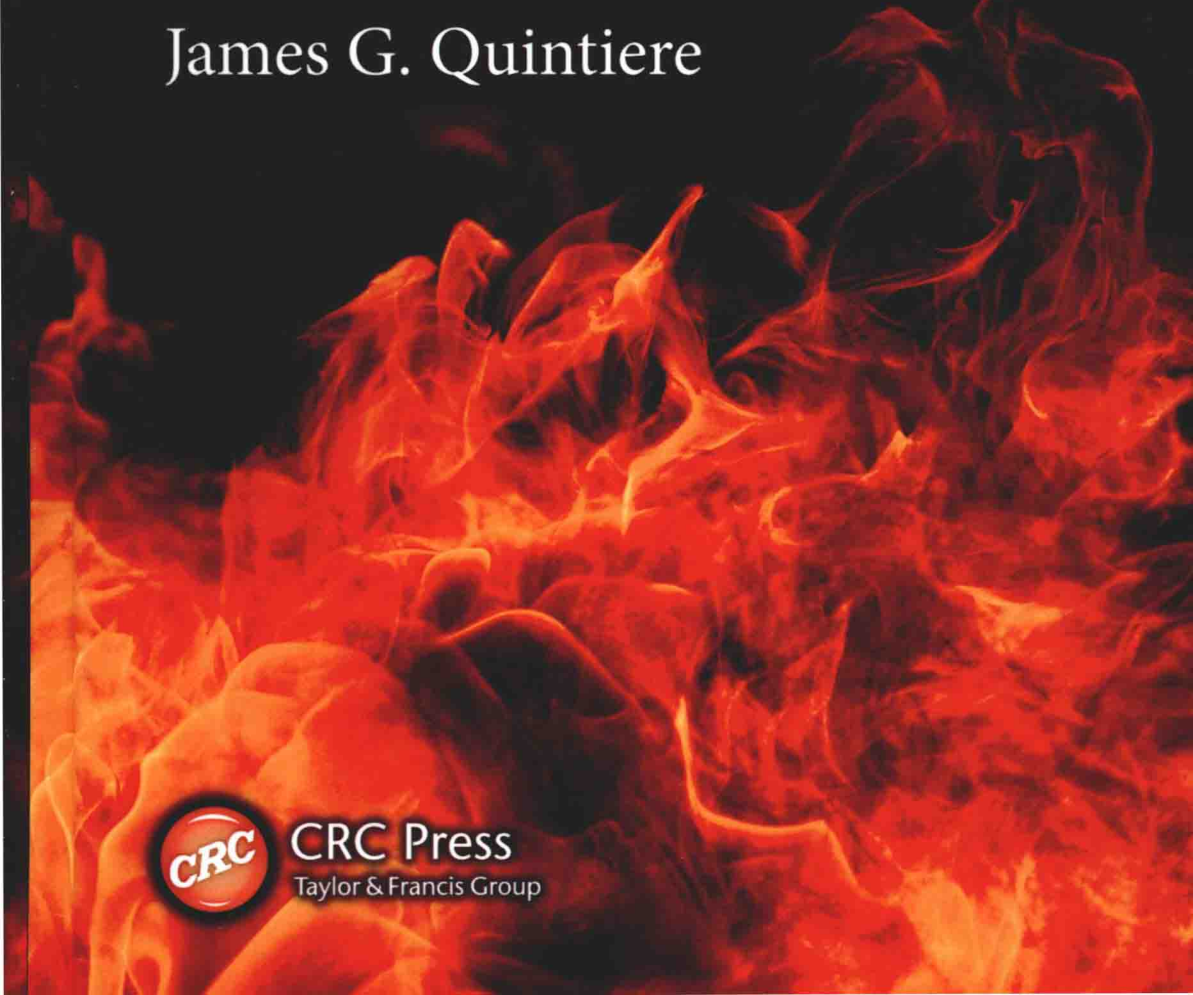
Principles of Fire Behavior

SECOND EDITION

James G. Quintiere



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Principles of FIRE BEHAVIOR

SECOND EDITION

To the memory of Philip H. Thomas, a friend, a mentor, and the father of fire science. He developed the science for many aspects of fire before others. He set the path.

Preface

The genesis of this book is early short courses given to fire investigators of the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) starting in 1992 at the University of Maryland, College Park. The material grew into a book by Delmar Publishers in 1997 within their series on fire and rescue books. The book received wide usage among institutions for the education of firefighters in the United States. Internationally, that use continued with a Korean translation in 2004 and a Japanese translation in 2009. The book was maintained as the basis in fire investigation training courses offered by the ATF for both federal and state investigators.

In early 2012, a new edition was submitted to Cengage (formerly Delmar), and it received positive reviews. Unfortunately, in July of that year, financial matters caused Cengage to terminate their fire series and this book. Now out of print, the book languished until 2015 when a fresh revision was prepared for Taylor & Francis Group/CRC Press.

The new edition aims to improve the introduction of science and math to the student. An Appendix has been added to introduce or review principles of algebra and to explain the need for mathematics in science. The book has been significantly expanded with new information and improved explanations. More examples are presented in each chapter with many related to real-world incidents. New figures and graphical results have been added, and the use of color in some should be a significant enhancement.

The student will gain knowledge of fire behavior through scientific principles and will achieve the means to make quantitative estimates for aspects of fire. The book is intended for those with a secondary education and is *not* a fundamental book for scientists and engineers. Introductions to the subjects of combustion, chemistry, heat transfer, and fluid mechanics will allow the student to learn what constitutes fire and its effects. The style of presentation is to offer simple explanations for component fire processes and to demonstrate the use of formulas to make estimations. The formulas are based on sound developments from fire research and can be tested potentially in classroom or field demonstrations. Carefully planned experiments can make much of the material in this book resonate with the students.

The book covers all aspects of fire behavior. Fire is combustion, and the student is introduced to premixed flames, the basis of ignition and explosions, diffusion flames that personify accidental fire, and smoldering, which slows down potentially deadly process. The rudiments of heat transfer are introduced with simple presentations for conduction, convection, and radiation. The concept of *heat flux* is introduced as that effect of fire that causes harm, damage, and ignition. Buoyant fluid flow caused by fire is explained in terms of the chimney and then related to flows in rooms and buildings. Fire growth involves the trifecta of ignition, flame spread, and continued burning. Each of these elements is explained in terms of simple ideas and with information on practical data and results. The student will learn how combustion products are generated in fire, why they can do harm, and how lack of air will affect the results. Flame dynamics are explained in the open and in compartments. The stages of fire development in a room are explained in terms of flashover and ventilation-limited fires. In all cases, aspects of these subjects are given in simple but sound mathematical formulas that allow estimations. The student will learn the elements of fire and how to express them in quantitative values in the same way measurements are used to describe how to build a house. The final chapter discusses case studies related to performance-based fire safety design and to real fire investigation cases. The material in the book aims to illustrate the aspects of these cases. Application and agreement with hypothesis may not establish truth, but the examples are given to illustrate an approach.

This book is intended for several audiences. It has been used in curriculum for students in firefighting to learn the behavior of fire. Although some have found the mathematics a distraction to learning, hopefully this new edition will ease or eliminate that effect. It is essential that firefighters adopt science to guide their practices. Short courses to fire investigators have given them an additional set of tools to defend their conclusions. In addition, the use of science and its education can support their credentials in expert testimony. While the book is intended for nonengineers, I have been told that the first edition has proved a ready reference for practicing fire protection engineers and to new engineers to the field. Hopefully, the second edition will be of added benefit. Finally, the average person can learn about fire using this book. Indeed, Professor Marino diMarzo has taught "Why Do Things Burn?" an honors seminar class for nonengineers at the University of Maryland College Park since 2010, using this book. That course is a mix of lectures and hands-on student experiments to reinforce learning. It cannot be emphasized more strongly that supportive experiments for the material in this book, safely conducted, can enhance and enliven the learning process.

Acknowledgments

Before the second edition was aborted at Cengage, reviewers had sent me their comments. The unfinished form of the manuscript put an extra burden on their task with corrupted text due to a poor conversion from the original. Their positive comments and constructive suggestions gave me encouragement to complete the final second edition. I am very grateful for their input and have tried to meet their suggestions. The reviewers include the following:

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Auburn Career Center
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California State University

Acronyms

AIT	Autoignition temperature
ASTM	American Society of Testing and Materials
BATF	Bureau of Alcohol, Tobacco, Firearms and Explosives
BTU	British thermal unit
CDT	Central Daylight Time
CFD	Computational fluid dynamics
FLETC	Federal Law Enforcement Training Center
FLIR	Forward-looking infrared
GDP	Gross domestic product
LFL	Lower flammable limit
NBS	National Bureau of Standards
NFPA	National Fire Protection Association
NIST	National Institute for Standards and Technology
PMMA	Polymethyl methacrylate
PRC	Product Research Committee
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl chloride
RH	Relative humidity
RMV	Respiration minute volume
SI	International System of Units
UFL	Upper flammable limit

Nomenclature

a	Constant associated with t-squared fires, $\dot{Q} = at^2$
A	Area
$A_{F,b}$	Area of fuel covered by the flame
AIT	Autoignition temperature
$A_o\sqrt{H_o}$	Ventilation factor
c	Distance in radiation fraction equation
c	Specific heat
c	Speed of light
CHF	Critical heat flux, threshold heat flux for piloted ignition
d	Diameter
d	Thickness
D	Diameter
D_b	Maximum fireball diameter
D_m	Mass optical density, pertains to visibility
D_o	Optical density per unit path length
E	Energy
f	Frequency
f	Friction factor
F_{12}	View factor
Fr	Froude number, ratio of momentum to buoyant force
g	Earth's gravitational force per unit mass, 9.81 N/kg
h	Convective heat transfer coefficient
H	Height
H_L	Smoke layer height
H_N	Neutral plane height
HRP	Heat release parameter, $\Delta H_c/L$
HRR	Heat release rate, same as $\dot{Q}$
I	Intensity of light
k	Thermal conductivity
$k\rho c$	Thermal inertia
l	Length
L	Heat of gasification
L_b	Maximum height of fireball
L_f	Flame length
L_v	Visibility, distance able to see through smoke
LFL	Lower flammability limit
m	Mass
m	Mass of fuel burned
$\dot{m}$	Mass loss or burning rate
$\dot{m}''$	Mass burning flux, or burning rate per unit area

$\dot{m}_{a,\max}$	Maximum air flow rate
m_{CO}	Mass of CO
$\dot{m}_{smoke}$	Mass flow rate of smoke
$M_{species}$	Molecular weight of species
p	Pressure
q	Heat
Q	Chemical energy
$\dot{q}$	Flow rate of heat
$\dot{q}''$	Heat flux, or $\dot{q}/A$
$\dot{q}''_{ext}$	External radiant heat flux from hot surroundings
$\dot{q}''_{flame}$	Incident flame heat flux
$\dot{q}''_{rr}$	Reradiation heat flux from ignited surface
Q	Energy from combustion
$\dot{Q}$	Combustion energy release rate of fire
Q^*	Zukoski number, $Q^* = \dfrac{\dot{Q}}{\rho_a c_{pa} T_a \sqrt{gD} D^2}$
RH	Relative humidity
s	Stoichiometric air to fuel mass ratio usually for complete chemical reaction
S	Surface area
t	Time
t_b	Duration of burning
t_1	Time to reach 1 MW in t-squared fire growth
t_{ig}	Time to ignite
T	Temperature
T_a	Air temperature
T_{ig}	Ignition temperature
T_s	Surface temperature
T_∞	Air or initial temperature
TRP	Thermal response parameter, Equation 4.4
UFL	Upper flammable limit
V	Flame spread velocity
V_f	Original fuel volume in fireball equations
w	Width of the fuel
x_f	Flame height
x_p	Pyrolysis length
X_r	Fraction of chemical energy radiated from flame
$X_{species}$	Mole or volume fraction of species in mixture
$y_{species}$	Mass of species produced in combustion per mass of fuel supplied
$Y_{species}$	Mass fraction of species in mixture
z	Vertical height
α	Thermal diffusivity, $k/\rho c$
δ_f	Flame forward heat transfer length in spread

ε	Emissivity
ΔH_c	Heat of combustion
Δ	Means difference
κ	Absorption coefficient of the smoke or flame
κ_s	Light extinction coefficient, Equation 8.10
λ	Wavelength
ρ	Density
ρ_b	Bulk density
σ	Stefan–Boltzmann constant, 5.67×10^{-11} kW/m^2-K^4
ϕ	Parameter in Equation 5.6
Φ	Equivalence ratio