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INCORPORATING DYNAMIC FLAME BEHAVIOR INTO THE SCALING LAWS OF WILDLAND FIRE SPREAD

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INCORPORATING DYNAMIC FLAME BEHAVIOR INTO THE SCALING LAWS OF WILDLAND FIRE SPREAD

Dissertation

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Engineering
at the University of Kentucky

By
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ABSTRACT OF DISSERTATION

INCORPORATING DYNAMIC FLAME BEHAVIOR INTO THE SCALING LAWS OF WILDLAND FIRE SPREAD

A challenge for fire researchers is obtaining data from those fires that are most dangerous and costly. While it is feasible to instrument test beds, test plots, and small prescribed burns for research, it is uncommon to successfully instrument an active wildland fire. With a focus on very specific facets of wildland fire, researchers have created many unique models utilizing matchsticks, cardboard, liquid fuel, excelsior, plywood, live fuels, dead fuels, and wood cribs of different packing densities. Such scale models, however, only serve as valid substitutes for the full-scale system when all functional relations of the scale model are made similar to corresponding relations of the original phenomena. The field of study of large wildland fires therefore was in need of a framework that researchers could use to relate the results from many previous experiments to full-scale wildland fires; this framework was developed during the research for this dissertation. This further work developing laws for instability scaling in wildland settings was founded on the established work in dynamic similitude of G.I. Taylor, H. C. Hottel, F. A. Williams, R. I. Emori, K. Saito and Y. Iguchi. Additionally, in this work, a new dynamic flame parameter was incorporated into the scaling laws for fires that had not previously been assessed and proved to provide additional, important insight into flame spread. The new dynamic parameter enabled improved St-Fr correlations and was established for a wide range of fire sizes and fuel types.

Keywords: scale modeling, wildland fire, combustion, fire spread, dynamic flame behavior

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NOMENCLATURE

a	constant
B_{value}	blue value of RGB pixel
c_l	heat capacity per unit mass for fuel l
c_p	specific heat at constant pressure for gas mixture
E	radiative heat flux
E^*	radiative heat flux scale factor
F_b	buoyant force of air and gas
F_ω	inertial force associated with instability
$F_{i,up}$	inertial force of the initial flow
g	acceleration due to gravity
G_{value}	green value of RGB pixel
H	fuel height
I	fire intensity
l_c	crib stick length
l_λ	width of flame tower base
L	characteristic fire length
L_a	height of fire plume
L_e	effective length where a majority of heat transfer occurs
L_f	flame length
L_w	flame zone depth
L_α	other geometrical lengths, α = 1, 2, …
q_2	heat value per unit mass of fuel
Q	heat generated
Q_C	thermal energy delivered to unburned fuel via convection
Q_{c1}	thermal energy associated with the air and gas temperature rise
Q_{c2}	heat stored in unburned fuel
Q_R	thermal energy delivered to unburned fuel via radiation
Q_r	radiant heat received by unburned fuel
Q_λ	latent heat of fuel

R	spread rate of flame front
R_{value}	red value of RGB pixel
t	time
t^*	time scale factor
t_b	burning time
t_0	ignition time
T	temperature
T_i	fuel surface temperature
T_l	gasification temperature for fuel l
T_∞	ambient temperature before pyrolysis or ignition
u	horizontal airflow velocity (horizontal wind speed)
V	characteristic mass average velocity of the gas mixture
W	fuel loading (weight of fuel per unit ground area)
α	angle of fuel bed slope
Δh_l	heat of gasification per unit mass for fuel l
$\Delta\rho$	density change
$\Delta\theta$	temperature rise
λ	latent heat per unit mass of fuel
μ	viscosity coefficient
ν	vertical speed of rising gas
π_i	pi-number
ρ	density
ϕ	ratio of consumed fuel to the total fuel available
Φ	arbitrary function
Γ	vertical component of vorticity vector in the ambient atmosphere
$\bar{\kappa}_v$	average absorption coefficient per unit mass, for radiation
σ'	Stefan-Boltzmann constant
ω	frequency of convective event experienced by unburned fuels

Subscripts

a	ambient atmosphere

ad	adiabatic; identifies adiabatic lapse rate of the atmosphere
i	pi-number index
max	maximum
$value$	pixel value of RGB image for indicated component
1	property of combustion gasses and air
2	property of fuel

Superscripts

$'$	identifies variables of one particular scale
*	indicates the scale factor for the given variable

Dimensionless Numbers

Fr	Froude Number
St	Strouhal Number

CHAPTER 1: INTRODUCTION

Wildland fires have become increasingly common and their destruction and cost increasingly severe in the past decades. Fire is a natural process in wilderness land; fires shape the structures and patterns of forests, influencing vegetation composition, density, size, arrangement, and age structure [1]. Years of aggressive suppression policy has disrupted the natural, historical processes within forests that periodically would destroy or disrupt dense underbrush; fire suppression has caused extraordinarily high fuel loadings within forests, particularly in parts of the western United States, creating forest structures vulnerable to catastrophic fire [2].

The response to wildland fires is complicated by their unpredictable and extreme fire behavior. The research and data required for a better understanding of wildfire behavior are usually not attainable from a catastrophic burn because instrumenting these fires is not possible. Although laboratory experiments have identified certain behaviors of fire under very specific conditions, no models exit that can adapt to the varied fire conditions within wildland fires.

This dissertation proposes and then uses scale modeling as a framework for relating laboratory experiments to full-scale fires, and develops scaling laws that incorporate dynamic fire behavior for fire in the convection-driven regime.

1.1 Motivation for Fire Research

Wildland fire is a general term describing any non-structure fire that occurs in a natural landscape. There are two categories of wildland fires: (1) prescribed fires or burns, which are, by definition, planned ignitions; and (2) wildfires, which can be either unplanned ignitions or prescribed fires that are declared wildfires [3]. Of the unplanned ignitions, some are allowed to burn, since they pose no threat, others are easily contained, but a few, exacerbated by conditions like dry, hot weather and high fuel loading, will burn out of control for a significant amount of time and do significant damage before they are contained. Generally, some combination of terrain, weather and unpredictable and extreme behavior prevents a fire from being contained. Unfavorable terrain and weather may restrict the number of firefighters able to work in close proximity to the fire on the ground, but unpredictable and extreme fire behavior is a situation that endangers firefighters and can render their localized preventative efforts useless. As our understanding of the basic principles of combustion improves, our predictive capabilities should also improve, and result in increases to the efficacy, efficiency and safety of the resources needed to control prescribed fires and fight wildfires.

1.1.1 Why U.S. Land Is at Risk for Extreme Wildland Fire Events

Fires burn through wildland areas periodically as a part of natural occurrences; their frequency has been coincident with the levels of fuels accumulated and generally have resulted in burns of relatively low intensity [4]. In the Sierra Nevada Mountains, for example, dendrochronology studies found a high frequency of fire prior to human settlement, with fires in many stands occurring every 5–25 years [5]. Aggressive suppression efforts and policy in the latter half of the 19th century and throughout the 20th century dramatically reduced the frequency of fires in wilderness areas [5].

During the first half of the twentieth century, the official firefighting policy in the US mandated aggressive suppression efforts. The term ‘conservation’ often was fiercely accompanied by a call for war-like acts of patriotism to battle and suppress fires [6]. In 1910, from a progressive and rather ostentatious stance on fighting fire, Pinchot, the first Chief of the newly formed agency of the National Forests, wrote, “It was assumed that (forest fires) came in the natural order of things, as inevitably as the seasons or the rising and setting of the sun. Today we understand that forest fires are wholly within the control of men.” [7] Pinchot’s successor, Chief Graves, also supported a rather strong fire-suppression program that same year, writing, “The first measure necessary for the successful practice of forestry is protection from fire.” [8]

The year 1910 was a historically bad year for wildland fires: fires burned three million acres of Montana and Idaho and took eighty-five lives [6]. Although these fires suggested wildland fires could well be out of the control of those who were fighting them, the Forest

Service’s resolve to fight future blazes increased. The campaign against wildland fires achieved success beyond prevention - generations had been instructed and then come to believe wildland fires were catastrophe events that could be suppressed [9].

This fire suppression shifted ecological successional patterns, increased the density of small trees in forested lands, and produced an unnatural accumulation of ground fuels [10], which ultimately led to fewer, but larger and more intense fires that would destroy the vegetation they passed [11]. Beginning in the 1920’s, research initiated in the western United States identified changing ecological conditions that could be attributed to fire suppression efforts. For the first time, researchers documented significant changes in the structure, composition, and fuel loads in forests that had previously experienced frequent, low- to moderate-intensity fire regimes [12]. In 1924, Lee wrote, “if the fire is not too severe, the burning may be beneficial to forest succession, as light fires usually help to kill back the underbrush, open resinous cones, stimulate germination, and encourage the development of the major forest tree species.” [13] Along with Lee, others found ecological and financial benefit to more frequent, less intense, wildland fires [14-16].

The fact that forest fires could be beneficial to forest development was recognized in the field of ecology much earlier than it was incorporated in US policy. George L. Hoxie wrote a piece in Sunset in 1910 arguing for controlled burns every 1-3 years in California. Although he emphasized that his experience was limited to a certain type of forest, he explained that frequent fires running through tall stands of pines actually improved biological health of the area and increased the yield of timber for landowners who were harvesting timber [17]. Larsen, in 1929, similarly found fires to be part of the natural cycle of forestation in the Bitterroot Mountains [18].

Starting in the 1940’s the US Department of Forestry began cautiously using fire as a silviculture tool in Southwest regions, where Native American culture, which supported light burns, was more prevalent [19]. A catalyst for a real change of policy arrived with the 1963 Leopold Report, in which the Special Advisory Board on Wildlife Management recommended ecosystem management tools to the United States Secretary of the Interior. The report focused on elk habitat and only mentioned fire as a natural regulator of that environment. It noted the recent absence of fires and observed that, “Today much of the west slope is a dog-hair thicket of young pines, white fir, incense cedar, and mature brush - a direct function of overprotection from natural ground fires." Most influential, however, was its recommendation that "Management based on scientific research is, therefore, not only desirable but often essential to maintain some biotic communities in accordance with the conservation plan of a national park or equivalent area [20, 21]." This was the first interdisciplinary cooperation between politics and ecologists in the field and it further encouraged developing a policy written on the recommendations of scientists.

Beginning in the late 1960's, US firefighting policy began to shift as more discoveries substantiated fire's natural role in wildland maintenance and evolution. The National Parks Service even employed prescribed burns in conifer forests in the Sierra Nevada Mountains [22]. In the 1988 Report on Fire Management Policy, the Review Team noted, "some agency employees support a policy of allowing naturally caused fires to burn free of prescription so long as they do not cross park or wilderness boundaries [23]." The largest change in policy came in 1995 though, in a report by the US Department of the Interior and the US Department of Agriculture. The Federal Wildland Fire Management Policy and Review recognized the danger resulting from years of wildfire suppression and reported that, "wildfire now threatens millions of wildland acres, particularly where vegetation patterns have been altered by past land-use practices and a century of fire suppression," and recommended an altered course that stated "wildland fire, as a critical natural process, must be (cautiously) reintroduced into the ecosystem [24]." Federal fire policy has continued to evolve since 1995, recognizing and embracing the role of fire as an essential ecological process, and scientific research as a foundation for planning and policy [25-27].

Fire, as a critical natural process, is now integrated into land and resource management plans, and the response to wildland fires is based on ecological, social, and legal consequences of the fire. The appropriate response to a fire is determined by factors, which include: the circumstances under which a fire occurs, the value that can be saved, the likely consequences on firefighters, public safety and welfare, and the natural and cultural resources available [24].

To increase the effectiveness of agencies that were individually or collectively tackling wildfire incidents, The Boise Interagency Fire Center (BIFC) was created in 1965 to coordinate efforts of the US Forest Service, Bureau of Land Management (BLM), and National Weather Service. The National Park Service and Bureau of Indian Affairs joined BIFC in in the mid 1970’s. The US Fish and Wildlife Service later joined in 1979. The Center's name was changed in 1993 from the Boise Interagency Fire Center to the National Interagency Fire Center to more accurately reflect its national mission. Subsequently, the US Fire Administration-FEMA joined NIFC in 2003.

Because of the policies in place for over a century, fire suppression has changed the vegetation patterns within wildland areas. Had small periodic burns occurred naturally over the years, the forests would not stand today with an overabundance of underbrush and high tree density that exists. In other words, most new forest fires would not pose the same threat that is faced with the fires today; for example, even control burns in these forests now burn so hot that they destroy not just the smaller vegetation and dead kindling that would have accumulated since the previous natural fire, but instead burn even the largest and oldest of trees to devastate the area, and impose changes to the landscape and new threats to the environment. Furthermore, the containment of even control burns when an overabundance of vegetation exists causes both dangerous and expensive events.

1.1.2 The Cost of Wildland Fire Today

Even with the large expenditures and substantial infrastructure dedicated to fire suppression in the United States, the annual area burned by wildfires has increased in the last decade [20]. For fiscal year 2013, and as illustrated in Table 1.1, the cost to all responsible federal agencies approached $31.4 billion.

The cost of wildland fire arises from the coordinated suppression efforts, the damages incurred, and the ensuing restoration efforts. New costs are also emerging because of the preventative measures that are taken in the hope of reducing total costs of fighting wildland fires by introducing early fuel management strategies. These strategies include: thinning; harvesting and mechanical treatments and prescribed burning, all of which are meant to reduce fuels and the consequent risks of loss or long-lasting damage resulting from wildland fires [26]. The federal land management agencies undertake all of these activities under general authorities within wildfire protection and land and resource management [28]. With as much as 190 million acres at risk of catastrophic fires today, these new preventative costs are increasing.

Table 1.1 Wildland Fire Budgets for involved US Agencies.

US Federal Agencies	2013 Agency Budget (thousands $US)
US Forest Service [29]	7,824,836
Bureau of Land Management [30, 31]	1,756,469
National Weather Service [32]	972,193
National Park Service [33, 34]	3,041,435
Bureau of Indian Affairs [35, 36]	2,678,755
US Fish and Wildlife Service [37]	2,435,504
FEMA [38]	10,222,236
Wildland Fire Management [39]	1,636,946

1.1.3 Limitations of Combustion Research

Research in fire spread has historically been motivated by the need of fire suppression operations [40]. With mounting suppression costs [41], the accuracy and efficacy of suppression efforts become more essential. However, available predictive fire models offer little in the way of solutions to fire behavior. Rather, they provide gross-scale relations that may hold true only in specific scenarios (e.g. the relation of mean wind speed to flame length in crown fires) [40]. There is no lack of study of fire behavior; however, most studies are limited to explicit situations and fuels, or cannot be related to actual wildland fire behaviors and spread. Furthermore, the corralling of all the available knowledge is ineffective because fuel variety and specific fire conditions are challenging to recreate. Therefore, a strong impetus exists for developing a more comprehensive understanding of the fundamental physics governing wildland fire spread.

1.2 Overview of Fire Research

Figure 1.1 displays a broad view of topics of importance to fires; it shows wildland fires, and particularly the role of scaling for wildland fires, in the general field of fire research. Each branch in Level 3, for example under biology, could be expanded downward into more sections that define more specific fields of study, such as ecology or silviculture. Also to be noted is the scope of topics included in the Combustion branch. Here, combustion research encompasses everything from jets (inertia driven flows), methane hydrate entrapment, structure fires, chemical kinetics, material properties, fire extinction, rockets, and wildland fires. For the purposes of this dissertation, the topic of combustion focuses on wildland fires. While this Figure shows where scaling research would fit within the greater study of fire science, it also shows other branches of study, such as Structural Fire, that are not explored in this dissertation.

Level 1 in Figure 1.1 addresses only unintentional burning (diffusion) fires; this excludes areas such as combustion for power generation or transportation. Unintentional fires have been divided into three groups for clarity: structural files, wildland-urban interface (WUI) fires, and wildland fires, as displayed in Level 2.

Structural fires are the fires that occur in an urban or suburban setting. They primarily involve buildings, and the hazards of fighting these fires are compounded by the possibility of the presence of burning chemicals and the threat of explosive scenarios. These fires occur relatively infrequently, but because they consume such a variety of fuel, they are heavy contributors to anthropogenic pollutants from combustion events.

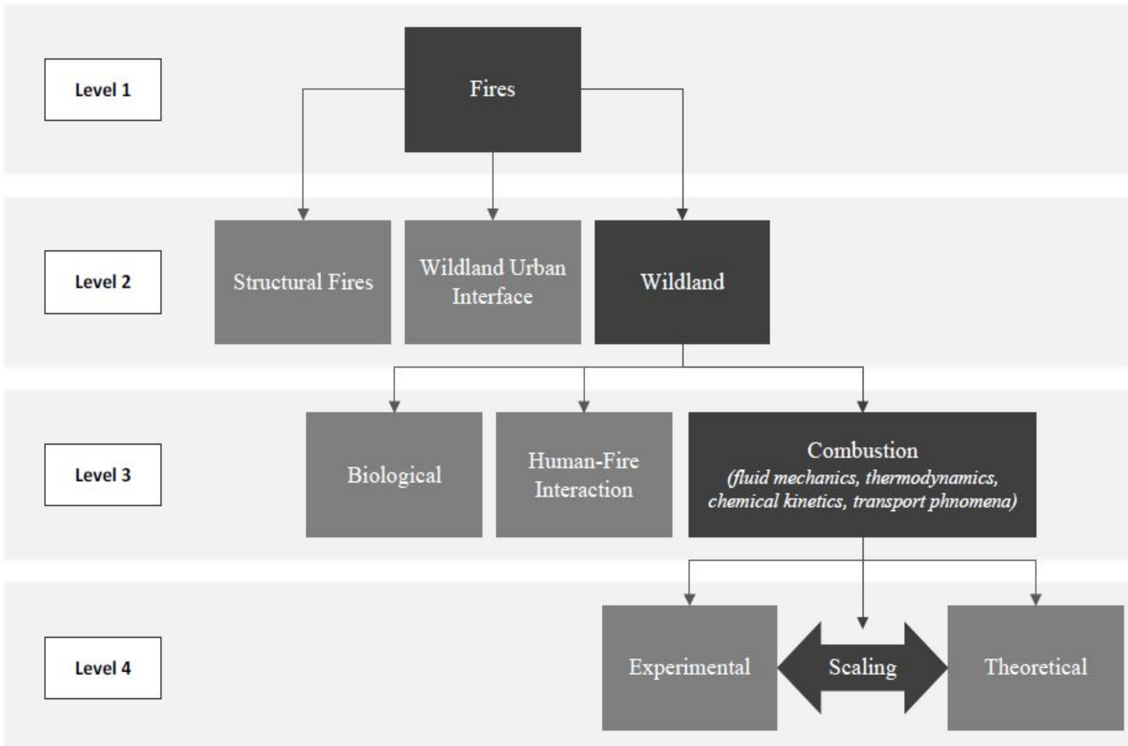

Figure 1.1 Branches of fire and combustion research branching into many sub-fields. This current work is concerned with scaling wildland fire phenomenon.

WUI fires occur on the boundary between an urban or suburban setting and wildland. The length of this boundary between developed land and undeveloped land has grown as developments have sprawled out from cities. Neighborhoods and stores now crowd right up to the edge of protected lands in some places, particularly in states in the Western US. These fires present their own complications since many different agencies and groups can have unique interests in the progress of fire through a WUI. The fires are also challenging to the crews that fight them because they are neither totally structural nor completely wildland fires. Wildland fire fighters often lack necessary gear to tackle a structure fire, and are not trained to handle household explosives (e.g. ammunition or propane grill tanks) and chemical dangers to the level that structural fire fighters are. Structural fire fighters' gear is not conducive to wildland firefighting, and they are not trained to identify or avoid extreme fire behaviors like flare-ups in dry grass. Complicating the issue, private homes that line the WUI do not have access to water mains for structural fire fighters to utilize.

This dissertation focuses on the third type of unintentional, wildland fire. Wildland fires are generally influenced by the fuel available, weather, and location. These fires are started by either natural or human activity, and generally occur in the warmer months.

Level 3 in Figure 1.1, shows three sub-fields of wildland fire studies. They include: Biological topics, associated with or affected by wildland fire like ecology, biology, silviculture, entomology, zoology, *etc*.; Human-Fire Interaction, like anthropology, policy, history, economics, *etc*.; and finally, Combustion, with its concomitant specialty issues of fluid mechanics, thermodynamics, chemical kinetics and transport phenomena. This dissertation focuses on the sub-field of Combustion within wildland fires and the scaling of it that may help to form a useful model for firefighters to apply reliably even under diverse conditions of fuel availability, weather, and location.

Biologically, wildland fire effects and restoration have been popular topics of study for about a century. Fire has been described repeatedly as a dominant factor in the history and biology of plant communities [42]. As a result of genetic diversity, plants evolved distinctive material properties that inhibited or enhanced the flammability of an area; as an example, grasslands are examples of areas which are highly flammable. A plant's holocellulose-lignin-extractives content, and deciduous, annual, or perennial natures, among other qualities, can make those plants more or less flammable, and more or less conducive to spreading fire. The chemical composition of various species establishes the energy base for fire intensity and influences the rate of energy release [42].

There are also certain species that require periodic fires to maintain their position in an environment. In terms of its strategy of serotinous cones, the giant sequoia differs dramatically from other members of the family Taxodiaceae [43]. Giant sequoia cone development takes more than two years and these serotinous cones may then remain green and closed for over twenty years [44]. However, the giant sequoia is dependent on the seeds from these mature cones for its sole method of reproduction. Kilgore explained the function of fire for these species, stating "The original conifer forests of the Sierra Nevada were dependent on fire," although he cautioned that the role of fire as a benefit or detriment to that ecological system was solely dependent on the frequency and intensity of the fire, a sentiment that was earlier expressed by Van Wagner in 1965 [4, 45].

Kilgore further described the function of fire in an ecosystem. Fire: (1) prepares a seedbed; (2) cycles nutrients within the system; (3) adjusts the successional pattern in various ways; (4) modifies conditions that favor wildlife; (5) influences the mosaic of age classes and vegetation types; (6) alters numbers of trees susceptible to attack by insects and disease; and (7) both reduces and creates fire hazards. Each of these roles is affected by fire intensity and frequency [4].

In the study of human-fire interactions, it is worthwhile to note that over the past three centuries Americans have had a very strained relationship with wildland fires. Native Americans used fire in versions of prescribed burns for thousands of years, but their practice was overlooked as scientifically unfounded and barbaric. Later, settlers and large logging operations did their best to keep forests from burning, inadvertently eliminating the primary mechanism for fuel reduction in the arid climates of the West that do not support fungal decay [46, 47]. The idea that fire was a tool for wildland management began with biologists and ecologists, but it took until nearly the end of the twentieth century to be integrated into land management policy.

This history of America's relationship with fire is important because it has guided technologies that developed in tandem with America's changing opinions of fire. Chemical suppressants, flame resistant Nomex®, the inclusion of geographic information system (GIS) technologies in firefighting, and the Incident Command System (ICS, which is now used in all manner of disaster response), would never have been developed without the strong, insistent backing of the government to find solutions to challenges faced while restraining fire from public and private lands.

Combustion, the third field of study under wildland fires in Level 3 of Figure 1.1, represents the work of physical scientists and engineers investigating topics like fuel types, flame composition, heat transfer, and fire spread (among others). Within those fields of study, scientists work to understand relations between important parameters - both environmental parameters (e.g. fuel composition or wind speeds) and fire related parameters (e.g. flame lengths or spread rates). This dissertation focuses on the topic of convection-driven wildland fire spread.

Level 4 provides the two main approaches to combustion research - theoretical work and experimental work. The validity of theoretical development can be confirmed with experimental work, and the validity of observed experimental trends can be corroborated with theoretical explanations. Neither theoretical work alone nor experimental work alone can confirm apparent trends.

The introduction of scale modeling offers scientists the ability to confirm experimental trends with data from a similar experiment that differs only in scale. The resulting confirmation of parameter relations contributes to the theoretical development of the subject. For example, field researchers studying crown fires could establish statistical trends in the data supporting their observations. These trends would traditionally need to be substantiated by theoretical work, thereby establishing a dependable relationship between parameters. Scaling theory helps identify and understand fundamental physical laws governing these parametric relationships. Scaling laws offer those wildland fire experimentalists the ability to confirm suspected relationships between parameters measured during the full crown fire with data from another, properly scaled experiment which could be of laboratory size. Any confirmed parameter relationships ultimately contribute to the theory of wildland fire science.

1.3 Research Objective

The main objective of this dissertation is to develop a framework for correlating fire behavior observed in experimental fires to the behavior of actual wildland fires. Specifically, this work develops scaling laws for wildland fires where the heat transfer from the flame front to the unburned fuel particles is convection-dominated and incorporates a new time-dependent parameter to evaluate convection-dominated fire spread.

This work examines scaling relations by drawing on experimental data from the USDA, literature and experiments conducted for this dissertation. The scaling laws specify the mathematical relations of several parameters of the fires and the environment, including spread rate, flame flickering frequency, characteristic flame lengths, wind speed, and fuel bed properties. The relationships between fire spread rates and a new parameter having potential broad implications - the fire flickering frequency - are investigated and discussed herein, and then discussed relative to their validity and importance.

1.4 Outline of Dissertation

Chapter 1 introduces fire research, the motivation for this dissertation, and the objectives of this research.

Chapter 2 serves as the literature review of wildland fire science and fire spread. It also discusses the lack of sufficient research in flame spread in wildland fires and the challenges of wildland fire research.

Chapter 3 introduces scale modeling and offers a literature review of scale modeling and scale modeling in fire research. In it, a differentiation between radiation-dominant fire spread and convection-dominant fire spread is reviewed and discussed. Chapter 3 also includes the development of the scaling laws for convective-driven fire spread.

Chapter 4 details the experiments conducted to confirm the scaling laws' relations and the results of the experiments. Data from three main experiments are presented which validate the scaling laws. The first experiments were fires conducted in the wind tunnel facility at Missoula Fire Science Laboratory. The second experiments were large crib fires, burned outside in light wind. The third type of experiments was instrumented prescribed burns near Bastrop, Texas.

Chapter 5 presents conclusions and recommendations for future work based on the experimental work of Chapter 4, which confirmed St-Fr scaling for convective-dominated wildland fire spread over a wide range of fire sizes.

CHAPTER 2: REVIEW OF STUDY OF FIRE SPREAD

Advances in the understanding of combustion and fire phenomena have greatly benefitted society by allowing for increased control of fuel resources. Despite the improvements in firefighting for controlled forms of combustion, wildland fires have largely remained beyond human control.

This chapter provides a review of combustion studies pertinent to wildland fire science. The first section offers a review of combustion, the role of fuels, and the anatomy of diffusion flames; the second section is a literature review of the science of fire spread; and, the third section enumerates the challenges faced in wildland fire science research.

2.1 Review of Wildland Fire Science

Combustion generally refers to the rapid exothermic oxidation of an organic fuel characterized by visible flames and a thermal energy release achieving locally gas temperatures around 1400K [48]. Some exceptions that do not fit this description, albeit absent in wildland fire scenarios, include hydrocarbon reacting with fluorine instead of oxygen [49]; nonluminous flames [50]; and low temperature fuel oxidation [51]. The combustion that is addressed in wildland fire science is the burning of vegetation in atmospheric conditions, producing, in most cases (excluding smoldering), a visible flame.

Depending on the surrounding environment, the flow around flames can be laminar, transitional, or turbulent; these flow regimes identify different fluid behavior in and around the fire [52]. For wildland fires, the flow is turbulent [53]. Additionally, wildland fire flames fall under the category of diffusion flames because the fuel and the air are not homogeneously premixed. In diffusion flames, the heat from the flame causes a steady production of flammable vapors as solid fuel undergoes various forms of thermal decomposition [48]. In a diffusion flame, the fuel-oxygen ratio will vary throughout the flame.

A difficulty with diffusion flames, unlike premixed flames, is that no fundamental characteristic parameter, such as burning velocity, can be readily measured [48]. In some diffusion flames, buoyant convection plays a characterizing, dominant role because it sustains the flow of the oxidizer towards the flame [54]. In other diffusion flames, the strength of contributing governing forces or energies, like the strength of the imposed flow, or wind, increasing to such a level that the buoyant force is negligible, can overshadow the overall influence of the buoyant force. Because of the appreciable gravitational force of earth, the effect of the buoyant force never disappears. For the sake of simplicity and in some calculations describing specific wildland fire scenarios, researchers find it is beneficial to neglect terms of buoyancy which are either too challenging to find experimentally or unfavorably complicate the mathematics despite having an influence that is orders of magnitude less important than other contributing factors [55].

During combustion, the fuel experiences chemical changes. Chemical kinetic assessments have shown that in the complete combustion of a single hydrocarbon fuel over two hundred individual reactions take place in a chain reaction [56]. Some fuel properties tend to be transient during the combustion of a solid fuel, as is the case with emissivity. Understandably, wildland fuel is much more complicated than a single hydrocarbon fuel, as fuel properties and environmental conditions change during the time spanning pre-heating-to-ignition and during combustion itself. For example, in the idealized primary combustion reactions of wood, oxygen and gas-phase fuel combine in the combustion zone and at their stoichiometrically preferred concentrations undergo a series of free radical reactions ultimately producing the complete products of combustion, H_2O and CO_2.

2.1.1 Fuels

The ability to predict the potential behavior and effects of wildland fire is essential in fire management. One of the most challenging problems faced by combustion scientists is the dynamic interaction between the flame, the fuel and the flow field [57].

Researchers have created mathematical models for predicting surface-fire behavior, fire-effects and predictive systems. Inputs typically include fuel properties such as load, bulk density, fuel particle size, heat content, and moisture. Within each fuel model is a particular set of fuelbed inputs that serve to facilitate the use of fuel data for a particular fire behavior or fire effects model. Rothermel's surface fire spread model [58], for example, utilized its own fuel model [59].

The extensive variety of wildland fuel, each with its own composition and material properties, provides a challenge for the study of wildland fire. However, it is worthwhile to note that thousands of studies relevant to wildland fire fuel exist; papers and reports can be found bridging the fields of forestry, ecology [60, 61], fire science, biology, climate change [62] and chemistry [63]. Moreover, the chemistry and thermal decomposition of wood has been essential to industry and civilization for centuries. Wood is a biofuel, a paper source, and a source of chemical products, albeit less well-known, like turpentine and artificial vanilla flavoring. An extensive knowledge of wood, its fuel properties, and behaviors during thermal decomposition exists. While far from the only fuel burning in wildland fires, most studies focus on wood as the fuel even while exploring other aspects of fire behavior. Although hundreds of studies exist with wood as the fuel, many stem from structure-fire research not wildland research. Matchstick arrays [64] and excelsior (sometimes referred to as wood wool) [65] have proven to be popular fuels in previous laboratory studies on fire spread, radiation and emissions.

Basic wood chemistry is relevant to fire spread studies. Wood is comprised of lignin, cellulose, hemicellulose, and extractives in varying amounts, depending on the species of tree. The timber used for paper production generally comes from deciduous or conifer trees.

In the papermaking process, the lignin of bark-free woodchips is cooked and dissolved in an acid solution in large pressure vessels called digesters. The undesirable quality of lignin, which motivates its removal, is its penchant for causing the paper to yellow and brittle over time. However, the newsprint manufacturing industry does not remove all of the lignin before making paper because lignin initially renders stronger paper and the nature of newspaper does not necessitate longevity of the product. In fire research, lignin is of interest in fire research because it has a higher net heat of combustion than either cellulose or hemicellulose [66]. In addition, lignin degrades gradually over a wider temperature range than carbohydrates, cellulose, or hemicellulose [67]. These differences were important to assess during this dissertation because research carried out during wind tunnel experiments in cooperation with the USDA Fire Sciences Laboratory used a fuel of choice

- a brown cardboard chipboard made from recycled paper scraps [68] – that had lower lignin content than wood. Hence, it was assumed that this choice would have some influence on the ensuing characteristics of test fire using the chipboard material (it has a lower lignin content than wood and even newspaper, but does have a higher lignin content than white paper).

While a number of studies have been reported in the literature on pyrolysis of lignin and holocellulose [69–73], no comprehensive combustion, pyrolysis and gasification studies for an intact biomass have been compiled into a functional data set [21]. To integrate the biological and chemical combustion work that currently exists into fire research, scientists would need to create exhaustive data libraries of empirical information for each species or an acceptable method or model for accurately obtaining these properties on a per-species basis.

Mapping wildland fuel and fire regimes across broad geographic areas generally requires advanced geospatial informatics, in-depth knowledge of wildland fire science, incredible brute computational power, and statistical analyses [74]. While a comprehensive treatise of wildland fire spread should include a review and analysis of fuels involved in the fires, this dissertation focuses on the technical issues, influences and principles associated with convective heat flow; hence, a comprehensive review and analysis of fuels is not presented.

Since the charring temperature of wood is lower than its ignition temperature, thermal decomposition of the solid phase fuel to gas phase fuel (pyrolysates) precedes combustion; in other words, the combustion of wood is the combustion of the products of thermal decomposition [75]. Extensive research exists on the thermal decomposition of wood and on wood chemistry; for example, in the area of fire science chemistry, Hawley [75] wrote that the term “destructive distillation” was used quite interchangeably with the terms thermal decomposition, carbonization, pyrolysis, dry distillation, and destructive distillation. In fire science, some of these words have taken on different connotations. This work uses the terms carbonization and pyrolysis as they are explained below.

The term "carbonization" denotes the process of decomposition by rise of temperature and the conversion of a carbon compound into a solid residue. The residue is richer in carbon and approximates carbon more closely as the temperature is higher and the time of heating more prolonged [76]. In general, "carbonization" relates particularly to the evolution of a fuel to char during combustion.

Pyrolysis is the thermal decomposition of materials in the absence of oxygen or when significantly less oxygen is present than required for complete combustion. Pyrolysis is endothermic and leads to the release of volatiles and the formation of char [77]. The chemical changes that occur to wood fuel during pyrolysis can be seen in Table 2.1. The volatiles or pyrolysates are the gas-phase fuel that combusts either by auto-ignition, when sufficient concentrations of mass and sufficient thermal energy is added to the system [78]), or by piloted ignition, when an impinging flame begins the combustion chain reactions.

The typical initiation of pyrolysis in wood occurs at 200°C and lasts through a temperature of 500°C, but depends on the species of wood [79]. During pyrolysis, the combustibles in the wood react in two stages. In the first stage, the mass rapidly decreases due to cellulose volatilization. In the second stage, the mass decreases more slowly due to lignin decomposition [80]. From the viewpoint of energy consumption in the course of pyrolysis, cellulose behaves differently from hemicellulose and lignin in that the pyrolysis of cellulose is endothermic while the pyrolysis of hemicellulose and lignin is exothermic [81]. When pyrolysis is exothermic, the pyrolyzing gases generate heat that in turns produces more gasses; consequently, sustained combustion of the fuel particle is possible. The steps in Table 2.1 enumerate the general changes that occur during pyrolysis, according to Sinha et al. [77].

Combustion on the surface of a piece of wood was idealized and described by Hawley [75]; Figure 2.1 provides a schematic. Zone 1 represents the char, with the flaming surface (E) with a temperature, T_i. Surface D is the division of Zone 1 from Zone 2 and is defined as the wood undergoing pyrolysis. Surface D is around 320°C, i.e. $T_D = 320$℃. Pyrolysates from Zone 2 force their way to the surface, through the char, and combust when they receive enough thermal energy and are in the presence of sufficient oxygen.

Table 2.1 Changes to wood fuel occurring during pyrolysis (from Sinha et al. [77]).

Changes to Wood Occurring Pyrolysis	
1	Heat transfer from a heat source, to increase the temperature inside the fuel;
2	The initiation of primary pyrolysis reactions at this higher temperature releases volatiles and forms char;
3	The flow of hot volatiles toward cooler solids results in heat transfer between hot volatiles and cooler unpyrolyzed fuel;
4	Condensation of some of the volatiles in the cooler parts of the fuel, followed by secondary reactions, can produce tar;
5	Autocatalytic secondary pyrolysis reactions proceed while primary pyrolytic reactions (item 2, above) simultaneously occur in competition;
6	Further thermal decomposition, reforming, radical recombination, and dehydrations can also occur, which are a function of the process's residence time/ temperature/pressure profile.

Surface C is the division of Zone 2 and Zone 3, typically around 280°C. Zones 3 and 4 represent wood at temperatures from 280°C down to the wood's original temperature, T_∞. Zone 3 is differentiated from Zone 4 because in it some movement of combustible gases occurs, above a temperature of about 180°C. Combustible gasses from Zone 3 rarely reach the surface though and do not participate in the combustion.

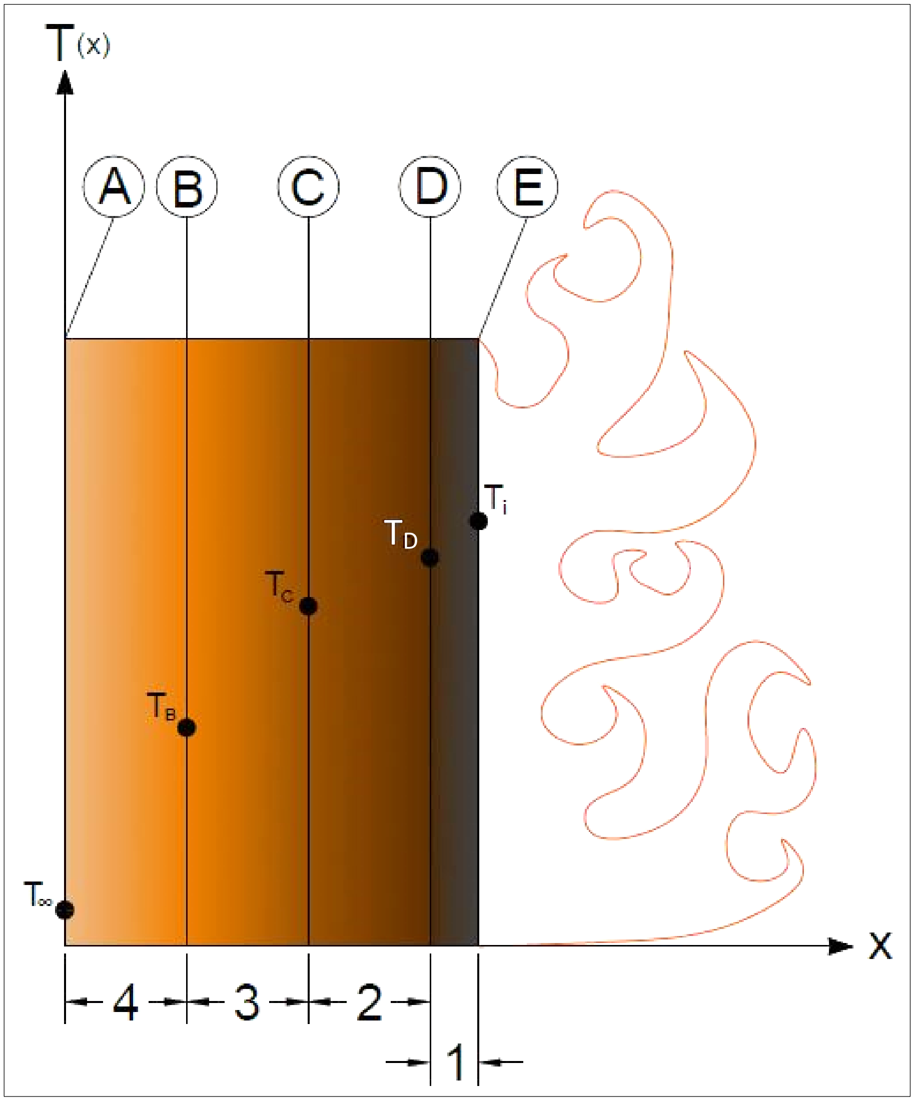

Figure 2.1 Idealized combustion on the surface of wood as described by L. F. Hawley in a USDA Forest Service Report on the combustion of wood [28].

With continued combustion, boundary between Zones 1 and 2 move inward from the surface, encroaching on Zones 3 and 4. The thickness of the char in Zone 1 grows, further reducing the thermal energy that reaches the unburned fuel, slowing the combustion process.

The combustion of plant material from open fires is seldom completely like that presented in Figure 2.1 and seldom 100% efficient; hence, products of incomplete combustion are of concern from an air pollution standpoint. Whereas carbon dioxide and water are the products of complete combustion, carbon monoxide is the major product of incomplete combustion with smaller amounts of the oxides of nitrogen, phosphorus, and sulfur that affect the mix of pollutants generated by burning plant material [82]. Most plant materials also contain classes of compounds known as extractables, consisting of aliphatic and aromatic hydrocarbons, alcohols, aldehydes, gums, and sugars. These extractables, as a group, have a higher heat value than cellulose, lignin, and hemicellulose. [82]

Generally, in fire growth models, ignition is treated as occurring at a definite temperature (or temperature rise), as was discussed by Cox [83]. His description was based on previous research work of Bamford, Crank, and Malan [84]. In the current research and during the wind tunnel experiments conducted at the USDA Fire Sciences Laboratory, the engineered cardboard combs ignited between 315°C and 360°C. However, Finney et al. [40] made a case for not using temperature as an indicator of ignition, but rather visible flames. Hence, in this dissertation the latter method of determining ignition shall be used, i.e. it is defined by the presence of a visible flame and, thus, flame spread.

Ordinarily, wood ignites when enough heat has been generated to start active pyrolysis and then, after the combustible gaseous products have escaped and become mixed with air, applying a pilot flame or other source of high temperature. Under such conditions, the products will be set afire and, if the wood retains enough of the heat of combustion to maintain the pyrolysis, the burning may continue of its own accord until the wood is consumed except for inorganic products left as ash.

In the absence of a pilot flame, pyrolysis products struggle to ignite, and much more heat is necessary for the pyrolysis products to cause fire or a flame. As examples, the minimum rate of heating necessary for ignition by pilot flame is near 12.6 kW/m^2, whereas for spontaneous ignition it is near 25.1 kW/m^2 [85].

Wood may burn directly if its surface is irradiated so intensely that the temperature is raised within a fraction of a second to the point of spontaneous ignition; under this condition, pyrolysis and combustion are practically simultaneous. However, even then, only a thin surface layer may experience direct combustion.

2.1.2 Governing Heat Transfer Mechanisms

Heat transfer represents the movement of energy between media or within a medium due to the presence of a temperature gradient. To understand the mechanisms governing wildland fire spread, a fundamental understanding of the heat transfer processes is required. For wildland fires, all three modes of heat transfer, including conduction, convection and radiation, contribute to the combustion process but in different ways [86].

Conduction is generally assumed negligible due to the lack of contact between most discrete fuel particles [87]. In addition, the interior of a heating or burning fuel particle acts as a heat sink and pulls heat away from the surface and thus reduces the production of pyrolysates and the potential for continued combustion [88].

For spreading fires, radiation and convection play critical roles in the heating and burning of unburned fuels. Generally, radiation in wildland fire scenarios describes the process by which the fuel receives energy that sustains the pyrolysis reaction and the burning flame. Convection supplies the energy required to bring the fuel ahead of the flame front to its ignition point and thus contributes new fuel to the fire [88]. However, radiation and convection are not always limited to those exclusive roles.

In the past, most research assumed radiation was the controlling mechanism of heat transfer in wildland fire spread. For example, Albini [89] and Telisin [90] suggested that intense radiation from the flame front contributed to fuel preheating and thus fire spread. Subsequently, Butler et al. [91] suggested that convective cooling can be significant prior to ignition and that convective heating immediately prior to and at the time of ignition is extreme.

This stance lends credence to the idea that prior to ignition, convective heat transfer either from direct flame impingement or natural convective heating from buoyancy driven circulation is significant and may play a more substantial role in the spreading of wildland fires than previously believed. Moreover, the balance between (and more importantly the interaction between) the contributions of radiation and convection in wildland fires is still not well understood. Note: When we deal with the mechanism of heat transfer in the condensed phase, the dominant heat transfer mechanism is conduction which also controls fuel pyrolysis process (as shown in Fig. 2.1), which directly interacts with the gas phase heat transfer and chemical reaction.

2.1.3 Basic Diffusion Flame Structure

In wildland fires, two main causes exist for luminous flames: temperature radiation and chemiluminescence. The necessary energy required for the temperature radiation contribution is from collisions between atoms or molecules that cause excited states from which light is emitted. This temperature radiation emission is often mixed with chemiluminescence, which results from energy release through emitted light during chemical reactions [92]. The wavelengths of the familiar visible flame from combustion are in the visible spectral region, i.e. wavelengths between ~380 nm to 700 nm [93]). Flames also emit thermal energy in infrared wavelengths; for example, a 2009 study of spectral emission of flames from vegetation fires used a compact and portable Fourier-transform infrared spectrometer to measure emission from fire having wavelengths between 10,000 nm to 2,222 nm [94].

Michael Faraday conducted the first thorough study on the structure of diffusion flames in his famous lecture on the chemical history of a candle [95]. Almost a century later, Wolfhard and Parker [96] detailed the anatomy of a flame with spectroscopy. The study of the structure of a laminar diffusion flame then progressed to laser-based optics in the 1980's [83]. Recent studies on laminar diffusion flames have focused on diffusion flames under adjusted conditions, like high pressure or very specific aspects of soot formation.

It has been shown that in hydrocarbon-oxygen diffusion flames the hydrocarbon thermally decomposed before it encountered any oxygen [48]. Smyth et al. [97] recorded steady, radial changes in chemical compositions from the center of diffusion flames and developed the profile of reactants and products shown in Figure 2.2. In it, the fuel and oxygen decrease to zero around the same location where combustion takes place on the flame front. In laminar flames, the flame front is stationary whereas in wildland fires the flame front is not stationary. Rather, wildland fire flame fronts surround the pyrolysates, which move with the convective flow; this turbulent flow of burning gas-phase fuel produces the light observed in the 'dancing appearance' of flames.

The luminosity of a flame, caused by the thermal decomposition of the hydrocarbon constituents of the fuel, is dependent on how the fuel and air meet at the flame front, e.g. the ratio of fuel-to-air, the extent of mixing and flow. Luminosity is strongest in regions of active soot oxidation [98].

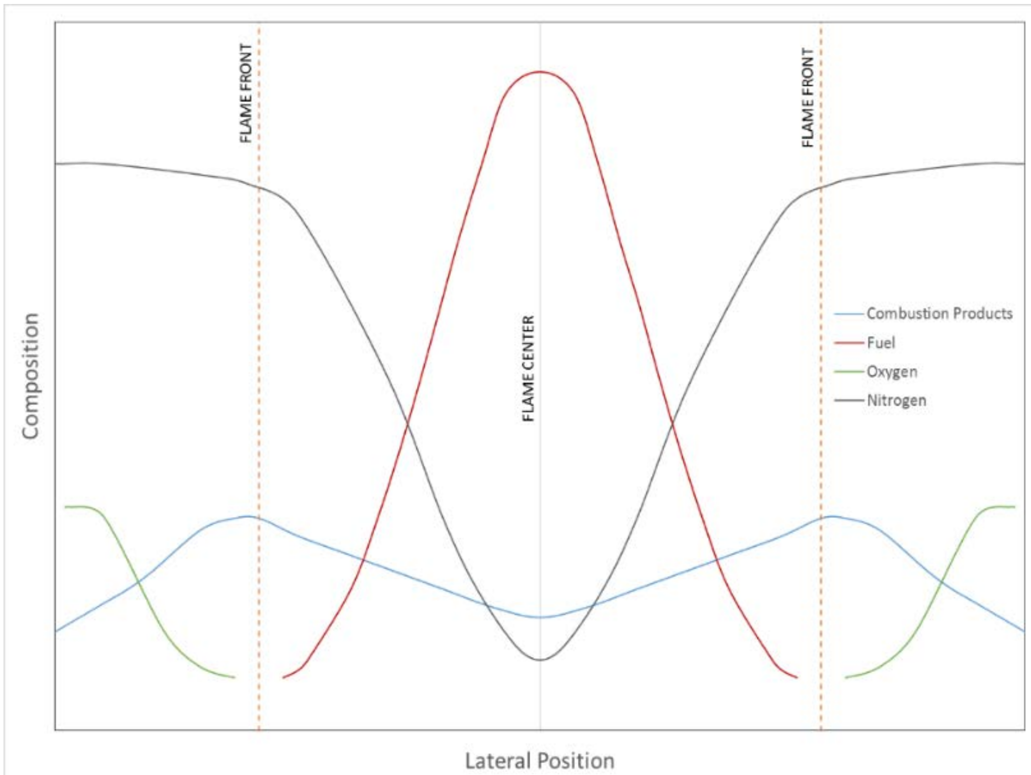

Figure 2.2 Idealized diagram of mole fraction profiles of major species across a simple, generic laminar diffusion flame; the flame front is considered infinitesimally thin (after Smyth et al. [51]).

In the systematic advancement of a physical science, conservation equations are sought which express, in a mathematically precise manner, relationships among various quantities that govern a particular process or reaction In applied physical sciences, research directed toward solving known conservation equations seeks to find and understand quantities of interest, typically under conditions of practical importance. In combustion science, the conservation equations include partial differential equations expressing conservation of mass, momentum, energy and chemical species [56].

2.2 The Fire Spread Problem

Forest managers as well as those engaged in research involving wildland fires need a consistent method for predicting fire spread and intensity [58]. It should be a relatively simple matter for fire scientists to answer the question of how fire spreads, especially in a nearly uniform bed of dry and dead fine fuels like grass [40]. In general, both fire scientists and practitioners have made correct, intuitive decisions about fire, primarily because common underlying principles in combustion science, fire behavior, fire weather, fire ecology, economics, anthropology, fire suppression technology and prescribed burning exist and have been studied extensively. However, not all of these principles are known with sufficient rigor [99]. As a result, current fire behavior models used for operational predictions are empirical and tied closely to gross-scale observations (like fire spread rate) rather than dealing with the underlying principles and processes [40].

In 2013 the USDA published a paper "On the need for a theory of wildland fire spread" that called attention to one specific part of the general field of fire - the understanding of growth and spread [40]. This report acknowledged that scientists have done a great deal of work on the theoretical problem of how forest fire spreads, both by semi-empirical laboratory modeling and by pure physical deduction. Almost all this work, however, has been devoted to single, homogeneous fuel layers in contact with the ground [100].

In addition to these empirically derived models, other models attempt to represent the physical processes responsible for observable behaviors [101]. These 'physically based' models should be able to help the scientists answer questions about fire spread if the models accurately incorporated the governing physics and chemistry. However, close inspection indicates that these models have not shared a common formulation of the physical and chemical processes influencing fire spread [99]. Differences do not appear to be just about model implementation or numerical methods. Rather, an examination of these physically-based models reveals that the fundamental processes of fuel particle ignition and subsequent fire spread are largely assumed without an experimental basis. Researchers do not know what processes explicitly occur and how they control fine fuel particle burning [40]. Without a comprehensive theory, researchers cannot claim an understanding of wildland fire behaviors that are the manifestation of the effects of sequences and influences of unknown combustion and heat transfer processes.

2.2.1 Fire Spread in Wildland Fires

Recent studies by Finney et al. [40, 68] found that forest fires are inherently dynamic, but the sources and mechanisms of the dynamic nature are not clearly understood. Time dependent flame behaviors like flickering, pulsing and vortex shedding have all been observed when diffusion flames interact with flow, although studies noting these behaviors have primarily focused on diffusion flames originating from circular nozzles or jets [102-104]. Wildland fires, particularly when they interact with wind, exhibit these behaviors as well [105-107]. Time-averaged analyses of these fires, while somewhat mathematically palatable [108], disregard key time-dependent mechanisms like vortex shedding which has been found to significantly increase convective heat transfer [109, 110]. A time-average, static analysis could not capture nor explain the entirety of convective heating phenomena, and thus would not accurately predict ignition or fire spread.

While considering fire spread, it is first helpful to envision a basic fire flame front spreading through a simple fuelbed (see Figure 2.3). The fire is propagating through unburnt grass, from left to right in the schematic. The burned area, i.e. the 'black,' behind the flames has little or no combustible material left. Because the 'black' would contain primarily inflammable constituents, it is considered a safety zone for wildland firefighters who need to escape from unexpected fire behavior. The flame zone depth, L_w, separates the black from the unburned fuel (or the 'green'). The flame zone depth is the horizontal length of the fuelbed that is actively burning. Flame zone depth is a characteristic length of a fire and is measured parallel to the direction of fire spread.

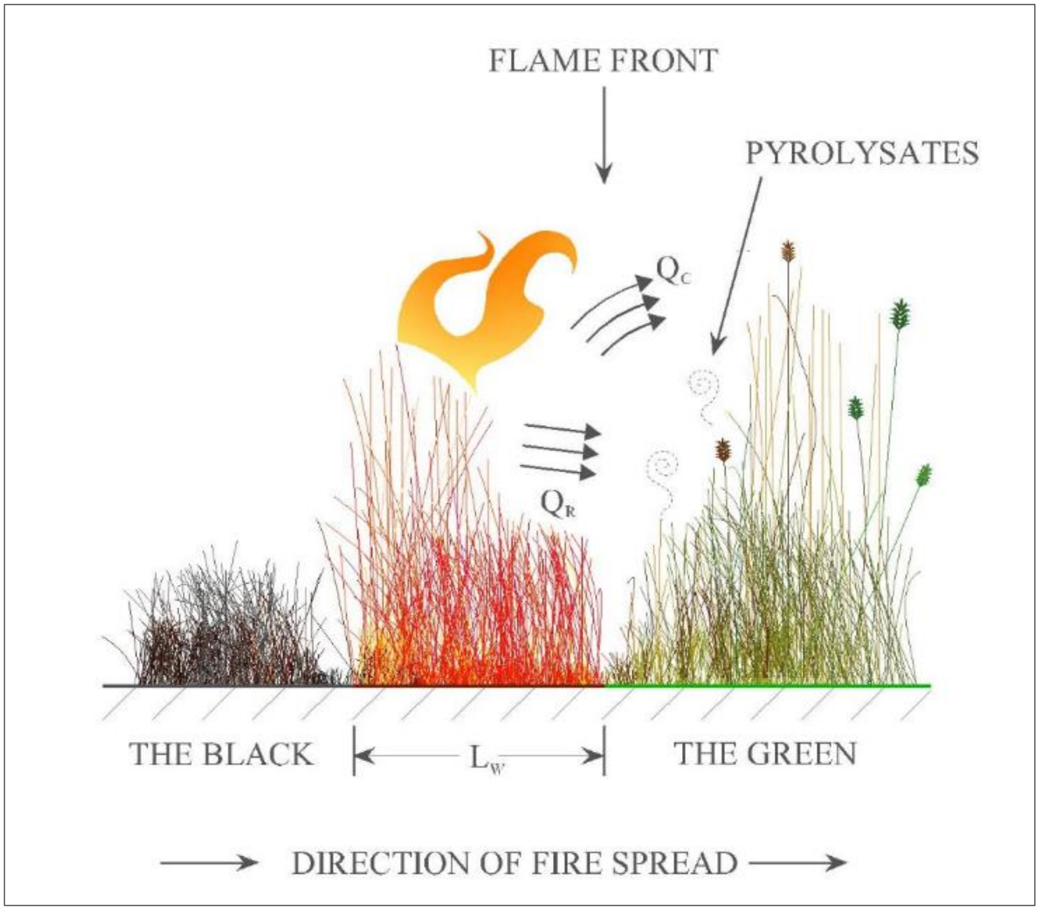

Figure 2.3 Flame spread through dry grasses.

The spreading flames in Figure 2.3 heat the unburned grasses ahead of the flame front by means of radiation and convection; conduction through the ground to the grass is negligible. The thermal energy given off from the fire, heating the unburned fuel is indicated as Q_R. The thermal energy transferred to the unburned fuel via convection is indicated as Q_C. The unburned fuel nearest the flames heats the fastest. When a solid fuel surface is sufficiently heated, flammable vapors from pyrolysis are liberated and escape the solid fuel surface via the gas phase [111]. An imposed airflow requires a higher rate of production of pyrolysates, because the flow carries the pyrolysates away from the burning zone. When the mass fraction of these flammable vapors reach a sufficient level and the temperature is high enough, the pyrolysates will ignite by either auto-ignition if the fuel is preheated sufficiently or by a pilot flame effect that is caused by the burning fuel and favorable convective currents. The threshold for flame spread is like a binary switch that gives either ignition or no ignition of the nearest unburnt fuel particles, and the rate of spread is governed by the time interval between ignitions of successive spatially-separated fuel particles. If no new ignition occurs ahead of the flame front, the fire will cease to spread in that direction, and will either turn or be extinguished as fuel within the burning area is combusted.

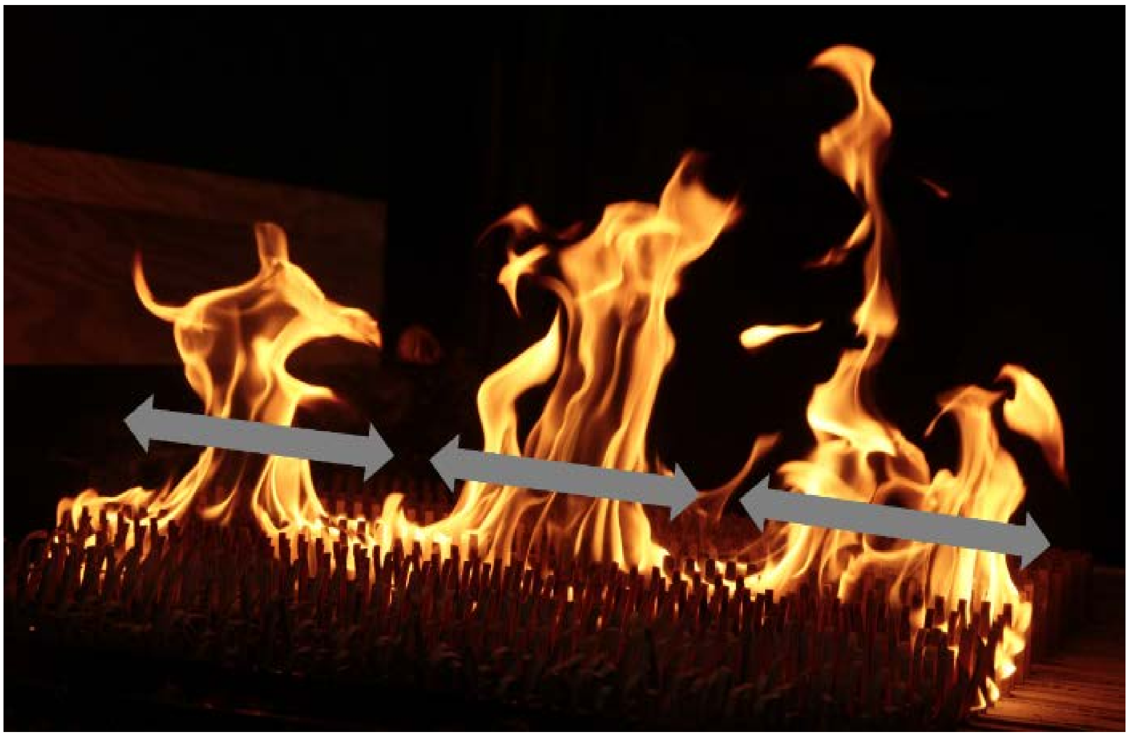

Figure 2.4 Tower and trough formation in a laboratory fire.

In spreading wildland fires, the flames of a progressing fire front break up into distinctive tower and trough patterns, as shown in Figure 2.4. The number of towers and troughs depends on the fuel. The complexity of the fuel arrangement also influences air entrainment into porous fuelbeds. The locations of the towers and troughs move laterally along the fire front with time. An imposed airflow or wind travels from upstream towards the fire front and is caught in the in-drafts of the fire, is heated and begins to rise because of its decreased density.

As flames stretch upward, they locally block the oncoming flow. If the fire under consideration was simply an individual, stationary pool fire in a similar cross flow, whirls of opposite rotation would be shed downstream of the fire, similar to Von Karman vortices [112, 113].

The scenario of multiple, stationary flame towers in an imposed flow, is slightly more complicated than a single pool fire, but still much more simplistic than the moving fire front; in other words, a line of pool or crib fires could simulate a stationary flame front and have been studied extensively [114-117]. Air entrainment into each pool fire is generally responsible for more interaction behavior, like the bending of two flames in relatively close proximity [118]. This scenario still lacks the lateral movement of towers along a fire front, and lacks the forward movement of a spreading fire.

The scenario of multiple, laterally moving fires better approximates an advancing flame front. Two frequencies are associated with this movement. The first is the frequency of downstream vortex shedding associated with each individual tower in the imposed flow. The second is a frequency associated with the lateral oscillation of each tower.

2.2.2 Distinguishing between convective and radiative heat transfer

Emori and Saito first established how fires with convection as the dominant mechanism of heat transfer spread differently than fires with radiation as the dominant mechanism of heat transfer [55]. They showed that pool fires fell into the radiation-driven regime, which abided different governing principles than fires controlled by the convective regime. Wooden crib fires are representative of the convection-regime burns.

Convection, by its definition, is thermally driven fluid movement. Convection transfers thermal energy either on a large scale by relocating a mass of heated air (advection) or on a small scale where random motion and collisions of molecules (thermal diffusion) transfer kinetic energy. The ability of a convection-driven fire to spread hinges on the surrounding fluid mechanics. If airflow efficiently transfers thermal energy from the fire to the unburnt fuel, a fire will spread.

Emori and Saito's work [55] was continued by Emori et al. [119], who extended the convective-driven heat transfer and radiative-driven heat transfer regimes to wildland fire scenarios. They examined fire spreading through uniform fuelbeds of different fuel arrangements on horizontal or upward slopes (Figure 2.5). Convection-dominated fires and radiation-dominated fires abide by different power law relationships between the fire's mean flame length, L_f, and the rate of fire spread, R (Figure 2.6). These power laws differentiated two regimes. Adam et al. continued this work further developing the equations describing convection driven spread [120].

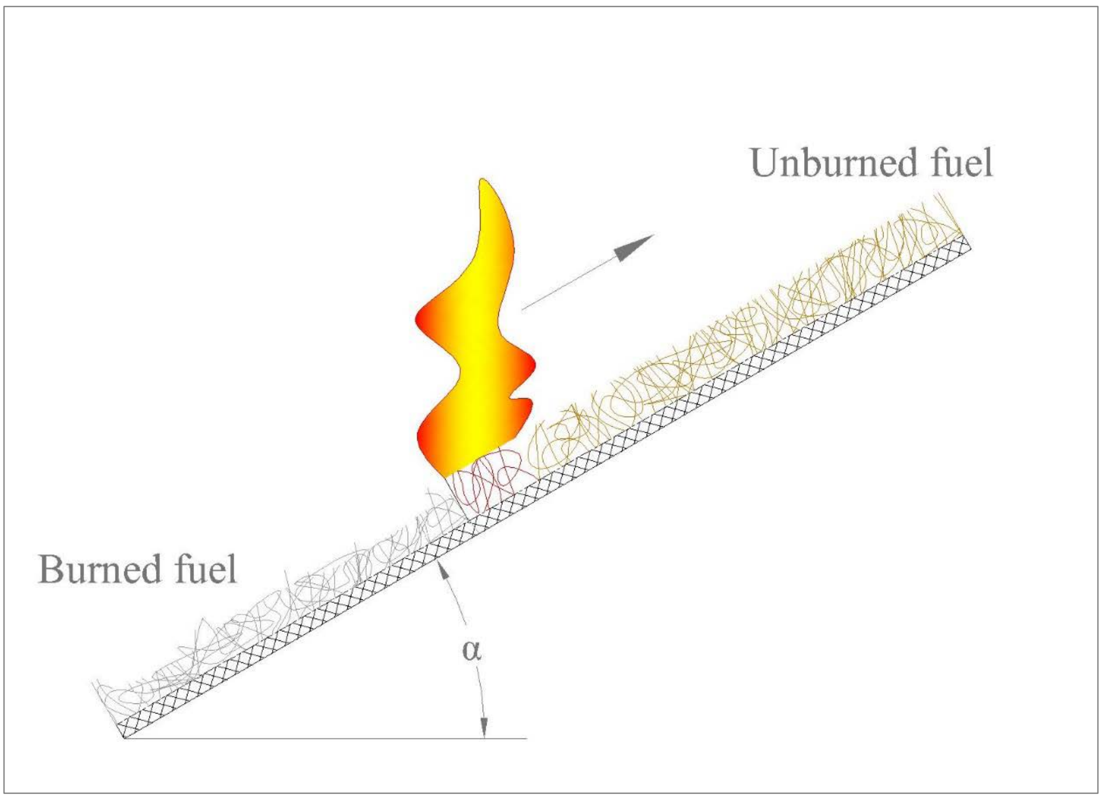

Figure 2.5 Experimental setup of Emori et al. with no imposed flow.

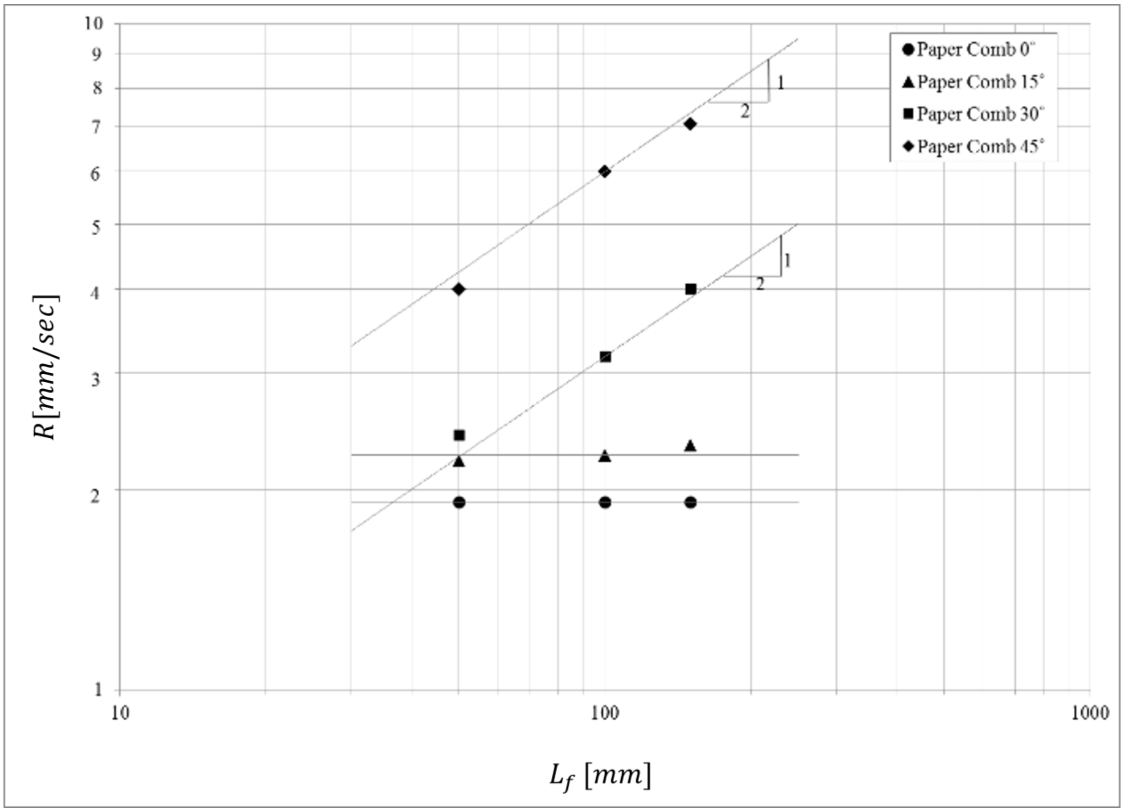

Figure 2.6 The relationship between flame length (L_f) and spread rate (R) for experiments of flame spread through horizontal and incline fuelbeds [120].

The spread rate, R, of radiation-driven fires takes the form:

$$R \sim L_f \tag{2.1}$$

The variable L_f represents flame length. Convection driven fires preserve the relationship:

$$R \sim \left(L_f\right)^{0.5} \tag{2.2}$$

The scope of this dissertation is limited to convection-driven fires. Because of the dependences within Equations 2.1 and 2.2, the dominant mechanism of heat transfer can be uniquely defined as either convection or radiation. It is shown that the dominant mechanism is convection for the fires in the experiments discussed in Chapter 4.

2.2.3 Fire Spread in the Convection-Dominated Heat Transfer Regime

As discussed in Section 2.3.1, fire spread through a fuel bed is a series of ignitions of spatially consecutive fuel particles. Figure 2.7 and Figure 2.8 illustrate the stages leading to ignition of a fuel particle in a fuel bed. The term "fuel particle" refers to an individual cardboard tine, a representative fuel particle used in some of the research for this dissertation. Cardboard tines having well-characterized dimensions were the fuel used during the wind tunnel experiments that are discussed in Chapter 4.

Referring to Figure 2.7 and Figure 2.8, during the fire stage the fire approaches a particle of interest (circled in blue). Because minimal heating of the particle occurs during this time, the particle temperature only rises a few degrees.

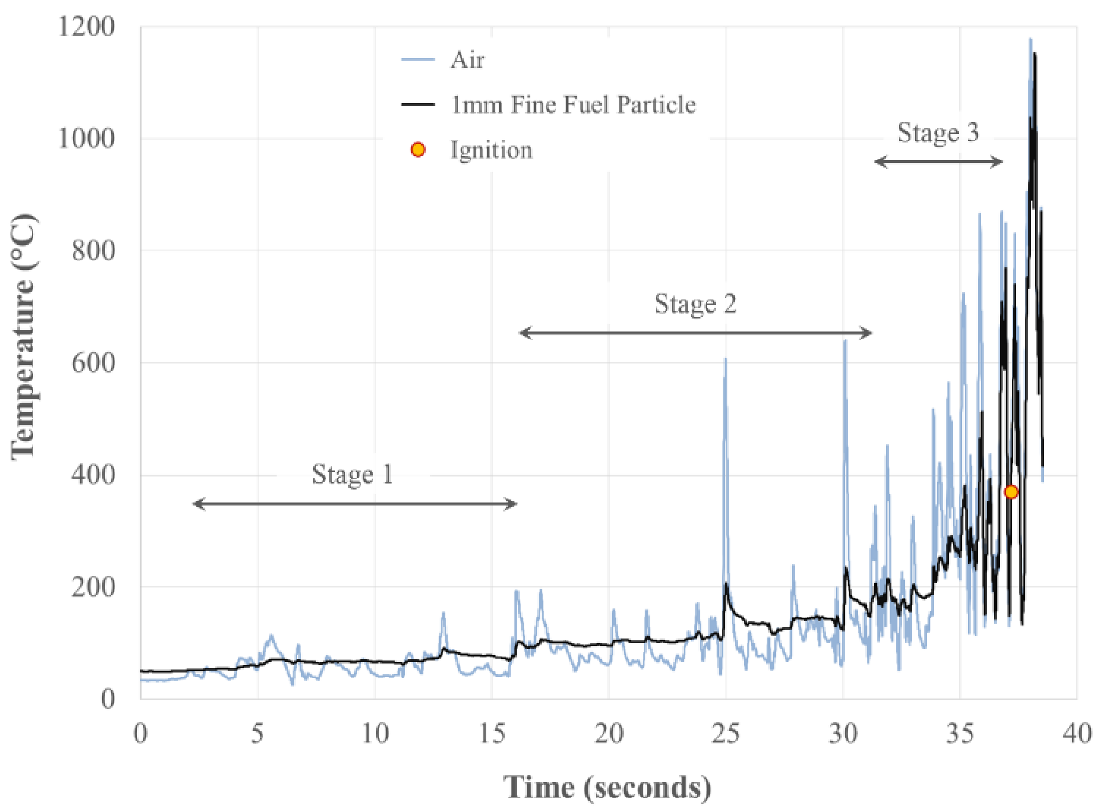

Figure 2.7 Fuel particle temperature heating up to ignition (data courtesy of Jack Cohen [202]).

During the second stage, the fire front is in close proximity and bathes the particle in flames infrequently. Each flame-bathing incident is referred to as a discreet event. The particle temperature does not immediately and rapidly rise because the time that elapses between the first and infrequent flame bathing events allows the particle to cool.

Effective convective heating typifies the third stage. When the fire is near, flames bathe the particle regularly and the time between these events is shorter and not sufficient to enable the particle to cool. Consequently, the particle temperature increases dramatically and, although convective cooling still occurs, the time between flame bathing is less than the pulse width of the heating events. Hence, the fuel particle enters a pyrolysis stage and pyrolysates begin to accumulate around the leeward side of the tines.

In the fourth stage, the particle's pyrolysates ignite. In most cases, ignition occurs when the pyrolysates reach a critical concentration and the fire bathes the tine location in a flame [40, 84]. Flames attach to the top, leeward side of the tine, and the fire spreads downward.

The heat transfer process in the condensed phase is governed by conduction. The magnitude of heat conduction may be small in comparison to radiation and convection in the gas phase. However, heat conduction process influences fuel pyrolysis and ignition (as shown in Fig. 2.1) in the gas phase. Because time scale in the condensed phase may be much shorter than the gas phase, it may be possible to ignore the condensed phase heat transfer process when dealing with flame spread. This assumption was also adopted in developing scaling laws in section 3.

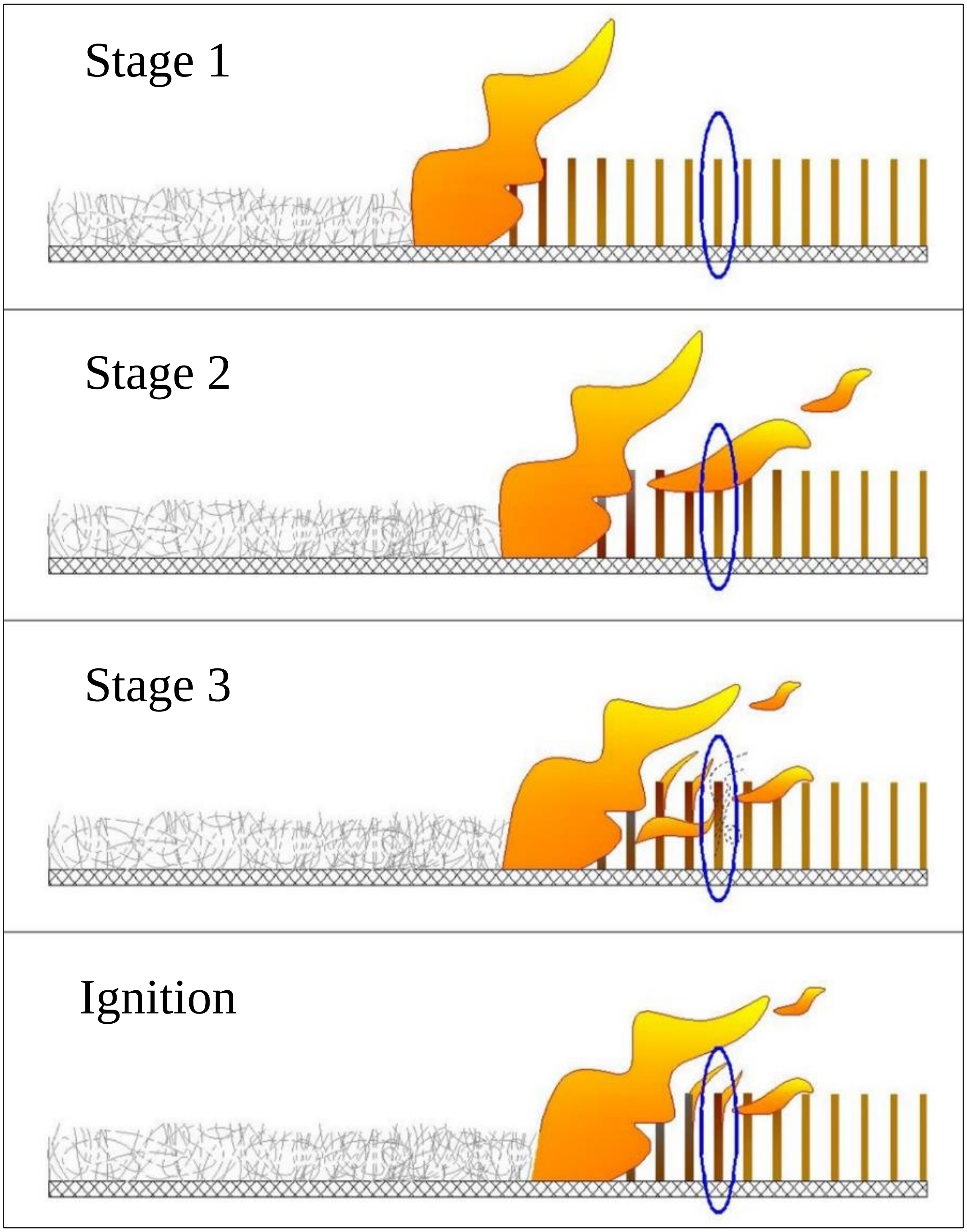

Figure 2.8 The three stages leading to ignition of a fuel particle in a fuelbed.

2.3 Challenges with Wildland Fire Research

Wildland fire science is not a mature science. Wildland fire spread is difficult to understand for at least three important reasons or challenges, including:

1. The mathematics of governing equations for fire spread are currently unsolvable for most conditions.

2. Variations in the fuel associated with wildland fires are extremely diverse, even in relatively homogenous fuelbeds like grasslands; here, variability in vegetation density, moisture, species, ambient temperatures and wind conditions all are factors influencing fire spread. Even if solutions to the governing equations describing the phenomena of wildland fire within a homogeneous fuelbed existed, firefighters would have to input accurate, detailed geospatial and chemical/physical data about the fuel and environmental data simultaneously to enable the creation of real-time predictions and firefighting approaches. The conservation of chemical species equation gets dramatically more complicated with real vegetation fuels burning in less than ideal stoichiometric conditions. The balance of chemical species created by real fuels, live and dead, in an actively burning environment with incomplete and complete products of combustion from, perhaps, hundreds of chemically distinct fuels is an input requirement probably too complex to be practical.

3. The inaccessibility of wildland fires in most instances is another challenge. Instrumenting actual, dangerous fires is largely impractical. Although prescribed burns allow for better exploration into the efficacy of new suppression tactics or gathering confirmation data, laboratory experimentation and data have also been unable to provide correlations between phenomena in the laboratory setting and in full-scale wildland fires.

Firefighters have long acknowledged the potential benefits of a predictive program or model that would help decision-making and management at the scene of a wildland fire. Unfortunately, while a model should offer both adaptability and accuracy, models currently available are not founded in the governing physics, and therefore are of little use in unknown terrains, weathers, or fuels [38].

2.4 Summary

Wildland fire science research has benefitted from studies of confined fires and extensive studies of combustion of well-defined fuels under specific conditions. There are many studies of the chemistry of wood, its fuel properties, and the behavior during thermal decomposition. Researchers have developed fuel-driven mathematical surface-fire behavior and fire effects models as well as some predictive systems. Most scientific work on the theoretical problem of how forest fires spread has been devoted to single, homogeneous fuel layers in contact with ground [56]. Considering wildlands, a vast variety of fuels exist beyond wood, i.e. wildland fires impose dynamic conditions because of the fuel varieties possible, and a vast variety of wildland scenarios also exists. While combustion science is a mature science, the science of wildland fire spread is not as understood as it could or should be because a comprehensive understanding of the processes that occur in wildland fire spread is yet to be discovered. Instrumenting actual, dangerous fires is largely impractical, so researchers use prescribed burns to gather confirming data and to gauge the efficacy of a new suppression tactics. Chapter 3 presents scaling as a method to design laboratory experiments to study wildland fire spread.

CHAPTER 3: SCALING IN WILAND FIRES

Obtaining data from fires that are most dangerous and costly is a challenge for fire researchers. While it has been uncommon to instrument successfully an active wildland fire, it is feasible to instrument test beds, test plots, and small, prescribed burns. A scale model, meaning an experimental model structured to mirror the true physical behavior of the original phenomenon, can serve as a valid substitute for the full-scale system.

With focus on very specific facets of wildland fire, researchers have created many unique models with specific fuels such as match sticks, liquid fuel, excelsior, plywood, live fuels, dead fuels, wood cribs of different packing densities, cardboard fuels, and paper fuels in a variety of environments such as wind tunnels, burn chambers, fields, and forests [68, 87, 120-127]. Although significantly contributing to the body of fire research, most of these experiments could not accurately represent any real wildland fire because the experiments were not properly designed to have acceptable levels of similarity (similarities beyond geometric similarity). Despite the fact that the laboratory models' data converge to accurately predict variations of their own respective laboratory scenarios, and thereby offer repeatability and predictive power for the specific experiments, no accepted method has existed to relate all the unique experiments to each other or to the actual physical behavior of wildland fires.

For the benefit of research, scale models provide insight into elusive behavior and provide empirical confirmation of numerical work. This dissertation employs scale modeling to develop new insight into, and new scaling laws to describe, behavior of convective-driven wildland fire and then confirms those laws. Future fire research could employ these scaling laws with experiments of increasing relevancy for further understanding of wildland fires.

3.1 Introduction to Scale Modeling

The study of a scaled reproduction of a physical phenomenon can be advantageous when the problem at hand is too complex or too little explored to be amenable to an analytical solution [128]. Carefully designed scale models can be seen in the fields of statics, dynamics, thermodynamics, fluid mechanics, and heat and mass transfer, and have ranged from explosive nuclear detonation [129], to railway car accidents [130], jetliner crashes [131], rocket design [132], and to geological applications such as glaciology [133].

The fundamental requirement of scale modeling is that the model and the original must be governed by the same physical laws [134]. A preliminary analysis of the inner mechanisms of the actual phenomena is necessary to develop a predictive scale model. The preparatory analyses are the most challenging aspect of scale modeling. This process involves the determination of the physical laws that govern a phenomenon and identification of those that can be neglected.

Models are capable of predicting responses because homologous states of time, length, mass, and temperature are being related. Scaling can be applied most easily to physical dimensions (e.g. states of length), like fuel height, area burned (eg. the ‘black’) and flame length. Equally important to geometric similarity in scaling are the other types of similarity: dynamic similarity, kinematic similarity, constitutive similarity and thermal similarity [135, 136]. For example, two systems have dynamic similarity if homologous parts of the systems experience homologous net forces; two systems have kinematic similarity if similarity of motion exists (the science of kinematics is the theory of temporal-spatial relationships); two systems have constitutive similarity if stress-strain curves or constitutive properties of the materials are identical; and, finally, two systems have thermal similarity if homologous states of thermal energy exist [135].

Quantitative predictions of fire structure, intensity, and propagation rate can be made based on the behavior of models only if all the important governing parameters are understood and incorporated into the model [137]. In theoretical and experimental physical studies, researchers attempt to obtain relationships among and between the quantities that characterize the phenomenon under study [138]. Unfortunately, the number of parameters in the problem of wildland fire spread is so large that it is not possible to solve the equations relating them. However, if the physical quantities involved are known, then dimensional analyses usually can find some of the necessary relations that subsist between these quantities and, in effect, reduce the number of parameters [138]. Dimensionless products of the governing parameters are established during scale modeling; these products are also called pi numbers or similarity parameters in literature [128, 135, 139]. The set of dimensionless products chosen to govern the scaling of a phenomenon are collectively referred to as a function relationship [55].

Homologous behavior of the corresponding model elements is assured if each quantity of each of the original's elements can be transformed into the corresponding quantity of the model's elements through multiplication by a respective constant factor or "scale factor." A characteristic quantity in a pi number can be substituted by any like quantity of the given phenomena to be modeled [134]. An incomplete model may reproduce faithfully only those aspects of the prototype considered of primary importance. In fact, the only models possible for processes of great complexity are incomplete ones [134].

As researchers perform and analyze more scale model tests, the understanding of the basic structure of a system grows. In this way scale model experiments of events are qualified to provide further insight into the fundamental nature of the event, help establish the design of the scaling laws, and confirm the scaling laws.

3.2 Review of Scaling Analysis

In a scale model of a system, the same laws governing the full-size event must prevail in the model, except that all model quantities must be scaled in accordance with the primary scale factors [128]. The objective of scale modeling is to obtain mathematical relations between parameters of a system, which subsequently can be utilized to simulate the behavior of the original system in a model.

The fundamental aspects of the scale modeling technique are listed in Table 3.1. First, the full-scale system and phenomenon of interest are specified. Second, the scaling laws are developed, defining mathematical relations between parameters of the original system. Third, a model of the original system is constructed, guided by the scaling laws. Data from the model confirms or disproves the scaling laws. Fourth, lessons from proven relations are applied to the original system.

Table 3.1 Fundamental aspects of scale modeling technique adapted from Saito 2008 [140].

Four Aspects of the Scale Modeling Technique		
1	Statement of the problem	Study of the full-scale system and phenomenon
2	Derivation of scaling laws	Identify the governing mechanisms controlling the full-scale system, make assumptions, derive scaling laws
3	Development of the model	Confirm scaling laws
4	Application of results	Developing new protocols

Figure 3.1 illustrates the processes of obtaining mathematical relations between parameters of a system and developing the appropriate scaling laws; it is also a more detailed representation of steps 2 and 3 within Table 3.1. The scaling work involved could complement theoretical work, which is shown as the parallel path in lighter grey in Figure 3.1; both the scale modeling and theoretical methods should make use of the same underlying assumptions. Thus, irrespective of whether scale modeling or numerical simulation is considered, both techniques should lead to comparable results.

Regarding the step pertaining to the derivation of scaling laws, three approaches exist: (a) the parameter approach; (b) the equation approach; and (c) the law approach [140]. The parameter approach utilizes the dimensional analysis of Buckingham's pi theorem [141] [142] whereas the equation approach begins with the system's governing equations. The law approach begins with quantitative statements about the system's forces, matter and energies [134].

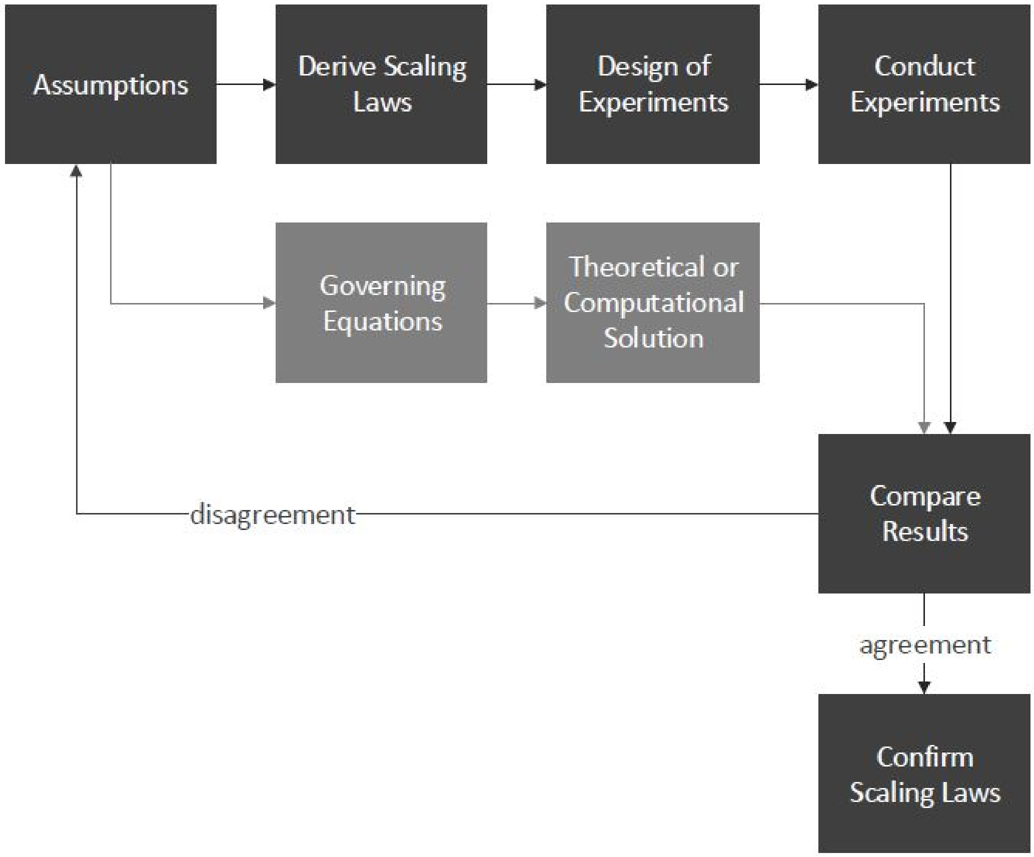

Figure 3.1 Flow diagram illustrating scale model development and confirmation process (steps from Emori et al. [128])

The parameter approach to establish scaling laws, also known as the "pi theorem" or "method of repeating variables", was first explored by Aimé Vaschy, Dimitri Riabouchinsky, and Lord Rayleigh (John William Strutt), but ultimately presented by E. Buckingham in a 1914 paper [142-145]. This approach involves an inclusive list of participating parameters; in this dissertation research on the scaling of wildland fire spread the parameters included are flame length, radiative heat flux, the density difference between the heated gas and the surrounding air, and vortex shedding frequency.

The equation approach to establish scaling laws formulates the governing equations and boundary conditions applicable to the problem in which only the solution is lacking and, without solving them, manipulates them with different transformational procedures until dimensionless groups emerge [128, 143]. Similarity is inferred by normalizing all the equations and boundary conditions in terms of characteristic quantities that specify the problem and identify the dimensionless groups that appear in the resulting dimensionless equations. This process is an inspectional form of similarity analysis.

The basis of the equation approach is that the governing equations are intrinsically, dimensionally homogeneous and, because of this, the governing parameters constituting the governing equations can be arranged in dimensionless groups [128]. This approach was used by Williams in the first part of his 1969 paper, “Scaling Mass Fires”, which systematically produced 28 pi groups ($\pi_i, i = 1$ to 28) pertaining to scaling fire [146]. This approach is very effective at producing pi groups [17], because the governing equations completely describe the physical system and no terms are lost during the algebraic manipulation producing the non-dimensional groups. Unfortunately, the equation method is limited to systems with known governing equations and offers no enlightenment to help determine the more influential scaling factors; rather, it methodically produces a quantity of pi groups that are all weighted of equal importance.

A proponent of the law approach, Hottel, expressed concern at the 1959 Symposium on the Use of Models in Fire Research with both the parameter and equation approaches. Hottel was of the opinion that Buckingham’s pi parameter method contributed to a reduction in the level of understanding of modeling because it defined a procedure so formal that it permitted variables to be introduced without identifying the physical reasons for them. In other words, the process could yield dimensionless groups which may or may not have been applicable to the problem [134].

His disappointment in the equation approach originated with the necessity of starting with the governing laws, discussed briefly above. The equation approach suggests that the governing laws of a system needed to be known to derive the scaling laws, which is not an essential requirement of scale modeling [134]. This approach is therefore limited in its application to problems where the governing laws are well established.

This dissertation employs the law approach to establish scaling laws, deriving the pi numbers from the governing laws. The parameter approach was not selected because it would require the derivation of all the possible variables of influence, unnecessarily complicating the initial analysis. The equation approach was not selected because the complexities of fuel variety within wildland fires suggested the most applicable model would be independent of fuel. Because the equation approach would include the conservation of chemical species, the resulting scaling laws would link back to fuel dependency. On the other hand, the law approach allowed the inclusion of the quantitative statements about the system's most influential forces, masses, and energies. Furthermore, significant breakthroughs by wildland fire scientists, who have discussed the influence of buoyancy on the instabilities observed in flame fronts [147], provided a guide for the initial choice of laws for this analysis.

Taylor, Hottel, Emori, and Saito previously elected to use the law approach in combustion studies and other studies [134, 148, 149]. A succinct recommendation for the law approach by Hottel follows:

> "It best permits the welding of similitude theory and a "feeling" for the problem at hand—also the one which has been applied so effectively in (G.I. Taylor's 1959 Symposium paper, Fire Under Influence of Natural Convection, [148])" [134].

Literature shows that the equation and parameter approaches to scale modeling have been successfully applied to areas of combustion research, including pool and crib fires [150] [55] and hazardous fire whirls [149]. Scale modeling by the law approach, verified by numerical modeling or experimentation, has been successfully implemented in diverse applications such as improving an over-spray paint-capturing device [151] and a steel teeming process [152], but the law approach has yet been applied to wildland fire spread dynamics.

3.3 Review of the Use of Scale Modeling in Fire Research

Experiments on smaller-size scale models are essential in fire research. Notable work in the field of scale modeling of fire research was done by: Hottel, Spalding, Emmons, Emori, Williams, and Saito, as is discussed in the following. H. C. Hottel addressed radiation in fire modeling and reframed previous experimental results [134]; Spalding [153] and Williams [146] both over-constrained their scaling laws, and found that the number of pi groups to be obeyed exceeded the number of degrees of freedom and, consequently, they addressed relaxation or partial modeling; Emmons focused on liquid pool fires and paper arrays [154, 155], paving the way for Emori and Saito [55] to differentiate radiative-dominated combustion in pool fires from convective-dominated combustion of crib fires.

In his work on scaling mass fires, Williams identified 29 pi groups that an accurately scaled model must obey in order to capture a large fire phenomenon completely [146]. If scaled correctly and if all 29 pi numbers are matched, the aspects of the model (velocities, forces, accelerations, energies, heat, temperatures, etc.) measured on the laboratory scale model would permit prediction of their corresponding quantities in the original, larger-scale fire. This predictive power would be incredibly valuable for wildland firefighters and their managers. Because the 29 pi groups were a nearly impossible standard for scaling, a subset of 11 was then suggested to offer "reasonable" relations; they are presented in Table 3.2. Williams then suggested keeping only one or two to achieve useful scaling, primarily retaining the Froude number, Fr, since inertial and buoyant forces are the major forces in fires [156].

Table 3.2 Applicable scaling laws for mass fires as given in the 1969 paper by Williams [146]. Note, some nomenclature changed from the original published work for clarity and continuity in this document, but the original pi numbering scheme is preserved.

Pi Numbers for Mass Fires (Williams, 1969)		
π_2	gL/V^2	A buoyancy quantity related to the Froude number, Fr
π_4	$L\ \rho_a\ \bar{\kappa}_v$	Ratio of characteristic dimension to radiation absorption length
π_6	$\mu_a/\rho_a V L$	Reciprocal of the Reynolds number, Re
π_{16}	$Q/c_{pa}T_a$	Dimensionless gas-phase heat of combustion
π_{18}	$\sigma' T_a^2/\rho_a V c_{pa}$	Ratio of blackbody radiation flux to rate of convection of enthalpy
$\pi_{19\,\alpha}$	L_α/L	Ratio of lengths specifying terrain, fuel size and location to characteristic length
π_{20}	$W/\rho_a V\ t_b$	Ratio of time-average mass burning rate per unit area to convective mass flux (fuel loading-burning time group)
$\pi_{24'}$	$[c_l(T_l - T_a) + \Delta h_l]/c_{pa}T_a$	Effective dimensionless total heat required to gasify a unit of mass of fuel
π_{26}	u/V	Dimensionless ambient wind velocity
π_{27}	$\Gamma L/V$	Dimensionless ambient atmospheric circulation
π_{28}	T_a'/T_{ad}'	Dimensionless ambient atmospheric lapse rate parameter determining atmospheric stability

Table 3.3 Applicable scaling laws for crib fires as given in Emori and Saito's 1983 work [55]. Note, some nomenclature changed from the original published work for clarity and continuity in this document, but the original pi numbering scheme is preserved.

Pi Numbers for Crib Fires (Emori and Saito, 1983)		
π_3	v/u	$\frac{\text{vertical speed of rising gas}}{\text{horizontal wind speed}}$
π_{16}	L_f/l_c	$\frac{\text{flame length}}{\text{crib stick length}}$
π_{22}	l_c/ut	$\frac{\text{crib stick length}}{\text{length wind covers}}$
π_{23}	$l_c g/u^2$	$\frac{\text{buoyant}}{\text{inertial}}$
π_{24}	$ET/\rho_2 l_c q_2$	$\frac{\text{heat released}}{\text{heat generated}}$

Emori & Saito's 1983 "Study of Scaling Laws in Pool and Crib Fires" [55] and "Unified View of Scaling Laws in Fires (First report): Scaling laws in stationary fires" [150], and then the later Emori et al. 1988 paper at the Fire Safety Science Symposium [119], provided further guidance in scaling fire behavior.

Saito and Emori [55] first identified seventeen pi groups to describe the scaling of convective-driven crib fires, and employed the parameter approach rather than the law approach. The number of pi groups was reduced to five when the experiments were run using similar fuel and under similar conditions. The five resulting pi groups can be seen in Table 3.3.

Emori published the work using the parameter approach because his audience was familiar with that method. He was, however, the pioneer of the law approach, and originally derived the same pi groups with the law approach [157]. His work established an important fact:

as long as the underlying assumptions are sound, the pi groups can be derived from any one of the proven techniques and can create reliable scaling laws.

Table 3.4 Applicable scaling laws for convective-driven fires as given in Emori et al. [119]. Note, some nomenclature changed from the original published work for clarity and continuity in this document, but the original pi numbering scheme is preserved.

Pi Numbers for Convective-Driven Fires (Emori, Iguchi, Saito, Wichman, 1988)		
π_1	$\rho_1 u^2 / \Delta\rho_1 L_w g$	$\frac{\text{inertial force}}{\text{buoyancy force}}$
π_2	$E l_\lambda L_e / I L_w$	$\frac{\text{radiant heat}}{\text{heat generated}}$
π_3	$c_p \rho_1 L_a R \Delta\theta_1 l_\lambda / I L_w$	$\frac{\text{thermal energy of air and gas}}{\text{heat generated}}$
π_4	L_e / L_w	$\frac{\text{thermal energy of unburned fuel}}{\text{heat generated}}$
π_5	$\lambda L_e / \phi q_2 L_w$	$\frac{\text{latent heat of fuel}}{\text{heat generated}}$
π_6	$\rho_1 L_a u^3 l_\lambda / I L_w$	$\frac{\text{work of inertial force}}{\text{heat generated}}$

Five years after Emori and Saito's work on scaling pool and crib fires, Emori et al. established the versatility of Emori and Saito's separate scaling laws for pool and crib fires [119]. The new work adapted the pervious crib fire scaling laws to convection-dominated flame spread over horizontal or upward-sloping fuelbeds. The new work also adapted the previous pool fire scaling laws to radiation-dominated flame spread when there was no imposed flow and little to no fuelbed slope. Specifically, for scaling of convection-driven fires, Emori et al. developed six pi numbers using the Law Approach (see Table 3.4) [119].

3.4 Theoretical Development of Convective-Driven Fire Spread Scaling Laws Incorporating Dynamic Behavior

Williams's pioneering study on scaling mass fires [146], the previous two studies introducing scaling laws for pool and crib fires [55, 150], and a study on flame spread by Emori et al. [119], all provide the guidance for developing scaling laws for convective-driven fire spread through wildland fuelbeds.

In wildland fires, the flames of a progressing fire front break up into a distinctive tower and trough pattern, and are subjected to different interacting flows, as discussed in Chapter 2. A schematic of a fire line advancing left to right can be seen in Figure 3.2. This work will develop parameter relations for this general scenario.

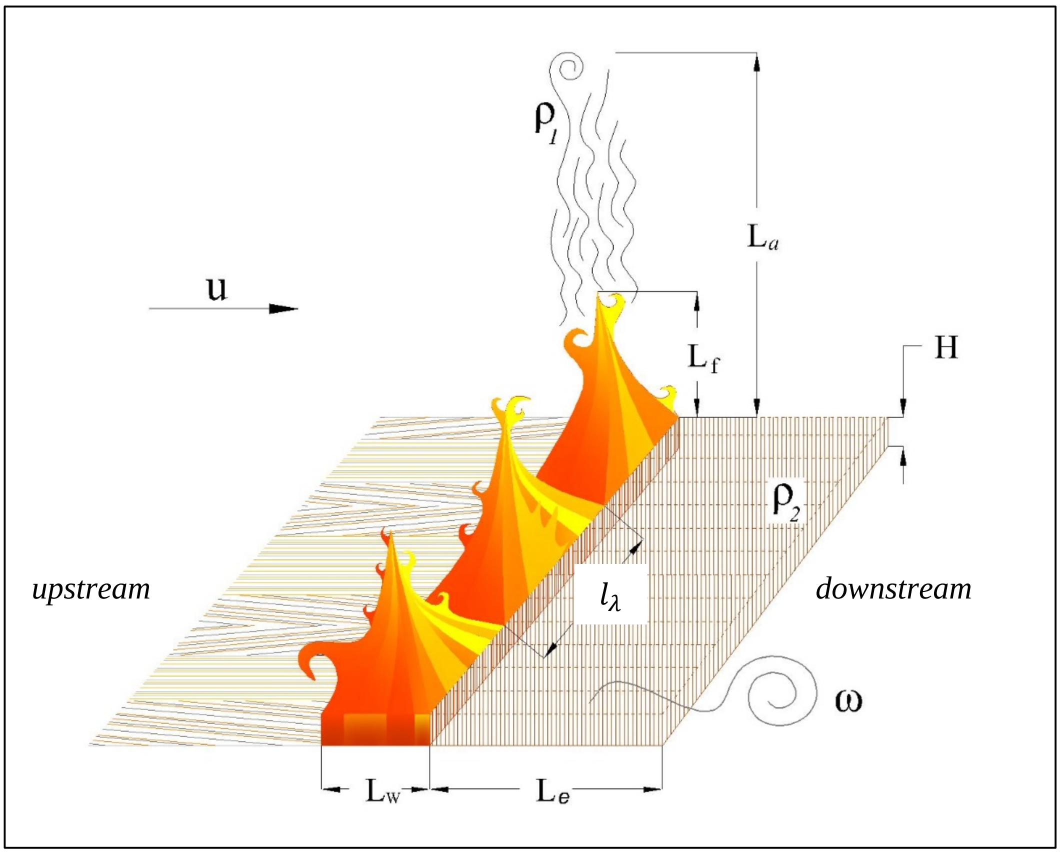

Figure 3.2 Schematic of flame spread over fuelbed and dimensions of flame height, plume height, and fuelbed *[202]*.

The imposed flow or horizontal wind velocity, u, approaches a fire of flame zone depth, L_w. The flame zone is where the active combustion takes place. The flame length is given as L_f, and the plume height is L_a, with the density of the heated plume gasses as ρ_1. The regular fuel bed is characterized by the fuel height, H, and the fuel density, ρ_2. The flames effectively heat the unburned fuel ahead of the fire to length L_e. The composite frequency, ω, is measured downstream of the fire, and is an indicator of vortex shedding, which is a consequence of fluid instabilities. The frequency is extracted from time-series temperature data or visual data from video.

3.4.1 Main Assumptions

Assumptions for this research were made, and are described in the following

First, it is assumed the flows in all fires under study were turbulent. The literature establishes that fire spread in wildland typically entails a turbulent, reacting flow [53, 158] in which case the inertial and buoyancy forces would dominant over the viscous force [159]. Numerous studies have classified flows as turbulent for the types of fires studied during this dissertation research, including: grass fires [160], crib fires [55, 161], crown fires [162, 163], and fires in smaller wind tunnel experiments [147]. Figure 3.3 shows the turbulent flame fronts of a spreading fire in: (A) a small wind tunnel experiment with cardboard fuel, (B) a ponderosa pine crib fire, and (C) a grassland fire prescribed burn, where the dominant species was a perennial grass, little bluestem (*Schizachyrium scoparium*).

Second, it is assumed that the heat transfer from the fire to the unburned fuel was convection-dominated. The differences between radiative-driven fire spread and convective-driven fire spread were discussed in Chapter 2. In the fires studied, literature has established that the dominant mechanism of heat transfer from the flames to the unburned fuel in large grass fires referenced in [164] were similar to those of crib fires [55] and small wind tunnel experiments [165], and were convection driven. The heat transfer from fire to fuel in crown fires that are exposed to sufficient winds, having 5-

second averaged, open wind speeds of 10-30 kph at a 10-m height of 10-30 kph, is known to be convective-dominated [166].

Figure 3.3 Turbulent burning zone in (A) a wind tunnel fire, (B) a large crib burn, and (C) a grassland prescribed burn.

Third, it is assumed that fires are spreading over horizontal or upward-sloping fuel beds. This work does not address wildland fire behavior on extreme terrain or extreme fire behaviors like the development of fire whirls or spotting. If the fire were in a steep gully, for instance, the most influential forces and energies might shift so that the combusting flow behaved like an inertial-driven jet instead of a convection-driven fire spreading through a porous fuelbed. The scale modeling laws developed in this research offer general insight to fire behavior and the relations between key parameters, forces, and energies.

Fourth, this work assumed a continuous, uniform fuel bed. Fuel variety and properties (e.g. moisture content) are not included in the governing parameters, but it is well established in literature that fuel properties are reflected in the fire's response (e.g. flame zone depth) [57], which naturally incorporates the fuel's influences.

3.4.2 Formulation of Pi Groups

As a result of the foregoing assumptions, the following key forces and energies were identified: buoyancy force of air and gas (F_b); inertial force of air and gas (F_i); heat generated (Q); thermal energy associated with the air and gas temperature rise (Q_{c1}); thermal energy transferred to the unburned fuel (Q_{c2}); radiant heat received by the unburned fuel (Q_r); and the latent heat of the fuel (Q_λ). These two different forces and five energies appear as the following, using characteristic parameters [119]:

$$F_{i,down} = F_\omega = \rho_1 l_\lambda (L_a)^2 u\omega \qquad F_{i,up} = \rho_1 l_\lambda L_a u^2 \qquad F_b = \Delta\rho_1 l_\lambda L_w L_a g$$

$$Q = \phi q_2 \rho_2 l_\lambda H L_w = I L_w t \qquad Q_r = E l_\lambda L_e t \qquad Q_\lambda = \rho_2 l_\lambda H L_e$$

$$Q_{c1} = c_p \rho_1 L_a l_\lambda L_e \Delta\theta_1 \qquad Q_{c2} = c_p \rho_2 l_\lambda H L_e \Delta\theta_2$$

The two different forces and five different energies discussed previously yield the independent pi numbers in Table 3.5 with the equations:

$$R = \frac{L_e}{t} \qquad I = \frac{\phi q_2 \rho_2 l_\lambda H}{t}$$

Table 3.5 Applicable scaling laws for mass fires as given in the 1969 paper by Williams [31].

New Pi Groups for Convective-Driven Wildland Fire Spread		
π_1	$\frac{F_{i,up}}{F_b} = \frac{\rho_1 u^2}{\Delta\rho_1 L_w g}$	$\frac{upstream\ inertial\ force}{buoyancy\ force}$
π_2	$\frac{F_\omega}{F_{i,up}} = \frac{L_a \omega}{u}$	$\frac{inertial\ force\ of\ flame\ pulsing}{upstream\ inertial\ force}$
π_3	$\frac{Q_r}{Q} = \frac{E l_\lambda L_e}{I L_w}$	$\frac{radiant\ heat}{heat\ generated}$
π_4	$\frac{Q_{c1}}{Q} = \frac{c_p \rho_1 L_a R \Delta\theta_1 l_\lambda}{I L_w}$	$\frac{thermal\ energy\ of\ air\ and\ gas}{heat\ generated}$
π_5	$\frac{Q_{c2}}{Q} = \frac{L_e}{L_w}$	$\frac{thermal\ energy\ of\ unburned\ fuel}{heat\ generated}$
π_6	$\frac{Q_\lambda}{Q} = \frac{\lambda L_e}{\phi q_2 L_w}$	$\frac{latent\ heat\ of\ fuel}{heat\ generated}$
π_7	$\frac{F_{i,up} u t}{Q} = \frac{\rho_1 L_a u^3 l_\lambda}{I L_w}$	$\frac{work\ of\ inertial\ force}{heat\ generated}$

The scaling criteria demand: $\pi_i = \pi_i'$ for similarity, where $i = 1$ to 7, the left hand π_i represents a full scale scenario, and the right hand π_i' represents a corresponding scale model. Note that π_2, is the ratio of the inertial force causing vortex shedding behind a flame, F_ω, to the inertia force of wind, $F_{i,up}$, is unique to the current wildland fire problem, where a flame acts similarly to a vertical, cylindrical obstruction, disrupting the flow around the fire [167].

Three of these pi numbers are familiar dimensionless quantities. The Froude number appears as π_1. The Strouhal number appears as π_2. The seventh pi number is the Byram number, which is used in plume studies [168].

Finney et al. [169] suggested the St-Fr correlation, which had been studied in pool fire puffing above a toroidal vortex [170], could be applied to larger fires. This St-Fr relation is equivalent to the $\pi_2 - \pi_1$ correlation, and the interest was based on field and laboratory observations and data acquisition. Using the same fuels for both the full scale and the model and assuming the same temperature at the corresponding locations, π_5 and π_6 can be automatically satisfied, and the above scaling criteria yields the following, Equation 3.1:

$$\Phi\left[\frac{u^2}{L_w}, \frac{L_a\omega}{u}, \frac{El_\lambda}{I}, \frac{L_aR}{I}, \frac{L_au^3}{I}\right] = 0 \tag{3.1}$$

Equation 3.1 includes the new parameter, ω, which is a thermally detected frequency associated with convective-driven flame spread. This new frequency is in a new pi group to convective-driven fire scaling, the Strouhal number. The derivation of the new scaling laws is provided next.

3.4.3 Development of Scaling Laws for Convection-Driven Type Fire

For convection-driven fire, contrary to radiation-driven type, fluid dynamics influences the heat transfer mechanisms, creating a coupling between the force and heat balances, and leads to the following Equation 3.2.

$$\frac{u}{u'} = \frac{R}{R'} = \frac{E}{E'} = \sqrt{\frac{L_w}{L'_w}} \tag{3.2}$$

The time scale factor can also be obtained, and is presented in Equation 3.3. It may be interpreted as the ratio of time intervals in which two homologous events (e.g. total fuel consumption) occur, and is equal to the square root of the ratio of the flame zone depth:

$$\frac{t}{t'} = \sqrt{\frac{L_w}{L'_w}} \tag{3.3}$$

3.4.4 A Note on Time Scaling

To better illustrate time-scaling, consider a plot of time-series data of radiant heat flux received at two geometrically similar points from two properly scaled, but different size crib fires of the same fuel. Both fires are in the convection-dominated regime, and exhibit the same behaviors, although on different scales. In experiment one, a small crib, the maximum radiant heat flux, E_{max}, occurs at time t. In experiment two, a larger crib, the maximum radiant heat flux, E'_{max}, occurs at time t'. The time of ignition is t_0.

Take t^* to be the time scale factor, a constant for this phenomenon being scaled.

$$\frac{t}{t'} = t^*$$

Similarly, $E^*$is the radiant heat flux scale factor.

According to Equations 3.2 and 3.3, $t^* = E^*$. Since experiment one is a smaller crib, it burns out faster. The peak radiative heat flux is lower than that of the larger crib: $E_{max} < E'_{max}$, and the peak radiative heat flux reading occurs sooner after ignition: $t < t'$ - see Figure 3.4.

A time series plot of both experiments' radiative heat fluxes illustrates the nature of the time scaling factor. When the x-axis of the larger crib's data is contracted by the time scale factor t^*, and its radiative heat flux axis is contracted by the scale factor E^*, then the second experiments' radiative heat flux-time curve will collapse onto the first experiment's radiative heat flux-time curve (this indicates and supports the existing scaling laws for crib fires [55]).

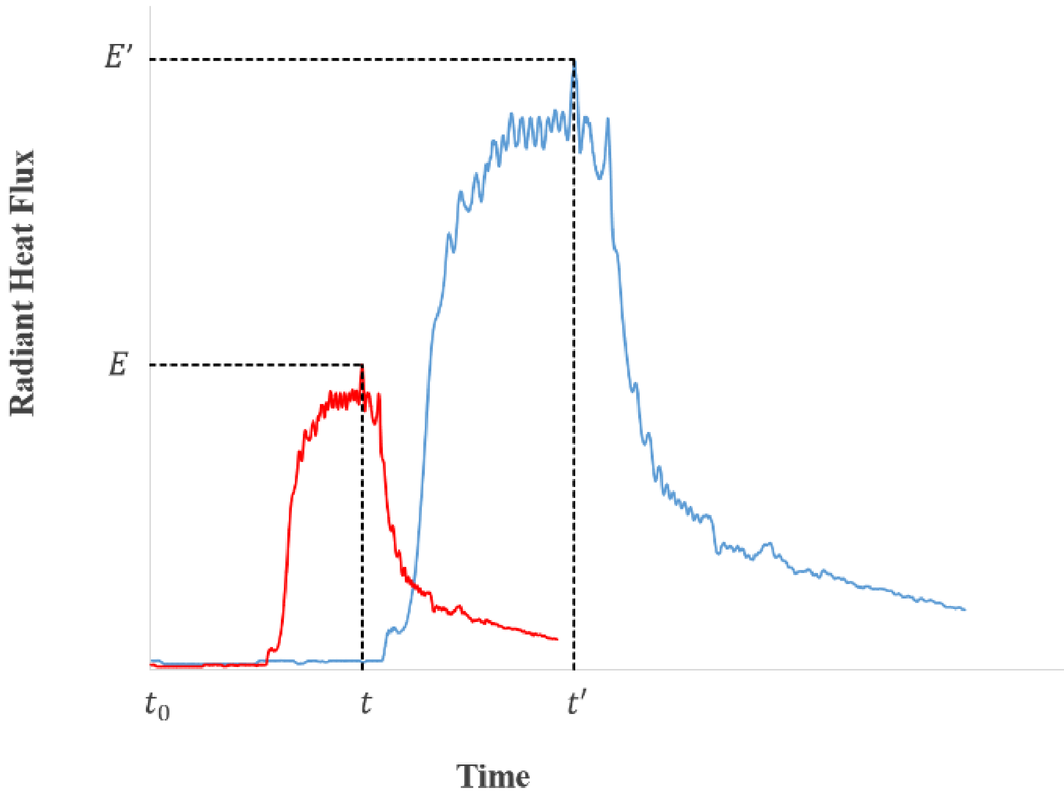

Figure 3.4 Illustration of time scaling using idealized radiative heat flux from two crib fires.

3.4.5 A Note on the St-Fr number correlation

To include the dynamic aspect of flame in relation to flame spreading in forest fires, the dynamic characteristics of flame needs to be assumed. Here the addition of the seventh pi-number to the already established six pi-numbers,

$$\pi_2 = (dynamic\ force)/(inertial\ force\ of\ horizontal\ flow),$$

is proposed. The denominator of π_2 is the same as the numerator of the Fr number, indicating that three different forces control flame dynamics: the buoyancy force acting on the heated gas and flame, the inertia force of horizontal flow, and the dynamic force due to turbulent instability or buoyancy-driven instability or possibly coupling of both. Investigating the specific nature of π_2, which depends on the condition and scale of fires, requires a series of scale model experiments. Through the first step of this investigation, however, π_2 is assumed as the Strauhal (St) number, and its validity is tested by conducting different size scale model experiments along with collecting available data to validate the St-Fr correlation. If a high correlation between St-Fr is obtained, then the assumptions associated with this correlation can be validated.

3.5 Summary

Scale models have proven to be useful for understanding physical phenomena otherwise too large, dangerous, costly, or complex to be easily studied. This dissertation builds upon the work of Emori and Saito [55] and Emori et al. [119], who developed separate scaling laws for both radiation-driven pool fires and convection-driven crib fires and then adapted those laws to certain wildland scenarios. In order to preserve better the dynamic nature of fire behavior in convection regimes, this dissertation employed the law approach to re-derive the scaling laws for convective-driven fires. The resulting group of seven pi numbers includes a new addition to characterize the dynamic behavior of flame flickering, based on a new interpretation of the role of the inertial force. This interpretation introduces a downstream, time-dependent frequency, ω, which captures the dynamic, vortex shedding behavior of flames due to the unstable nature of the turbulent flow. This downstream inertial term is in addition to the already accepted upstream inertial force due to the wind's initial flow. The new convection-driven wildland fire scaling laws were tested with data from experiments conducted during the research and from data and results available in scientific literature. Chapter 4 details the experiments conducted to confirm the parameter relations presented in this chapter.

CHAPTER 4: EXPERIMENTATION

This chapter describes the experimental tests and presents the data acquired during and analyzed after the testing. The tests include experiments which were conducted at the USDA Fire Sciences Laboratory in Missoula, Montana within their wind tunnel facility and two crib fires. In addition, data were acquired from a prescribed burn directed by the Fire and Environmental Research Applications (FERA) team of the Pacific Wildland Fire Sciences Laboratory that was performed at the Texas National Guard’s Camp Swift in Bastrop, Texas.

4.1 Wind Tunnel Burns

The USDA’s Missoula Fire Sciences Laboratory has been conducting fire spread experiments using uniform fuelbeds made of laser-cut cardboard since 2012. Data detailed in the USDA’s experimental record were augmented with new wind tunnel data that were collected specifically for this work between November 2013 and February 2014. These studies followed the well-established procedures of the USDA that had been developed during previous wind tunnel experiments in their facility. The combined data sets helped to validate the scaling laws discussed in Chapter 3. Section 4.1, in part, has been published in *Progress in Scale Modeling, Volume II*, "A Study of Flame Spread in Engineered Cardboard Fuelbeds, Part I: Correlations and Observations” by M. A. Finney, J. Forthofer, B. A. Adam, N. K. Akafuah and K. Saito, Cham, Switzerland, Springer, 2014, pp. 71-84.

4.1.1 Experimental Procedure

Laser-cut cardboard fuelbeds were burned in a wind tunnel having a 3 m x 3 m cross-section. The velocity profiles of the wind tunnel’s cross-section have been described previously [171, 172] and are laminar except along the bottom surface where an upstream trip-fence produces a turbulent boundary layer. Wind speeds varied between 0.11 m/s and 2.24 m/s and had a relative humidity of approximately 25%. The testing in the wind tunnel replicates fires having convection-dominated heat transfer [122].

The laser-cut cardboard fuel is more practical for use at scales larger than laboratory fuelbeds which typically use matchsticks [64, 173, 174] or toothpicks [175] during fire testing; it also offers more uniform particle spacing than excelsior [171] or pine needles [172]. Cardboard and paper strips had been used for fire studies as early as 1971 [154] and offer advantages of known homogenous properties such as density and customizable physical dimensions representative of discrete particles with prescribed lengths and surface areas. The cardboard fuel elements were cut at regular spacing along a common spine using a commercial CO_2 laser system (Figure 4.1). The cards or "combs" were then arranged in rows at various spacing to form a fuelbed with vertically standing 'particles' or tines (Figure 4.2). Fuelbeds constructed of these cardboard combs were 1.22 m to 2.45 m in width and 3.05 m to 6.1 m in length. The combs were supported and arranged on a foundation of cement-board strips (Hardy Board), with each having dimensions of 6.35 mm x 50.8 mm and separated by a steel spacer 1.58 mm x 25.4 mm, which was the same thickness as the cardboard tines. The steel spacers held the cement board strips apart so that the cardboard tines have just enough room to be held upright. All the tests were run on a horizontal fuelbed. Tine lengths ranged from 2.54 mm to 355.6 mm.

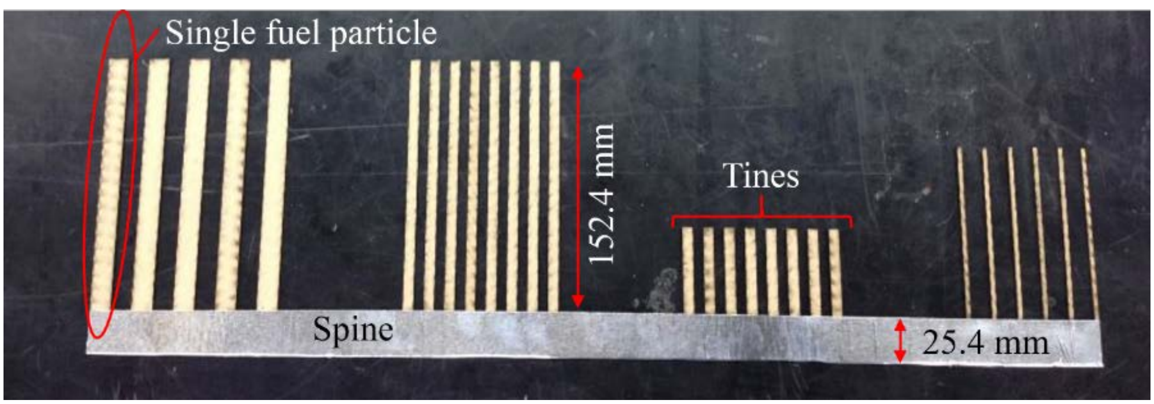

Figure 4.1 A cardboard comb of various size fuel particles. The fuel beds used in this work were made up of identical combs with identical tines, unlike the one pictured. These combs depict the variation in tine dimension available.

The cardboard used was 1.588 mm thick brown "chip board" with approximately 60% recycled content. Fuel particles were created having different lengths and widths and arranged with different row spacing to achieve specific fuelbed properties (Figure 4.2). The fuel elements were conditioned to equilibrium in an atmosphere maintained at 17.1 °C and 10.1% RH.

The laser cutter/engraver system was a Universal Laser Systems Inc. ILS12.150D model equipped with two 60W laser cartridges. The beams from both lasers were collimated for cutting. The table accommodates sheets of cardboard 0.61 m x 1.22 m so that multiple combs can be cut from the same sheet in one operation.

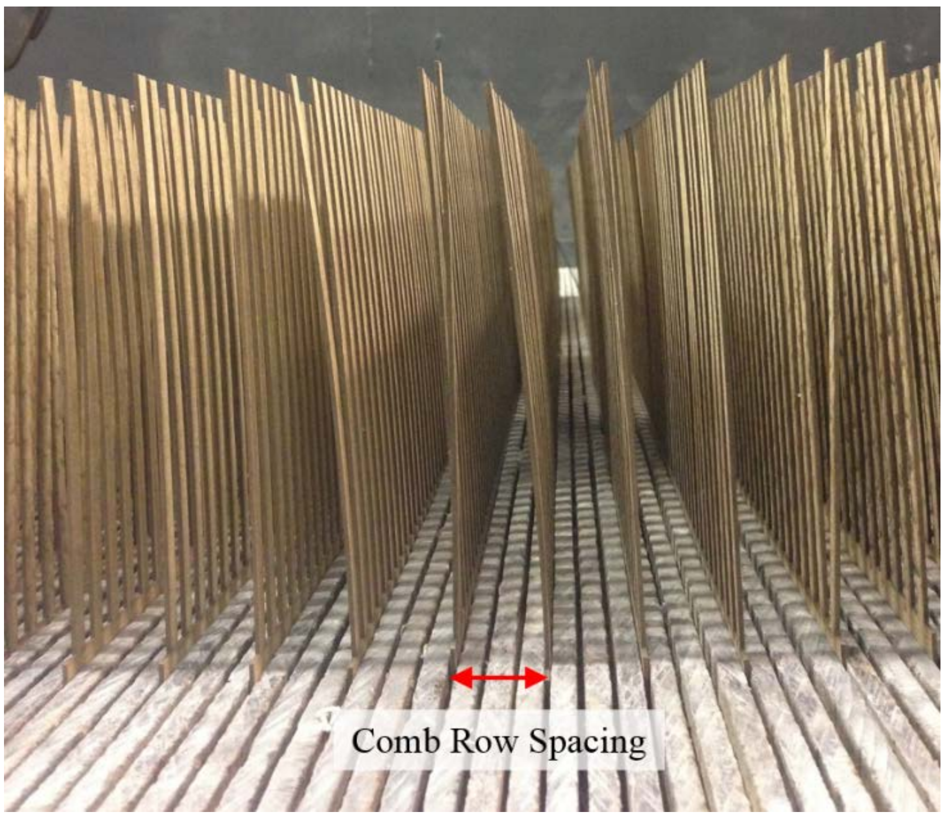

Figure 4.2 Laser-cut cardboard laboratory fuelbed. Tines used are those pictured at the far left of Figure 4.1 (152.4 mm x 12.7 mm).

To limit inflow to the combustion zone along the lateral edges during burning, the sides of the beds were lined with paper that was treated with the flame retardant diammonium phosphate, $(NH_4)_2HPO_4$. This technique was described by Byram et al. in a USDA report, where the fire retardant limits independent flaming combustion but allows the paper to burn in conjunction with the advancing fire front [176]. The consumption of the paper sideliners at the trailing edge of the burning zone avoids channeling of inflow air to the rear of the fire. Such inflow has been shown to affect fire spread on slopes [177] and would also effects the results from the fuelbeds, i.e. the treated paper sideliner effectively eliminated and/or limited edge effects. Cutouts within the sideliner permitted filming of the ignition and fire processes within the fuelbed. A series of preliminary burns of the cardboard fuelbeds in the wind tunnel were used to refine instrumentation like the digital video cameras and procedures like the various angles at which to record the videos.

The characteristic frequency of each fire was determined by examining the flame flickering. First, the time between events and event lengths were measured, and then the mean period was calculated. The mean frequency was taken from the mean period for each fire. Because visual assessments of the videos are inherently uncertain and subjective, two other methods of determining frequencies were also explored, including:

(1) Signal analysis of time series thermocouple data;
(2) Infrared images (IR) in false color processed images (explained below) from infrared video thermography (IRVT).

The use of thermocouple arrays enabled both fuel and air temperatures to be measured; they generally can withstand high temperatures, and are rugged, portable and low cost but are also stationary and time consuming to set-up [178]. The thermocouples were Type K with 0.076 mm diameter wire; they had a time constant of 166 Hz and an acquisition rate of up to 500 Hz. Because a 500 Hz acquisition rate was not needed, the measurements of fuel response frequencies were analyzed with an acquisition rate of 166 Hz. However, for measurements of thermal pulse frequencies or fluid instabilities in air, acquisition rates as high as 2000 Hz are needed to determine flame responses of up to 1000 Hz, based on the Nyquist frequency criterion. Hence, although the thermocouples used could measure fuel-based flickering they could not measure air-based flickering.

The second imaging method used IR thermographic techniques to visualize fuel particles during burns. The infrared (IR) camera was a FLIR® midwave camera (SC4000™, 3 μm-5 μm) with a Spectrogon bandpass flame attenuation filter with the spectral range 3.7 μm to 4.2 μm. The filter enabled the camera to image through flames but the emission of CO_2 during the fire obstructed the acquisition of quality images because it has an intense absorption peak at 4.3 μm. Perhaps with a narrower filter, having a more restricted viewing range of between 3.83 μm to 3.98μm, it would be possible to image the fire dynamics without significant interference from CO_2. The data acquisition rate, after superframing, was 200 fps (frames per second); this value is larger than that needed by the thermocouples which had a time constant of 166 Hz. The thermographic images were displayed in false-color. In a false-color IR image, the visual color associated with each pixel represents an IR intensity value at that location on the detector. The color scale is user defined, and the color scale appears as a gradient from a color representing the coolest temperature to a color representing the hottest temperature.

4.1.2 Results and Discussion

The visual videos revealed two principal and important dynamic features of the flame zone. First, the flame zone became divided in the transverse or span-wise (perpendicular to the direction of flow) direction into convective peaks and valleys having a fairly regular spacing (Figure 4.3). The peaks and valleys moved back-and-forth in the span-wise direction and the ignition interface at the leading edge of the combustion zone was populated with these flame structures. The valleys or troughs contained concave surfaces or structure between the peaks (Figure 4.4).

Second, the flame zone exhibited instabilities which, when viewed at an angle from upstream and above the fuelbed, showed that inflow air originated from upstream of the flame front/burning zone. In other words, the air mass traveled downstream and through the flame front, producing dish-shaped depressions in the flames that caused the observed valleys. As a consequence of the air mass traveling through the flame front, the flame was pushed down and into or toward the unburned fuels ahead of the fire front (Figure 4.4).

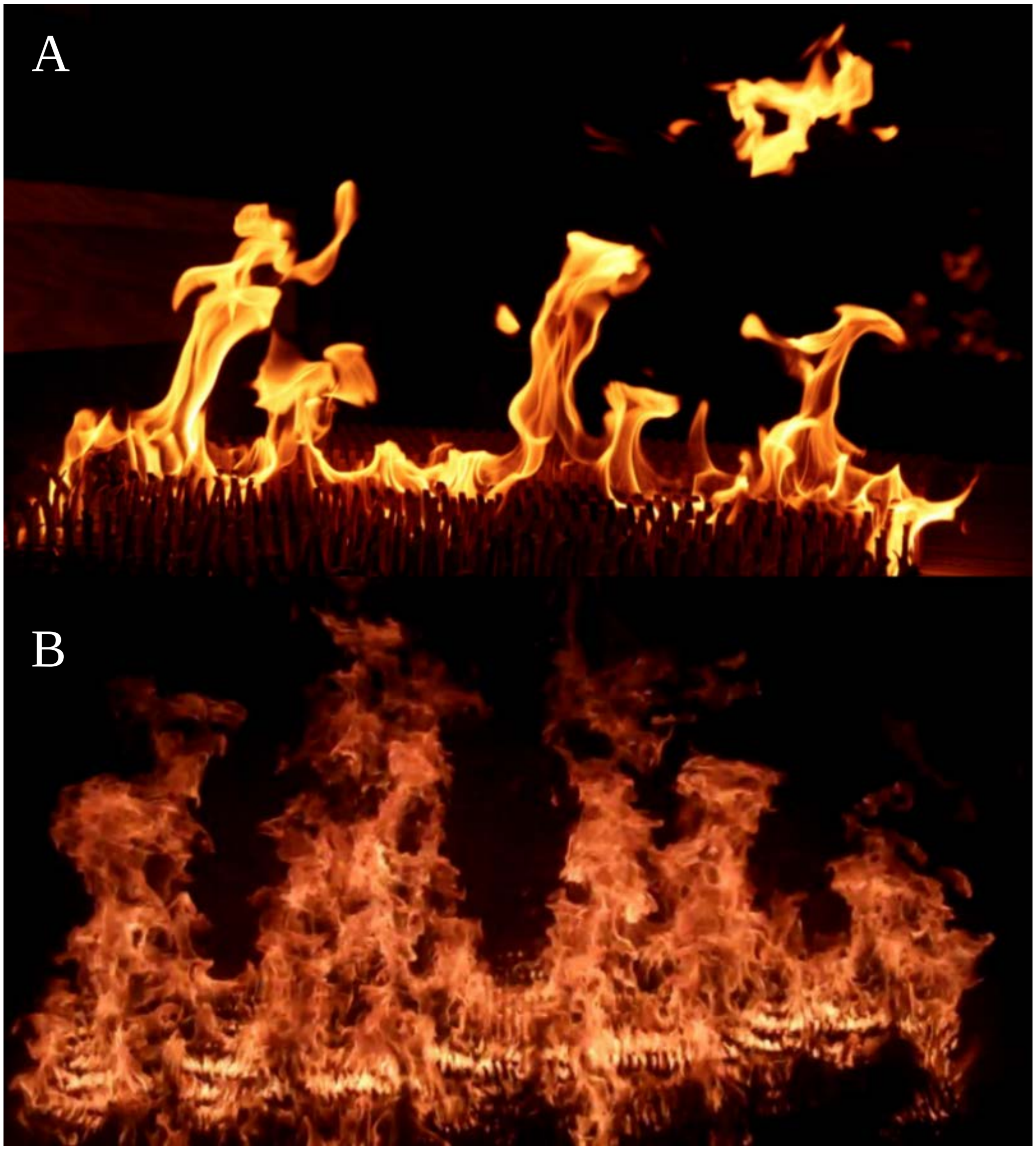

Figure 4.3 Peak and valley structure of flames looking downwind (looking from the black to the green, with a line of sight parallel to the imposed flow). (A) Flames are approximately 0.2m long (B) Flames are approximately 2m long.

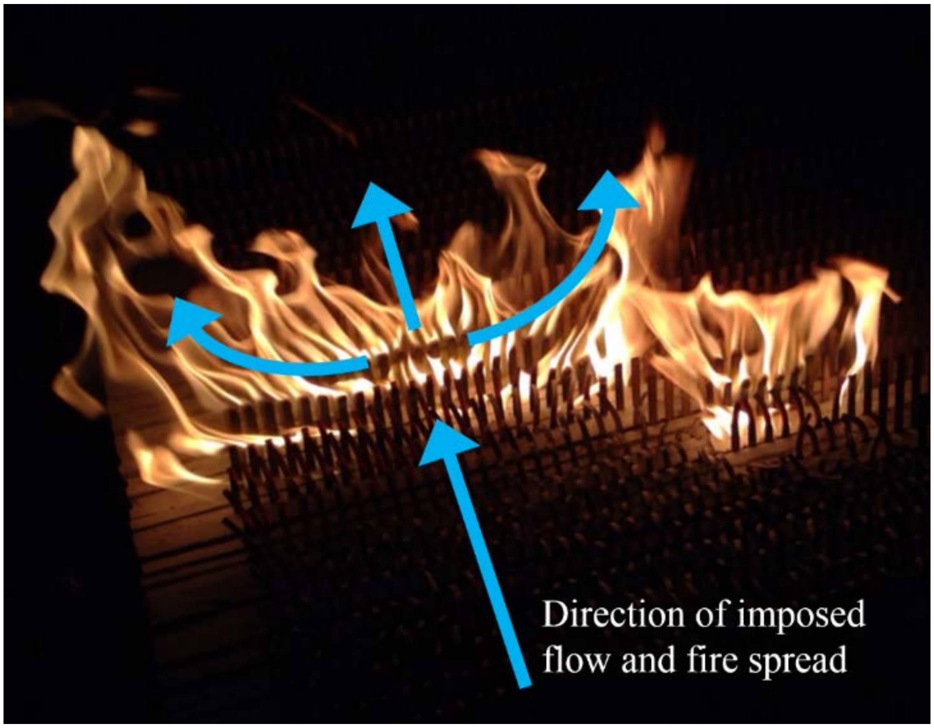

Figure 4.4 A mass of air originating upstream of the fire, travels downstream, through the fire front, splashing flames away from the line of its path and down into un-ignited fuel ahead of the fire (see narrative for the explanation).

Figure 4.5 Flame structure showing rotation of flame eddies.

Additionally, when the flame zone was videoed normal to the stream-wise direction (perpendicular to the imposed flow or wind), eddies also appeared on the upper and lower flame edges, which rotated in opposition to each other (Figure 4.5). From the perspective of the Figure 4.5, the whirls on the upper surface of the flames rotated counter-clockwise, while the whirls shedding off the lower surface rotated clock-wise.

The USDA conducted a preliminary investigation to obtain the dominant frequency of flame movement in fires in the wind tunnel from temperature data during the wind tunnel burns [179]. The stationary 2 mil diameter thermocouples showed repeatability in their temperature dynamics suggested three phases that fuel particles experience prior to, during and after burning: pre-heating, burning, and glowing. The flame bathing, discussed in the previous section, influencing an unburned particles' ignitions happens during pre-heating. The thermocouples, like fuel particles, experience around 10 flame-bathing events before temperatures attained the ignition point.

Flame bathing events occur over a shorter time span in small fires, and occur over a longer time in a large fire. A fuel particle or thermocouple does not move with a flame front, rather a flame front approaches unburned fuel (and thermocouples) and then moves through and beyond the stationary fuel. Thus, temperature excursion events related to flame bathing occur intermittently and over short durations and dictate that only a small number of events are available with which to work. However, visual videos moving with or in a far field view enable a fire to move across the field of view, and offer the ability to record and average the time between major flame bathing events even in different locations over longer durations. Large thermocouple arrays (of a length at least greater than twice the flame length in the stream-wise direction) may be able to achieve the same effect. Unfortunately, previous USDA data did not provide conclusive evidence for a flame bathing frequency [179]. Research for this dissertation focused on this dynamic aspect by using visual data and then established a mean bathing frequency for these phenomena.

Obtaining frequency from filtered infrared (IR) thermography was also attempted. It was a promising tactic because IR images showed fuel particle's response to heating and not the air temperature, and bathing events could be distinguished by fuel particle temperature rises.

Although the frame acquisition rate of the IR camera exceeded the maximum data sampling rate of the thermocouples, the IR frame acquisition rate was still too low to capture burning in air and flow around the flames. However, IR thermography offered the ability to see the fuel respond to heating from the fire, and even fluid motion of the products of combustion. The filter eliminated the flames but, because CO_2 is emitted during fuel burning and CO_2 contains an absorption band near $4.1\mu m$ which is within the IR filter range, the IR video frames were occasionally flushed with or obscured by CO_2 emissions. While these effects obscured images of fuel particles and made more difficult the research efforts directed toward particle responses to flames, the ability to image CO_2 evolution also acted as a natural tracer for conceptualizing a particle image velocimetry-type system - see Figure 4.6.

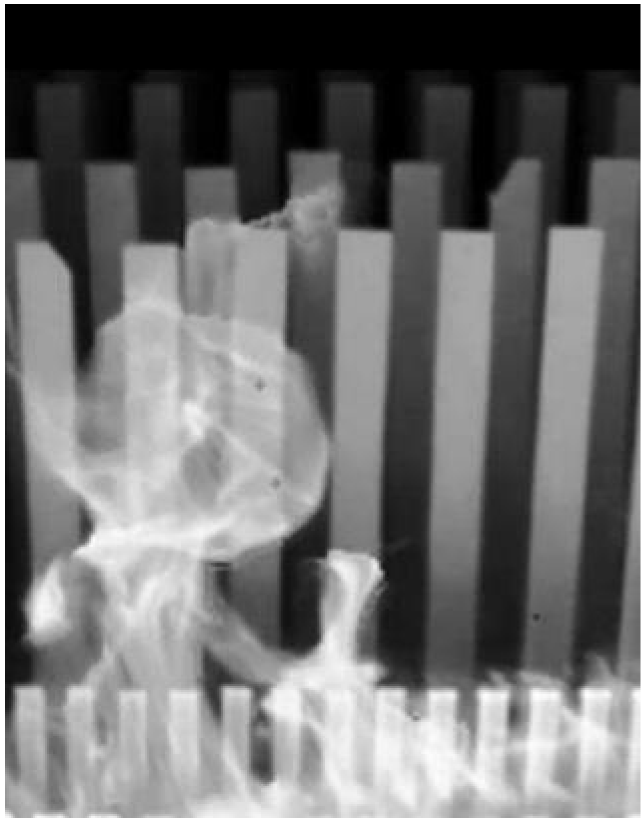

Figure 4.6 IR image of the front of a burning fire shows the flow developing a characteristic mushroom shape of Rayleigh–Bénard thermal instability. Flame spread is from the bottom of the frame to the top.

Even though the infrared imaging equipment used to conduct the experimental data collection for this work represented advanced equipment, continuing advances in infrared detector arrays will reduce the thermal time constants and improve the noise immunity resulting in improved measurement accuracy. Faster processing electronics will allow for higher frame acquisition rates that will permit verification that the underlying fluid dynamics have been properly represented by the sampled data, or uncover higher frequency fluid dynamics not represented by the sampling rates used to acquire data for this research.

Data from thirty-eight experimental burns provided sufficient information to calculate the Fr and St numbers. The statistics describing those parameters used to calculate the Fr and

St numbers are in Table 4.1. The parameters L_w and L_a, which were introduced in Chapter 3, represent the flame zone depth and the height of the combusting gasses, respectively.

Table 4.1 Wind tunnel experiment fire parameter ranges

	Wind Speed (u)	**Frequency (ω)**	L_w	L_a
Max	1.79 m/s	8.71 Hz	1.20 m	2.5 m
Mean	0.74 m/s	4.57 Hz	0.44 m	0.8 m
Min	0.11 m/s	1.80 Hz	0.10 m	0.1 m

The wind speed was an independent variable, set in the wind tunnel. The flame zone depth, the flame length, and the frequency were averaged over the length of each respective burn from visual observations. A few of the USDA's wind tunnel burns were exempted from the study because they did not provide enough data; hence, the resulting selected burns comprised the 38 fires discussed here.

4.2 Crib Fires

Fires in the USDA's wind tunnel revealed that buoyant instabilities were responsible for the pattern of non-steady flame contacts that ignited fuels [165]. The frequency of flame flickering contact with un-ignited fuel increased with wind speed but decreased with flame length, as depicted by a Strouhal-Froude relationship, which was trending towards $St \sim Fr^{-0.5}$, as predicted [120, 180]. Two very large, open-packed cribs were burned outdoors. These experiments were of interest to confirm if the St-Fr scaling held for larger fires.

4.2.1 Experimental Procedure

The research for this dissertation also included data and assessments from crib fires. Cribs are ordered arrays of known dimension wooden sticks (Figure 4.7), and are often used as ignition sources in fire tests. Examples of this type of use are described in codes for fire testing, like UL 1715, ANSI/UL 711, and ISO 9705. Cribs are useful in investigations requiring repeatable experiments and predictable heat release rates [181]. Cribs have been used in many different combustion experiments, ranging from fire safety, to structure fire, to fire science studies [55, 182-185].

Figure 4.7 Conditioned wood crib sections of ponderosa pine in the USDA's burn chamber in Missoula, MT.

Cribs for this work were made of 2.5 cm by 2.5 cm blue stained (*Grosmannia clavigera*) Ponderosa pine (*Pinus ponderosa*) square dowels from the University of Montana's Lubrecht Experimental Forest (See pictures and schematic in Figures 4.7, 4.8, and 4.9). The wood was cut and conditioned to equilibrium in an atmosphere maintained at 17.1 °C and 10.1% RH. The sticks were first assembled into smaller cribs, which were then used as building blocks to create larger cribs. The cribs were burned outdoors at the Missoula Fire Science Laboratory, during which high definition (HD), high-speed videos were recorded.

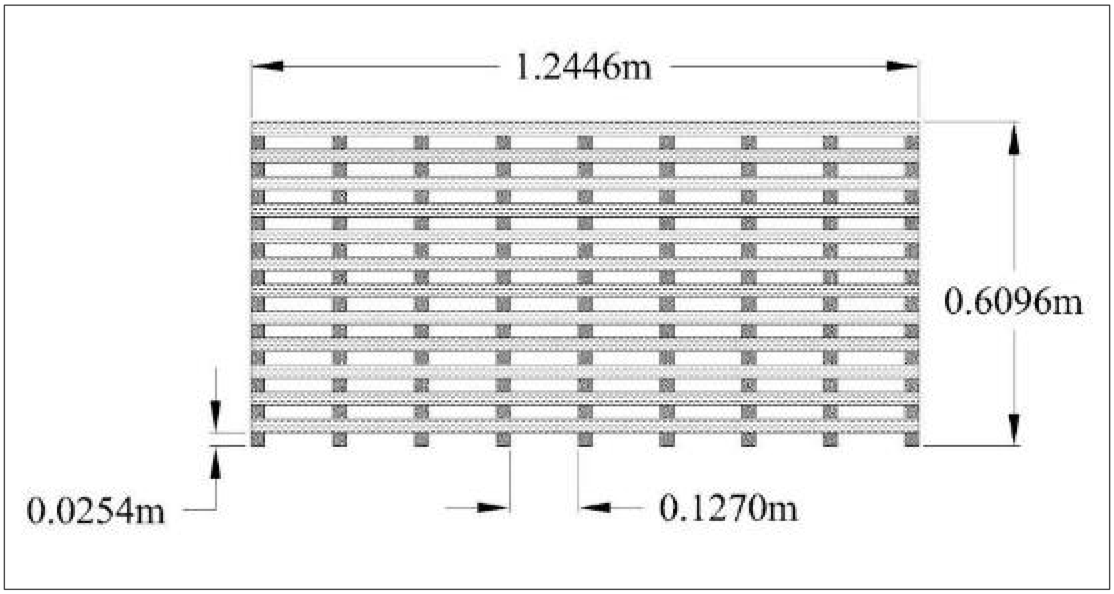

Figure 4.8 Schematic of cross-section of the wooden cribs used the first crib burn. These sections were aligned end to end to form a much larger crib and burned outdoors. This smaller crib face is the cross-section of the larger crib.

Each of the cribs was moved from the combustion laboratory after conditioning, adjoined lengthwise to the required length, and then oriented perpendicular to the wind direction. A shallow bed of dry excelsior (up to 5.08 cm in depth) was placed under the crib to serve as a long-burning wick for the gasoline-diesel ignition. Ignition was accomplished using a gasoline-diesel mix that was evenly sprayed over the crib, and then it was pilot-ignited using multiple manual, synchronized ignitions. The liquid fuel burned off first during approximately the first minute of the fire [186]. The videos and other data acquisition were then used to establish assessments on flame pulse frequencies, flame length, mass loss, wind speed, and radiant flux.

One crib, having dimensions of 1.219 m by 0.6096 m by 15.85 m, was burned on January 30, 2014. It was constructed in smaller sections with one section measuring 1.219 m by 1.219m by 0.6096m (see Figure 4.12). This smaller section was positioned at the middle of the assembled crib, and was placed on load cells to record mass loss. The other sections of the crib measured 2.438 m by 1.219 m by 0.6096 m.

A second crib, having dimensions of 2.438 m by 0.3048 m by 16.4 m, was burned on April 1, 2014. It was also constructed of smaller cribs measuring 2.438 m by 0.3048 m by 1.26 m. For both of these cribs, videos were acquired from different angles during their burning; the best video results proved to be positioned perpendicular to the wind direction.

Figure 4.9 Blue stained Ponderosa pine cants near a band saw in the University of Montana's Lubrecht Experimental Forest.

Figure 4.10 USGS topographical map of Northwest Missoula 7.5' Quadrangle with 1000m grid [44]. Yellow square indicates the crib location.

The crib burns in Missoula burned on flat terrain, in an open field; the location is marked with a yellow square overlaid on a United States Geological Survey (USGS) topographical map in Figure 4.10. The map is the Northwest Missoula Quadrangle [187] and is 7.5-minute series with 1000 m grids; the large orange square, slightly rotated clockwise from horizontal, is 1000 m by 1000 m. The brown contour lines indicate elevation in intervals of 6.10 m, increasing in elevation towards the northeast corner of the map. Universal Transverse Mercator (UTM) coordinates are provided at the perimeter of the map, near the orange UTM 1000 m grid axis. The large numbers of the UTM coordinates represent tens-of-thousands and thousands-of-meters. The millions and hundreds-of-thousands of meters are shown with small numbers.

The flame flickering frequencies were determined by assessing visual video footage of the fire. These video data were compared with thermocouple data acquired using four thermocouple rakes, the setups of which are presented in Figures 4.11 and 4.12. The rakes were installed having an orientation perpendicular to the crib and were evenly spaced from the middle, to avoid edge effects.

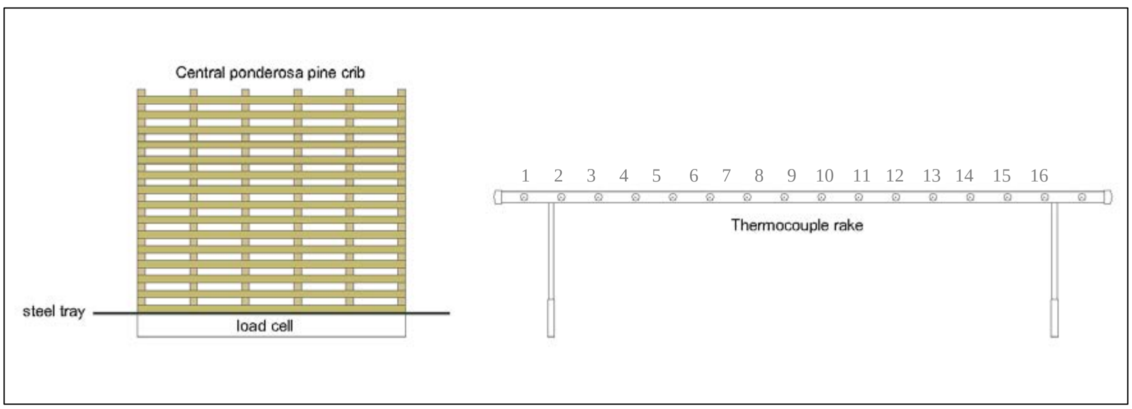

Figure 4.11 Schematic of the experimental setup for the outdoor crib burn. The thermocouple rakes were each set perpendicular to the length of the crib. Thermocouple 1 on each rake was closest to the crib, and thermocouple 16 was farthest from the crib.

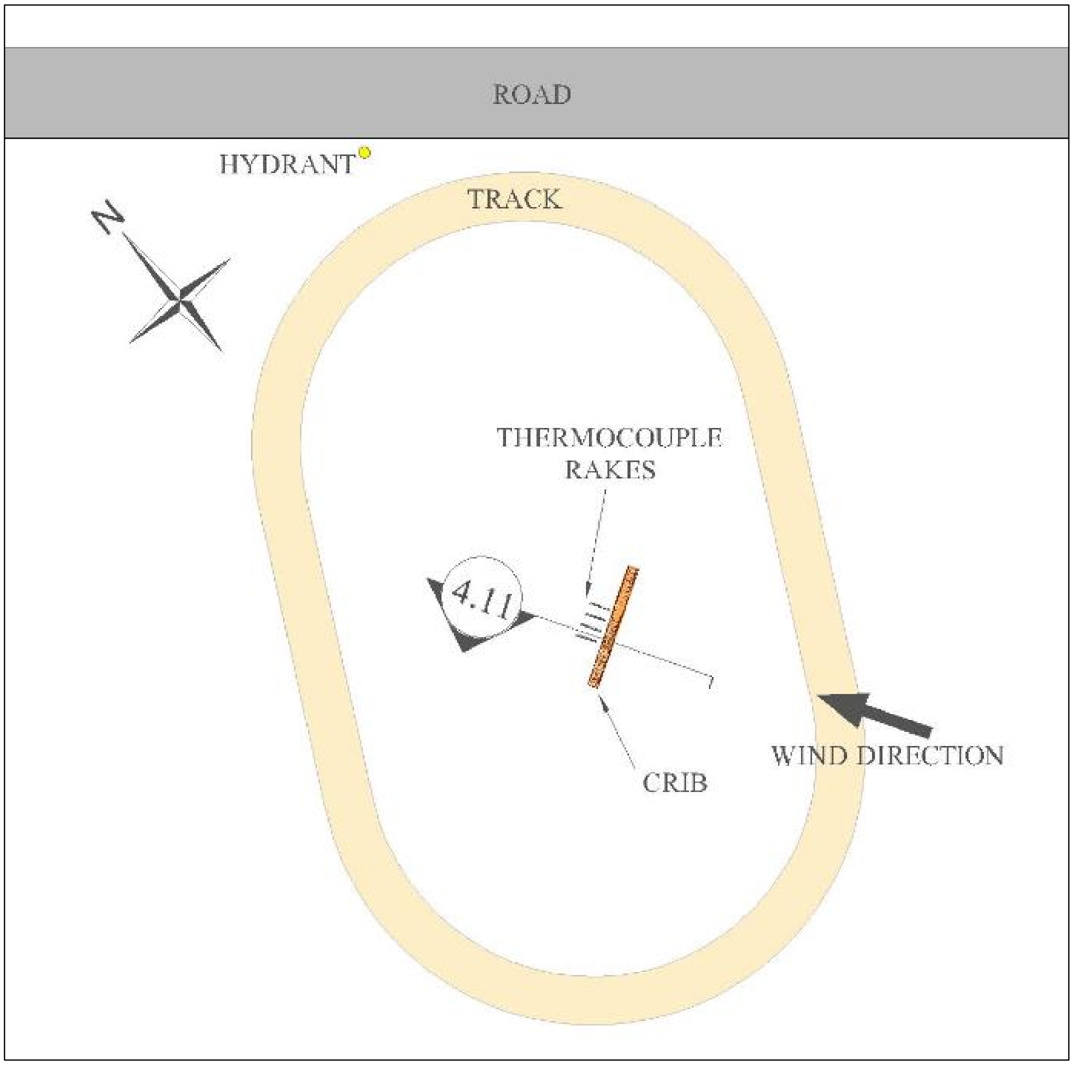

Figure 4.12 Arial view of the outdoor crib burn set up. A section elevation is shown cut through the middle of the crib. This elevation can be seen in Figure 4.12, as marked.

4.2.2 Results and Discussion

For the crib burns, thermocouple data confirmed that flame flickering frequencies could be determined and they could be correlated to flame flickering frequencies measured in the recorded videos; in fact, the thermocouples actually provided much more temporally and spatially refined information. Figure 4.13 provides a generic sample from three thermocouples (6, 10, and 14) recording temperature data every 0.03 seconds on the first of the thermocouple rakes, in which only data from three thermocouples are plotted for ease of visualization. In general, these data show an intuitive behavior: the plot of the thermocouple closest to the burning crib, TC(6), had the hottest temperatures , and the thermocouple farthest from the burning crib, TC(14), had temperature spikes which were lower than for TC(6). Furthermore, the closer a thermocouple was to a burning crib, the sooner it registered a spike in temperature as the flames flickered out and down the rake.

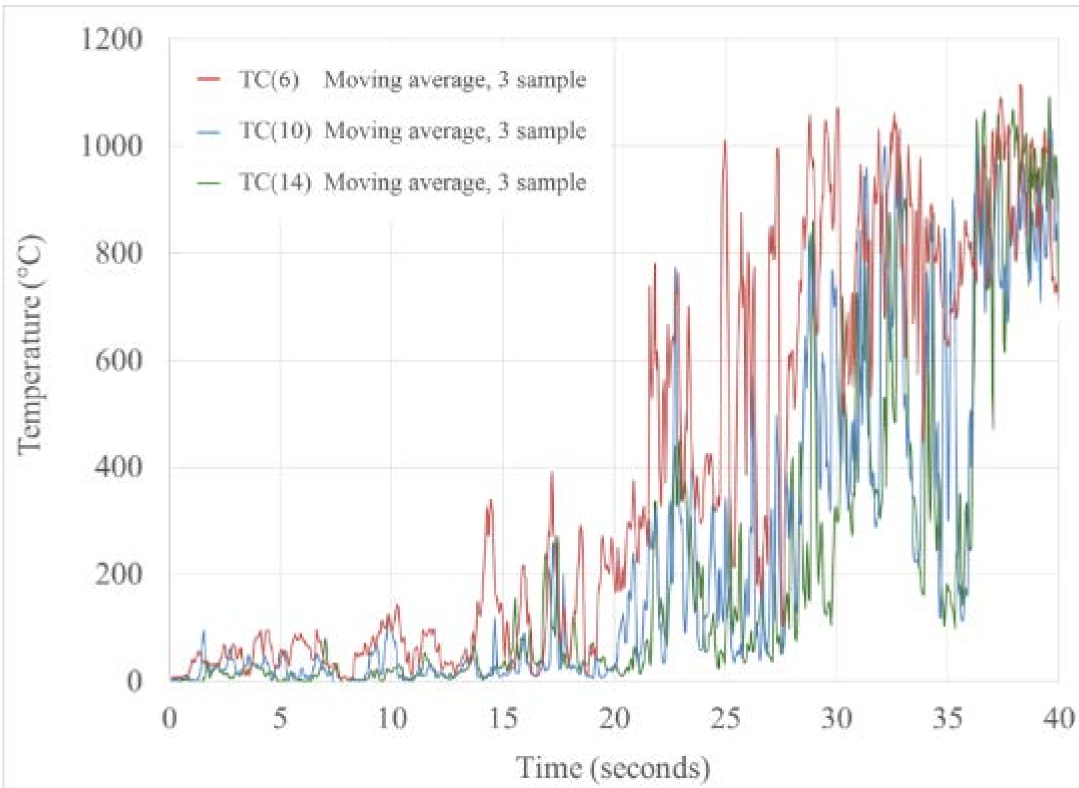

Figure 4.13 Time series temperature data, from the second large outdoor crib burn.

The thermocouple data were assessed to extract flame flickering frequencies, ω, and only the second crib offered a viable set of temperature data. However, the local ω's were inconsistent, with a variance of 1.96 Hz^2 and a range of 5.13 Hz. In fact, the thermocouple data varied from rake to rake and from thermocouple to thermocouple on the same rake.

As an example, the irregular event frequencies of flame impingements for temperatures over 350°C at thermocouple 14 can be seen in Figure 4.14.

In both crib fires, four large thermocouple arrays of 16 thermocouples each were installed to ensure that mean frequencies of flame flickering could be extracted from the temperature data. As a result, the flame front could be traced along thermocouple arrays, and gave a larger data set indicative of fire front behavior.

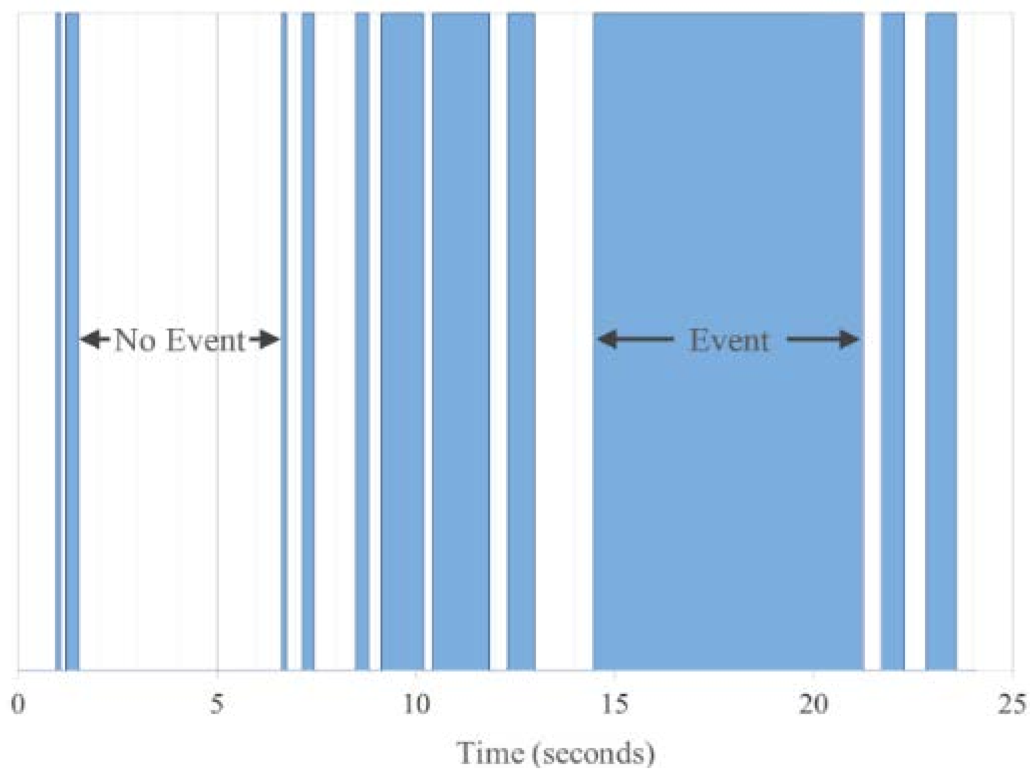

Figure 4.14 Pulse width diagram of thermocouple 14.

A distinction between flame flickering from thermocouples versus from video data was developed in which it was determined that thermocouples provided local frequencies while videos provided bulk frequencies. This distinction was necessary because the video recordings could not provide the spatial resolution that the thermocouples could but, on the other hand, the thermocouple data could not be integrated in a manner to provide overall bulk frequencies. The bulk frequencies, while useful in classifying a fire overall and reported as composite frequencies, were not useful for defining individual fluid instabilities because they were indistinguishable.

However, bulk frequencies were extracted from both of the described crib fires by using visual video data. To accomplish this task, the videos were first converted into .csv files for each frame and a region of interest was specified which was a constant for all frames. The region was placed $0.9L_f$ horizontally away from the downwind edge of the crib. The region of interest extended horizontally through $1.1L_f$. The lower bound of the region of interest extended from ground level up through $0.75H$. It is worth noting that this analysis approach is viable for the stationary crib burns but not feasible for fires that burned through large fuel beds.

For each crib, the RGB (red, green, blue) values for the pixels in the respective region of interest on each of the extracted frames were evaluated. Pixel RGB color values of the exposed flames were tabulated and compared to those values of non-flame pixels from all the video frames. The individual RGB values, recovered as ordered sets, were plotted against each other. The red and green values were highly correlated whereas the blue values were the lowest and had the smallest range. The fire RGB values were plotted with non-fire RGB values, and rules were developed to distinguish the two. A selection of pixel values for crib 1 are plotted in Figure 4.15.

By assessing the video data and extracting generalized RGB values and their behaviors, a binary decision basis was established to determine if a pixel image was fire or not. The relations for the RG values are presented in Equations 4.1, 4.2, and 4.3. Also, it was determined that the requirement for the B pixels was that the B pixel values for any pixel of fire would be less than the associated G pixel value.

if $0 > R_{value} > 90$ not fire **Eq. 4.1**

if $90 > R_{value} > 240$ and $G_{value} < 21.76e^{0.0074*R_{value}}$ Fire **Eq. 4.2** if $240 > R_{value} > 255$ and $G_{value} < 4.22R_{value} - 870$ Fire **Eq. 4.3**

The color blocks on the axis intersections of Figure 4.15 show the colors of the R and G values, with the blue values ranging from the lowest value found in the video to the highest values. For instance, the red-value axis 50 and the green-value axis 100 shows a color swatch that is a RGB gradient from (50, 100, 6) on the left to (50, 100, 114) on the right. Similarly, at the intersection of $R_{value} = 200$ and G_{value}=150, the gradient color swatch represents RGB's of (200, 150, 6) to (200, 150, 114).

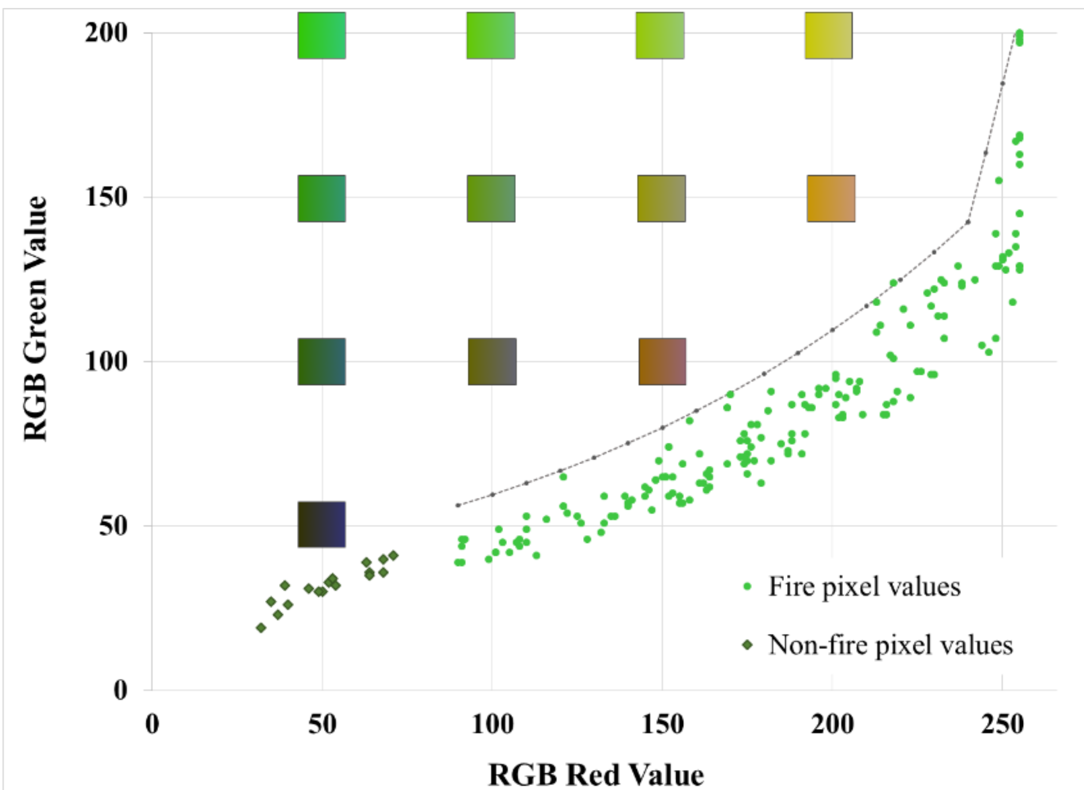

Figure 4.15 Red and green pixel values identifying fire pixels by color

The rules presented in the forgoing for distinguishing fire from non-fire pixels held for crib two, with the exception of the lower limit of the red-value (red) being raised 150. The later date and sunnier conditions may have contributed to that shift, increasing the requisite minimum red-value.

By assessing all of the data, the final parameters used to calculate the Fr and St numbers for the crib burns were established and are presented in Table 4.2.

Table 4.2 Fire parameters of large crib burns

Crib	Wind Speed (u), Direction	Frequency (ω)	L_w	L_a
1	0.19 m/s, NW	1.05 Hz	3.05 m	3 m
2	0.76 m/s, W	1.11 Hz	3.05 m	3 m

4.3 Prescribed Burns

Data from prescribed burns were assessed to expand upon the information available for assessing model development. Such prescribed burns are fires intentionally ignited by fire control management to meet specific objectives other than those for this dissertation, but the ability to assess and use these data sets was important for success within the modeling. Also, frequently, prescribed fires are used to restore a fire disturbance process to landscapes that historically experienced fire [188], and provide opportunities to collect and verify research findings on a full-scale wildland fires.

The Fire and Environmental Research Applications (FERA) Team from the Pacific Wildland Fire Sciences Laboratory directed three prescribed burns at the Texas National Guard's Camp Swift, in Bastrop, Texas. Scientists from the National Institute of Standards and Technology (NIST), Texas Forest Service, the Rocky Mountain Research Station, the Missoula Fire Sciences Laboratory, Colorado State University, the University of Kentucky, the University of Montana, and San Diego State University also joined FERA during the burns. They were originally designed to help evaluate the Wildland-Urban Interface Fire

Dynamics Simulator (WFDS) model, but results were used for other original research, including that in this dissertation.

4.3.1 Experimental Procedure

The prescribed burns in Bastrop took place over uniform, flat terrain, through three instrumented 100 m x 100 m burn units. The plot locations are marked as three yellow squares overlaid on two adjacent United States Geological Survey (USGS) topographical maps in Figure 4.16; the two maps are the Lake Bastrop Quadrangle [189] and Elgin East Quadrangle [190]. The burn site was at the north end of the Lake Bastrop Quadrangle and the south end of the Elgin East Quadrangle. The maps are 7.5-minute series with 1000 m grids; the large orange square is 1000 m by 1000 m. The brown contour lines in the maps indicate elevation in intervals of 3.05 m. UTM coordinates are provided at the perimeter of the map, near the orange UTM 1000 m grid axis. The large numbers of the UTM coordinates represent tens-of-thousands and thousands-of-meters. The millions and hundreds-of-thousands of meters are shown with small numbers. Hydrological features are shown in blue.

Figure 4.16 USGS topographical map of Lake Bastrop [34] and Elgin East [35] 7.5' Quadrangles with 1000m grid. Yellow, numbered squares indicate the three prescribed burn sites.

Camp Swift uses the open grassland in the rectangular region bordered by dirt access roads (Figure 4.16) for parachute training, and clears the area every winter with prescribed burns. The grasses in that area turn brown and dry during the winter months, the areas are burned between January and March, and then native basal cover generally increases the next spring following prescribed burns [191]. The annual burning creates a more uniform grassland, eliminating wood shrubs and small trees. The primary fuel in the clearing is a native, little bluestem grass (*Schizachyrium scoparium*), that was about 1 m high, as shown in Figure 4.17. Little bluestem is an upright, perennial, warm-season bunchgrass that reaches a height of 0.6 meters to 1.3 meters at maturity.

The anemometers (like those seen in Figure 4.17 B and 4.18) provided the time series wind speed data shown in Figure 4.21. The mean wind speed remained under 3 m/s during the three burns, but some gusts briefly registered above 4m/s. The three plots were burned in numerical order, each one about an hour after the previous one.

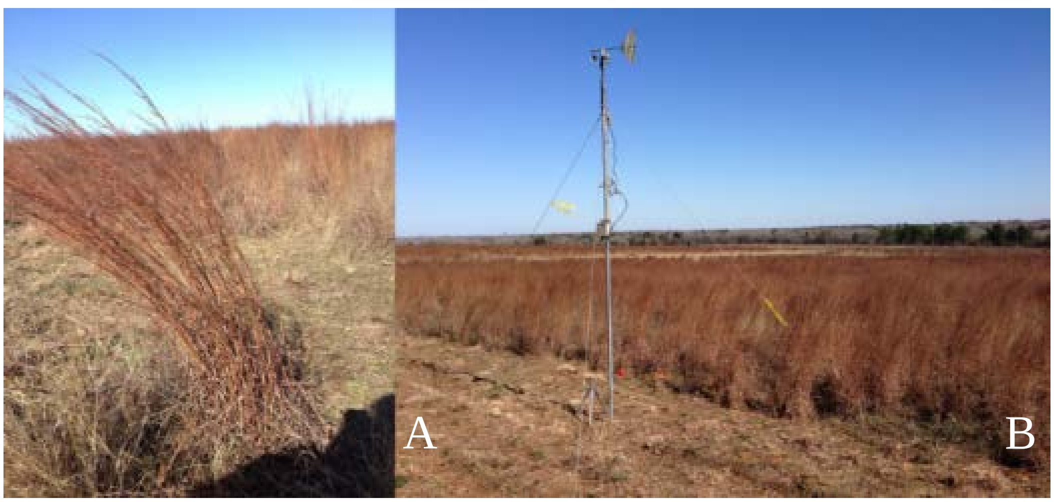

Figure 4.17 (A) An isolated little bluestem tuft and (B) experimental plot one, behind an anemometer tower, looking North.

Figure 4.18 Anemometer tower and thermocouple rake in plot one [42].

4.3.2 Results and Discussion

The three plots were burned on January 15th, 2014. Anemometers, like the one shown in Figure 4.17 B, and thermocouple arrays or "rakes" collected wind speed and temperature data, respectively (Figure 4.18). GoPro cameras captured in-situ video of the burns, and two independent camera crews (BBC and a drone documentary crew) captured HD video of the fires from both upwind in the plots and downwind outside of the plots. Figure 4.19 gives the layout of instruments in plot one. Plots two and three were instrumented similarly.

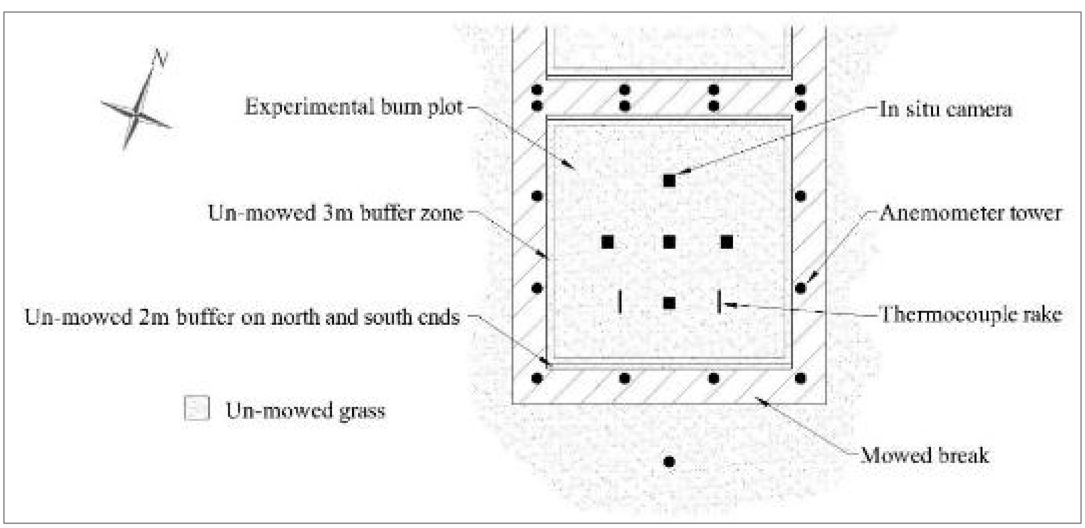

Figure 4.19 Plot one instrument layout

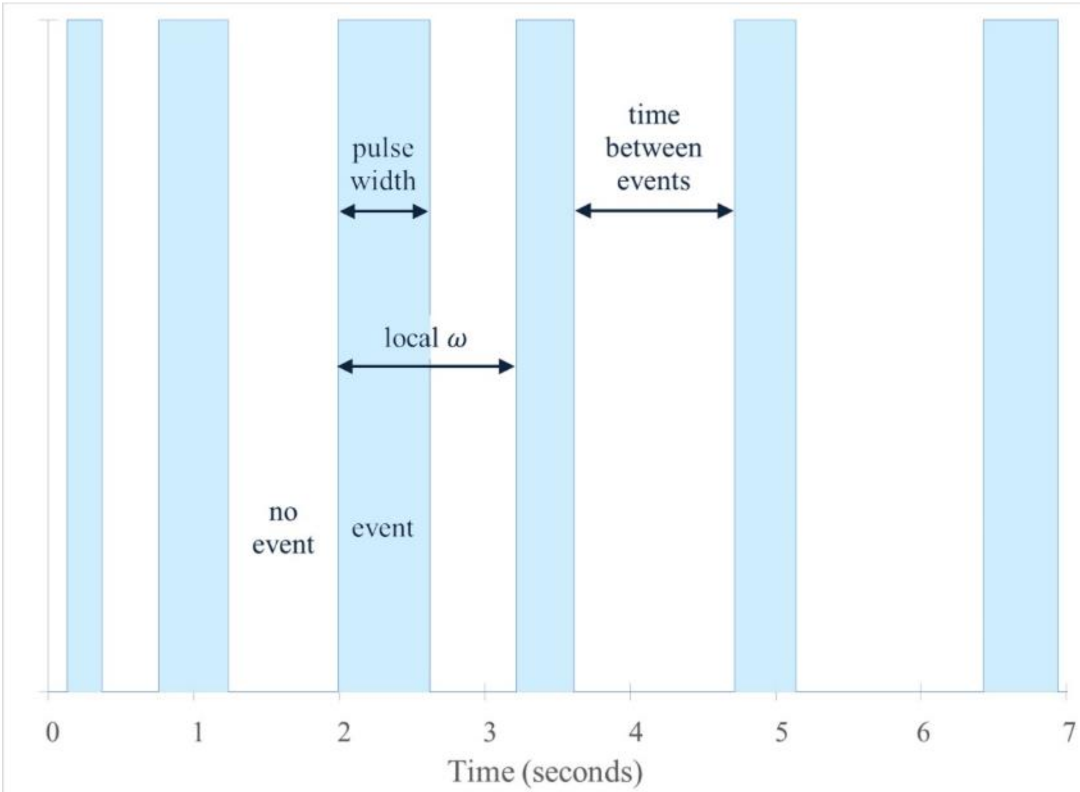

Figure 4.20 Time duration or pulse width of flame-bathing events (shaded in blue), and time between events (white) are times of convective cooling. Data generated by upward-crossing analysis of thermocouple data.

This instrumentation provided the time-series temperature data from which were extracted flame flickering frequencies. They were compared and then averaged with the appropriate observed flame bathing frequencies from videos for each corresponding plot. The flame front could be traced along the thermocouple array, giving a larger data set indicative of fire front behavior (Figure 4.22).

The drawback to extracting flickering frequencies from temperature data is twofold; first, the thermocouples are stationary and the flame front in the prescribed burns passed a stationary location in under 10 seconds with only a mean of 10 flame-bathing events, about half of which were indicative of fire front behavior. However, this effect was minimized in each fire plot because the USDA installed two large thermocouple arrays (or two thermocouple "rakes") of 16 thermocouples each to ensure that more accurate mean frequency data could be extracted.

The second drawback is that designating an air temperature for the flame-bathing event cutoff is similar to relying on a constant ignition temperature for a fuel. Finney et al. disfavored ignition temperature as an indication of ignition because it does not fully describe the conditions necessary for ignition [40]. Ignition has two requirements. First, it is necessary to have the existence of a near-stoichiometric fuel-air ratio; second, it is necessary to have either (a) sufficient heat to auto-ignite the gas phase fuel–air mixture, or (b) the presence of a pilot flame to ignite the gas phase fuel–air mixture. In other words, temperature is not the single determining factor for establishing a sufficient amount of pyrolyzates for burning to begin. In a still environment, solid-phase fuel temperature correlates to the fuel mass-loss during pyrolysis, and mass-loss rate correlates to concentrations of gas-phase fuel above the solid fuel, but pyrolyzate concentrations also depend on diffusion and imposed flow [192]. In any imposed flow, the rate of production of gas-phase fuel would need to compensate for gas-phase fuel loss due to advection. If ignition required a higher rate of production of gas-phase fuel in a certain environment, the fuel temperature would need to rise to facilitate faster thermal decomposition to provide enough gas-phase fuel for ignition.

Assigning a cutoff temperature for pyrolysis activity that will lead to ignition is equally dependent on situation and fuel. Hence, the variability in the environment of field burns necessitates that the temperature data be checked against observations of visible flame bathing.

In the air temperature data, the times between temperature excursions above 350°C were calculated; 350°C was selected as the cutoff temperature because it is the temperature at which thermogravimetric analysis (TGA) has shown dry bluestem mass loss rates from pyrolysis (not dehydration) to peak [193, 194]. The flame-bathing events in the field burns were only counted if they lasted longer than 0.1s, which is an order of magnitude value for a fine-fuel to respond to air temperature changes [165]). Any events that occurred with a time between events of less than 0.1s were not considered different flame bathing events.

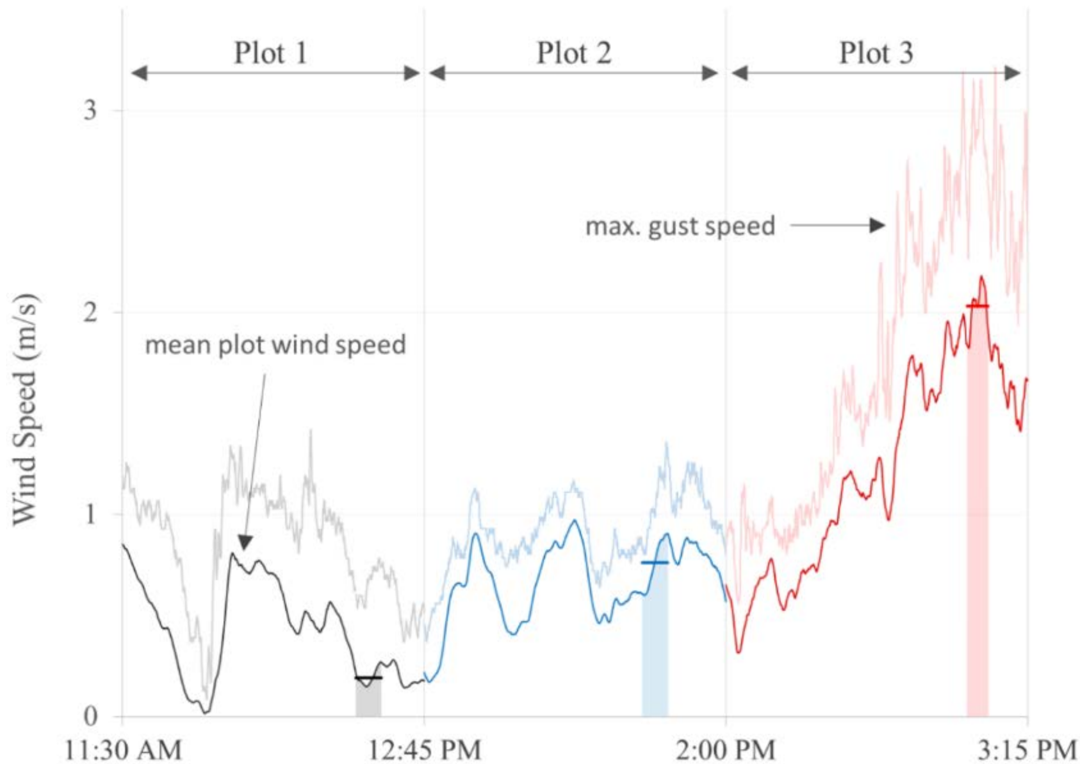

Figure 4.21 Mean wind speed, maximum gust speed, and average wind speed during each of the burns (bold, horizontal lines at the top of the shaded areas) are plotted. The prescribed burn durations are shown by the shaded regions.

The wind speeds at each plot are shown in Figure 4.21. The first plot's time series wind speed data is shown in dark grey between 11:30 am and 12:45 pm. That first prescribed burn took place between 12:28 pm and 12:35 pm, which is shaded on the plot. The wind speeds at plot two are shown in dark blue between 12:45pm and 2:00pm, and the burn took place between 1:39pm and 1:46pm. The wind speeds at plot three are shown in garnet between 2:00pm and 3:15pm, and the burn took place between 3:00pm and 3:06pm. In Figure 4.21, the light shaded areas indicate the times during the burns, with colors corresponding to plots. The light grey, blue, and garnet curves, above the corresponding darker curves, indicate gust speeds experienced around each plot.

Unlike during the crib burns, where the flame was stationary and perpendicular to the camera viewing direction, the footage taken of the grass burns showed flames did not remain perpendicular to the camera viewing direction; hence, the MATLAB script/programming developed and used for the crib burns could not be used for the field burns to analyze the videos. The frequencies were instead obtained manually over at least 12 seconds of video. In addition, the videos provided plume lengths (L_a), flame lengths (H_f), and flame zone depths (L_w).

Table 4.3 gives data extracted from the field burns. By using these data it is possible to calculate the Strouhal and Froude numbers and the Fr-St relations which are discussed in the following.

Table 4.3 Texas grass fire parameters

Plot	**Burn Time**	**Wind Speed (u), Direction**	**Frequency (ω)**	L_w	L_a
1	12:28 – 12:34	0.19 m/s, NW	1.21 Hz	3.05 m	3 m
2	13:39 – 13:45	0.76 m/s, W	1.11 Hz	3.05 m	3 m
3	15:00 – 15:05	2.034 m/s, W	1.14 Hz	3.05 m	3.4 m

4.4 Collective Results

Figure 4.26 presents the Fr-St values established during the analysis of wind tunnel experiments, large outdoor crib burn, and prescribed burns that were described in the foregoing information. It can be readily observed that the 0.5 exponent represents a correlative function for all of the data, including that from the current study.

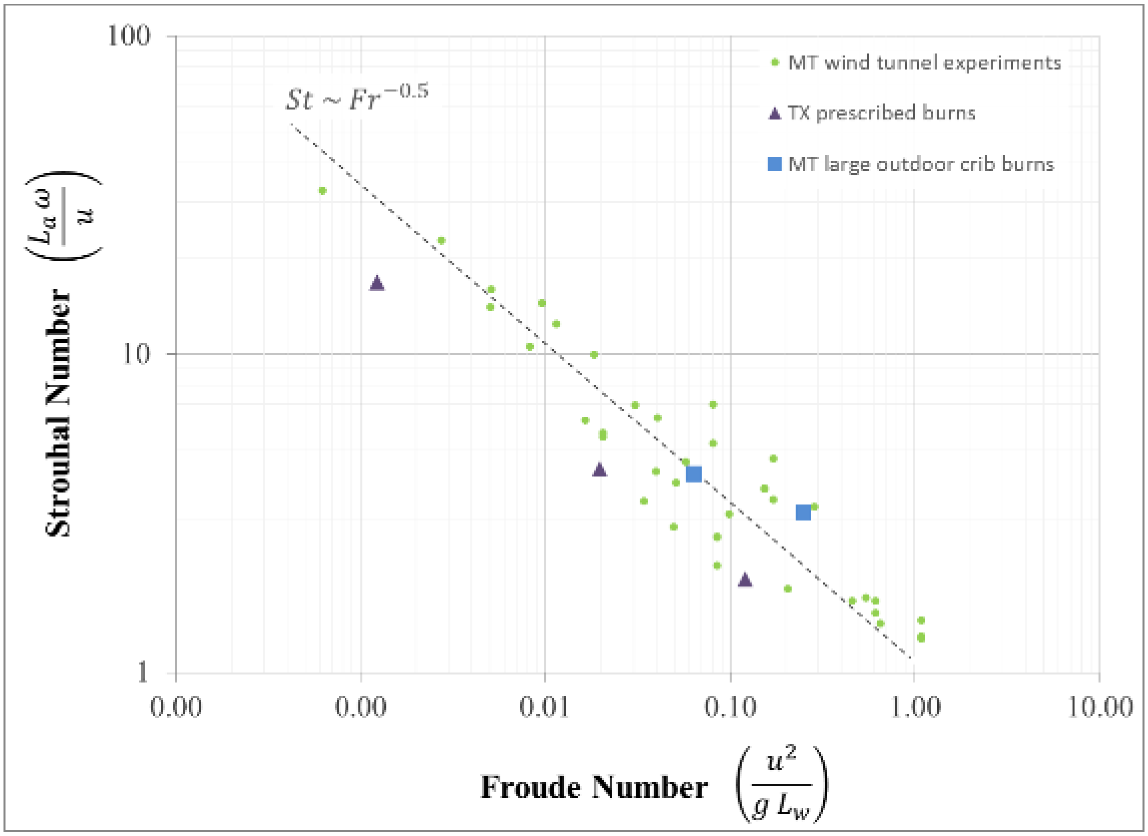

Figure 4.22 Strouhal-Froude correlation for experiments and data from literature.

Emori and Saito's work [55] indicated that the St-Fr correlation was St ~ $Fr^{-0.5}$, as is shown in Figure 4.26, which can lead to the following correlations:

$$\frac{F_\omega}{F_{i,up}} \sim \left(\frac{F_b}{F_{i,up}}\right)^{0.5}$$

So that

$$\frac{F_\omega}{\left(F_{i,up} F_b\right)^{0.5}} \sim const.$$

Using characteristic parameters, this relationship yields:

$$\frac{L^{1.5}\omega^2}{u g^{0.5}} \sim const. \tag{5.1}$$

It is proposed that the validity of this newly predicted correlation can be tested in laboratory experiments during future testing.

While it is established that cardboard comb burned under the imposed flow conditions in the wind tunnel testing were within the convection-dominated fire spread regime [165], some of the USDA's, previous wind tunnel experiments did not abide by the scaling laws developed in this work. Figure 4.23 shows a plot of flame length-spread values from just these previous experiments that were used in this work. The comparison of the slope of the best-fit line with the ideal line was established in Emori et al. [119].

The best fit equation, $y = 3.27\, x^{0.47}$, is in good agreement with the theoretical trend, $y \sim x^{0.5}$, but the model is not a good fit that has a low coefficient of determination. It is expected that the total sample of experiments in the wind tunnel which are in fact convection-driven could be better studied if they were grouped by certain parameters and plotted as individual series.

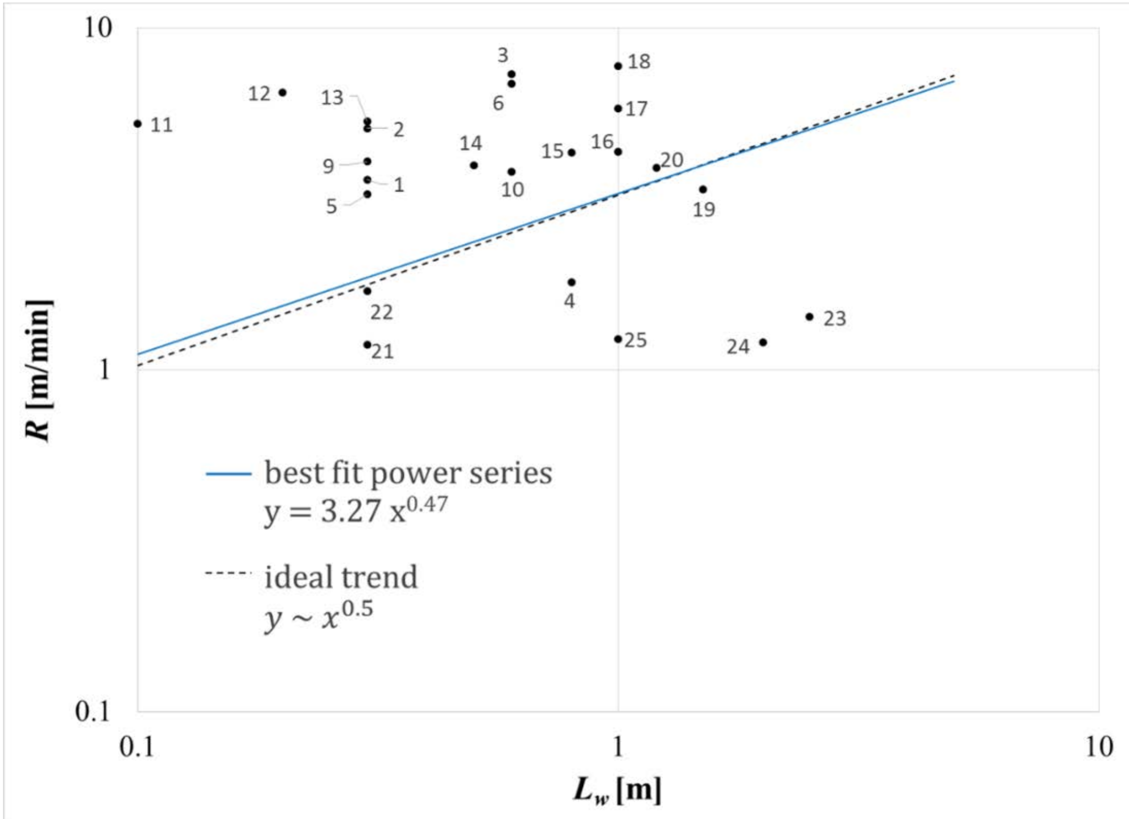

Figure 4.23 Wind tunnel experiments plotted to confirm convective-regime fire spread

CHAPTER 5: CONCLUSIONS

5.1 Conclusions

A major focus of this study was to develop new scaling laws for convection-driven wildland fires by incorporating a dynamic parameter. The conclusions from this research are summarized as follows.

(1) Wildland fire behavior is very complex, as established through a careful review of fundamental and applied combustion literature relevant to wildland fire research. The observations and the experimental research on fire behavior helped to focus the efforts of data assessment during this dissertation and identified a key behavior previously neglected. Specifically, an understanding and inclusion of dynamic flame flickering was developed that also agreed with and preserved scaling theory and laws during flame spread with specific rates within convection-driven fires.

This further work developing laws for instability scaling in wildland settings was founded on the established work in dynamic similitude of G.I. Taylor, H. C. Hottel, F. A. Williams, R. I. Emori, K. Saito and Y. Iguchi. The new dynamic flame parameter incorporated into the scaling laws for fires had not previously been assessed.

(2) The analyses in this dissertation were complemented significantly by research at the USDA Fire Sciences Laboratory; at this laboratory, unique engineered cardboard fuelbeds for wind tunnel fire were created and then used in experiments to provide a sound basis for understanding the behavior of full-scale wildland fires. Although prior to these experiments and the ensuing assessment in the research during this dissertation, several scaling laws on wildland fires were known. However, it was not clear what lessons from the engineered cardboard fuelbed experiments could be extended to full-scale wildland fires. The outcomes of this dissertation clearly show the importance of dynamic flame flickering influencing flame spread during both the wind tunnel and field burns.

(3) The question of the extension of engineered cardboard to full-scale wildland fires led to the review of a pioneering study by Emori et al. [119] on scale modeling fires using the law approach. Their efforts suggested the use of paper strip arrays, coated with paraffin,

would satisfy scaling laws that restricted the rate of heat release. In addition, they compared fire spread through the paper strip fuelbeds with fire spread through excelsior fuelbeds to develop two different types of scaling laws: one for convection-driven fires and the other for radiation-driven fires. Measured parameters of these fires like flame spread rates validated the scaling laws. Although the unsteady nature of the flames' behavior, specifically flame flickering or pulsation, was observed during these previous studies, scaling laws governing flame pulsation were not developed.

It had also been concluded that previous paper strip fire experiments fell within a radiative-driven regime due to the absence of an imposed flow, whereas the excelsior experiments fell within a convective-driven regime despite the absence of any imposed flow [119, 120]. Although the engineered cardboard fuelbeds were similar to the paper strips used by Emori et al., the presence of an imposed flow during the current study caused the conditions to be within the convective-driven regime.

(4) Hence, this study was conducted to improve the understanding of the unsteady nature of flames and flame pulsation in the convective-driven regime and, specifically, to examine potential relationships and scaling law parameters between flame pulsation and flame spread.

The large-scale experiments were conducted as a cooperative effort between many universities and government groups, including laboratory groups within the USDA and NIST. The data that was used in this work was available to all participating organizations, but was specifically collected to verify the scaling laws.

(5) The law approach was used to re-formulate scaling laws for convective-driven fire spread, and resulted in seven pi numbers. The newest and previously untested pi number, a variation of the Strouhal number, incorporated and represented the frequency of thermal pulses associated with the unsteady nature of flames. The Strouhal number's relation to the buoyancy force in a fire also offered insight because observations had suggested that intermittent flame bathing would drive fire spread, the influence of which was measured

as the frequency of thermal pulses in time series temperature data. This frequency factor was included in the new pi number.

6) It was discovered that the St-Fr correlation held over a wide range of different-scale fires and led to two new, important and practical implications of the St-Fr correlation [195]. First, time-varying convective heat transfer is derived from the buoyant instabilities of fire, and explained the scalability of flickering frequency from smaller-scale laboratory fires to larger-scale field wildfires. Second, because the frequency was related inversely to flame height, mechanisms that limited larger-scale and wildland fire spread rates were implicated. In other words, as fires move faster – perhaps due to increasing wind and the release more energy - flame height would increase but flickering frequency would decrease. This decrease in frequency increases the time between flame impingement events and increases the potential for convective cooling.

5.2 Future Work and Improvements

It is envisioned that this type of research should continue along two distinct paths. The first is an improvement in future experiments with the consideration of specific scaling laws.

The second path is to improve the understanding of underlying fluid instabilities ultimately contributing to a compound, down-wind frequency, as represented in the Strouhal number in this research. A caveat of this second option is that a need exists to improve the analyses of temperature data and other options should be explored to capture the nature of the instabilities.

Hardware and signal analyses improvements could better characterize the time series data that help to define the presence or importance of instabilities. Improvements in the data capturing rate would lead to more accurate and more complete descriptions and understandings of flame flickering. Also, non-stationary signal analyses would reveal more about the fire frequency characteristics.

As examples, infrared imaging with distinct wavelength sensitivity captured with the equipment used for this research allowed for significant insight but it is probable that multispectral image processing, that has shown great benefit in other image processing problems [196-198], would advance fire research significantly. In addition, an extension and improvement of processing techniques, like those developed for visual image capture or medical image synthesis, would permit analytical resolution enhancement of fire bed images.

An analytical system of practical use for future work is a high frame rate (≥1000 frames per second), IR camera that would be coupled with an advanced signal processing platform designed to examine non-stationary physical phenomena and to give wavelet transforms of image temperature data. Such wavelet transforms could extract frequency domain information from non-stationary processes such as the fluid instabilities motivating the flickering phenomenon. In addition, improvement in the windowed Discrete Fourier Transform (DFT) that was used to analyze the thermocouple data during this research to a dynamic DFT would lead to dramatic improvements in assessing and understanding fires and fire spread.

APPENDIX: FIRE FREQUENCY EXTRACTION FROM VISUAL VIDEO

```
%---------------------------------------------------------------------
% Frequency.m
%---------------------------------------------------------------------
% The following script was written to calculate the flickering frequency from
  a series of crib fire images
%---------------------------------------------------------------------
%
% Brittany Adam
%
% Original: October 12, 2014
%
% Modified: January 15, 2015
%
% Copyright (c) 2014 Brittany Adam
%
% All rights reserved.
%
%---------------------------------------------------------------------
%% Section 1: Clear Workspace
clear all

close all

clc

commandwindow
%% Section 2: Import Images
%
% Define directory where the images are stored
cd('C://Users/Brittany/Desktop/Frequency/regional_images')

imageFile = dir(fullfile(cd, '*.bmp'));

imageName = {imageFile.name};

dataFile = sort_nat(imageName); % Sort by numerical order using the
                                % function sort_nat.m. The file was written
                                % by Douglas Shwarz and can be found at
                                % the link in the appendix section of the
                                % code

% Preallocate for speed
imageData = cell(1, length(imageFile));
```

```
redPixels = imageData;

greenPixels = imageData;

bluePixels = imageData;

% Separate each image into its corresponding red, green, and blue pixels
% and store the results
for iFile = 1:length(imageFile)

    imageData{iFile} = imread(dataFile{iFile});

    redPixels{iFile} = imageData{iFile}(:,:,1);

    greenPixels{iFile} = imageData{iFile}(:,:,2);

    bluePixels{iFile} = imageData{iFile}(:,:,3);

end
%% Section 3: Red Pixel Section
%
% Store the red pixel data in the matrix redPixelMatrix and reshape the
% matrix according to the resolution of the crib burn images
redPixelMatrix = cell2mat(redPixels);

imageResolution = size(redPixels{1}); % Note all images have the same
                                      % resolution; therefore, any image
                                      % could be called for imageResolution

newRedPixelMatrix =
permute(reshape(redPixelMatrix,imageResolution(1),imageResolution(2),[]),
[1,2,3]);

% Restrict the red pixels to 90:255. This was necessary because red pixels
% lower than 90 were indicative of soot and smoke rather than fire
nFiles = length(imageFile);           % Total number of images

reshapeRedMatrix = reshape(newRedPixelMatrix,
[(imageResolution(1)*imageResolution(2)*nFiles), 1]);

reshapeRedMatrix(reshapeRedMatrix < 90) = 0;

restrictedRedMatrix =
permute(reshape(reshapeRedMatrix,imageResolution(1),imageResolution(2),[]),
[1,2,3]);
%% Section 4: Green Pixel Section
%
% Store the green pixel data in the matrix greenPixelMatrix and reshape the
% matrix according to the resolution of the crib burn images
greenPixelMatrix = cell2mat(greenPixels);

newGreenPixelMatrix =
permute(reshape(greenPixelMatrix,imageResolution(1),imageResolution(2),[]),
[1,2,3]);
```

```
% Restrict the green pixels using the green-red relation for fire colored
% pixels, which was determined through experimentation
[row,col,depth] = size(newGreenPixelMatrix);

for i = 1:row

    for j = 1:col

        for k = 1:depth

            if restrictedRedMatrix(i,j,k) == 0

                newGreenPixelMatrix(i,j,k) = 0;

            else

                newGreenPixelMatrix(i,j,k) = newGreenPixelMatrix(i,j,k);

            end

        end

    end

end

greenPixelMax = zeros(size(newGreenPixelMatrix));

restrictedGreenMatrix = greenPixelMax;

for i = 1:row

    for j = 1:col

        for k = 1:depth

            if restrictedRedMatrix(i,j,k) >= 90 && restrictedRedMatrix(i,j,k)
< 240

                greenPixelMax(i,j,k) =
21.757*exp(0.0074*double(restrictedRedMatrix(i,j,k)));

            elseif restrictedRedMatrix(i,j,k) >= 240

                greenPixelMax(i,j,k) =
(4.2187.*double(restrictedRedMatrix(i,j,k)))-870;

            else

                greenPixelMax(i,j,k) = 0;
```

```
            end

            if newGreenPixelMatrix(i,j,k) <= greenPixelMax(i,j,k)

                restrictedGreenMatrix(i,j,k) = newGreenPixelMatrix(i,j,k);

            else

               restrictedGreenMatrix(i,j,k) = 0;

            end

        end

    end

end
%% Section 5: Blue Pixel Section
%
% Store the blue pixel data in the matrix bluePixelMatrix and reshape the
% matrix according to the resolution of the crib burn images
bluePixelMatrix = cell2mat(bluePixels);

newBluePixelMatrix =
permute(reshape(bluePixelMatrix,imageResolution(1),imageResolution(2),[]),
[1,2,3]);

% Restrict the blue pixels using the blue-green-red relation for fire
% colored pixels, which was determined through experimentation
restrictedBlueMatrix = zeros(size(newBluePixelMatrix));

for i = 1:row

    for j = 1:col

        for k = 1:depth

            if restrictedGreenMatrix(i,j,k) == 0

                newBluePixelMatrix(i,j,k) = 0;

            else

                newBluePixelMatrix(i,j,k) = newBluePixelMatrix(i,j,k);

            end

        end

    end

end
```

```
for i = 1:row

    for j = 1:col

        for k = 1:depth

            if newBluePixelMatrix(i,j,k) < restrictedGreenMatrix(i,j,k)

                restrictedBlueMatrix(i,j,k) = newBluePixelMatrix(i,j,k);

            else

                restrictedBlueMatrix(i,j,k) = 0;

            end

        end

    end

end
%% Section 6: Count the Red, Green, and Blue Pixels
%
% This count will be used as a threshold to determine which pixels are used
% in determining the flickering frequency
redPixelCount = zeros(size(restrictedRedMatrix));

greenPixelCount = redPixelCount;

bluePixelCount = greenPixelCount;

for i = 1:row

    for j = 1:col

        for k = 1:depth

            if restrictedRedMatrix(i,j,k) ~= 0 && restrictedGreenMatrix(i,j,k)
~= 0 && restrictedBlueMatrix(i,j,k) ~= 0

                redPixelCount(i,j,k) = restrictedRedMatrix(i,j,k);

                greenPixelCount(i,j,k) = restrictedGreenMatrix(i,j,k);

                bluePixelCount(i,j,k) = restrictedBlueMatrix(i,j,k);

            end

        end

    end
```

```
end

redPixelCount = redPixelCount~=0;

greenPixelCount = greenPixelCount~=0;

bluePixelCount = bluePixelCount~=0;
%% Section 7: Sum all pixels that fall within the fire pixel regime
%
sumPixels = zeros(depth,1);

for i = 1:depth

    sumPixels(i,1) = sum(sum(sum(redPixelCount(:,:,i))));

    % redPixelCount is used for the summation even though greenPixelCount
    % or bluePixelCount would suffice (at this point all three matrices
    % sum to the same column vector due to the count in the above
    % section)

end
%% Section 8: Define Pixel Threshold
%
pixelThreshold = 4;

time = (1:depth)'/180; % Time in seconds

eventData = sumPixels >= pixelThreshold;

flickeringEventData = [time, eventData];

doubFlickeringPulseData = double(eventData);

% Determine the time of each flickering event
[rowPeaks,colPeaks] = findpeaks(doubFlickeringPulseData);

newTime = time(colPeaks);

flickeringPulseData = eventData(colPeaks);
%% Section 9: Limit the time between flickering events to 1/10 of a second or
             greater
%
% This limit between flickering events is needed becasue the fastest time a
% fuel particle can respond to a flickering event was determined through
% experimentation to be approximately 1/10 of a second
cutOff = 0.1;

increment = floor(cutOff/(time(2)-time(1)));

for i = 2:nFiles-1

    if eventData(i) == 0
```

```
        checkForward = logical(eventData(i+1) == 1);

        checkBack = logical(eventData(i-1) == 1);

           if checkBack == 1 && checkForward == 1

           eventData(i) = 1;

           end

    end

end

location = ind2sub(size(eventData), find(eventData == 1));

locationDifference = [0;diff(location)];

findIncrement = find(locationDifference > 1 & locationDifference < increment);

incrementTime = [location(findIncrement-1), location(findIncrement)];

for i = 1:length(incrementTime)

    eventData(incrementTime(i,1):incrementTime(i,2)) = 1;

end

updatedDoubPulseData = double(eventData);

[updatedRowPeaks,updatedColPeaks] = findpeaks(updatedDoubPulseData);

frequencyTime = time(updatedColPeaks);
%% Section 10: Compute Frequency
%
omega = mean(diff(frequencyTime))^-1;

disp('The flickering frequency in Hz: ')

disp(omega)
%% Appendix

% Natural Order Sort (sort_nat.m):
% http://www.mathworks.com/matlabcentral/fileexchange/10959-sortnat-natural-
order-sort/content/sort_nat.m
```

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