis gases in various orientations and heating conditions.

The study of orientation and ignition should be extended to other orientations such as a ceiling orientation. Previous studies into ceiling orientations appear to be less conclusive and consistent compared to other orientations [6] which could be due to a higher sensitivity to sample size and edge effects in the ceiling orientation as the pyrolysis gases need to move around the sample to be driven up by buoyancy. Studying the ceiling orientation may require more sensitivity studies to first understand the dependency on sample size, but an extension of understanding the ignition behavior of materials in a ceiling orientation would prove useful to the fire safety community.

As the profession pushes towards performance-based design solutions, engineers will require a better understanding of ignition in real fire scenarios and how to incorporate the system dependency of ignition into engineering analysis. Orientation is the most practical and easiest system dependency to characterize. Future work must further characterize the effect of orientation on ignition for use in engineering analysis and strive to break the misconceptions that ignition parameters like the CHF are material properties, when in reality they are inescapably system dependent.
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