A Novel Framework for Performance-Based Fire Safety in the National Building Code of Canada

by

Keith Calder

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Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner:	Dr. Brian J. Meacham Adjunct Professor Division of Fire Safety Engineering Lund University
Supervisor:	Dr. Elizabeth Weckman Professor Department of Mechanical and Mechatronics Engineering University of Waterloo
Internal Members:	Dr. Roydon Fraser Professor Department of Mechanical and Mechatronics Engineering University of Waterloo
	Dr. John Straube Associate Professor Department of Civil and Environmental Engineering & School of Architecture University of Waterloo
Internal-External Member:	Dr. Mahesh Pandey Professor Department of Civil and Environmental Engineering University of Waterloo

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The National Building Code of Canada (NBC) has traditionally applied a prescriptive-based framework to regulate fire and life safety in building design. While such a framework offers ease of enforcement, it limits innovative design. This framework transitioned in 2005 to be objective-based to provide greater design flexibility through clarity of intent, stopping short of a full shift to a performance-based framework due to concerns over challenges encountered by other jurisdictions during such transitions. 20 years later, the anticipated benefits of the shift to an objective-based framework have not been fully realized due to the lack of quantitative performance criteria and the reliance on primarily prescriptive and legacy-based acceptable solutions to define the acceptable level of performance for alternative designs.

Key factors in the development of the NBC that have limited design flexibility and ultimately its shift from a prescriptive to a performance-based framework are the “test of time” and “absence-based inference” methods traditionally used to confirm performance. These factors, together with generational amnesia, status quo bias, shifting baselines of performance, and the limited integration of fire science and fire engineering, have resulted in fire safety design being governed primarily by the application of regulations rather than by fire safety engineering principles. As the NBC becomes further entrenched in tradition, the design flexibility required to address the evolving challenges of modern construction and emerging environmental risks becomes increasingly limited.

To address these challenges, this thesis proposes a risk-based framework to facilitate the transition of the NBC from its current objective-based structure to a fully performance-based one. The proposed framework includes a historical analysis sub-framework to identify the rationale underlying the existing acceptable solution requirements, and a technical reconciliation sub-framework to align those requirements with current fire science and fire engineering principles, incorporating risk assessment methodologies to better quantify performance. It also includes a sub-framework, based on a modified IRCC hierarchy, that integrates the information identified and updated through the other sub-frameworks, establishing a clear and quantified link between the acceptable solutions and the societal objectives they are intended to achieve. By addressing factors in the development of the NBC that have limited its shift from prescriptive-based to performance-based, such as status quo bias, generational amnesia, shifting baselines of performance, and the limited integration of fire science and fire engineering, the proposed framework provides a structured approach that supports innovative design solutions while also achieving societal safety goals.

The efficacy of this framework is demonstrated through detailed case studies that review acceptable solutions regulating office occupant load, exit width, building size and type of construction, and spatial separation. Historical analyses of these acceptable solutions identified the passive ventilation basis for the office occupant load factors, the influence of military experience on minimum exit widths, the limitation of building size to align with fire service capability, and the conservative nature of the spatial separation requirements due to limited test data, among other notable details. Given the outdated and nontechnical nature of these findings, recommendations were made for their modification through technical

reconciliation with current test data, fire science, and fire engineering concepts. In particular, the finding that the flame front factor included in the spatial separation requirements may no longer be necessary is based on the results of a detailed risk-based analysis of incident radiant heat at a distance using an exterior venting flame model. The levels of the modified IRCC hierarchy were populated with information established from the historical analysis and updated through technical reconciliation for each case study, providing key basis information and quantified performance criteria within a risk-based structure that can be used to form a new and fully performance-based framework for the NBC.

The results of this study are relevant to various stakeholders by supporting designers and building officials through clarification of intent and definition of measurable performance, and by providing building code development organizations with a tool for regulatory reform that enhances the clarity, consistency, and adaptability of the fire and life safety requirements in the NBC. The results also provide the technical basis information necessary to facilitate a transition in the practice of fire and life safety design from the strict application of prescriptive regulations toward an engineering-based approach.

Additional research is recommended to evaluate the efficacy of the proposed framework through its application to other fire and life safety requirements in the NBC, to other aspects of the NBC, and to building codes in other jurisdictions. Further research should also focus on using the framework to quantify the technical risk basis necessary to support decision-making within a broader legal and regulatory context, thereby contributing to the continued advancement toward a performance-based NBC.

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I would also like to acknowledge several mentors throughout my career who have inspired my interest in researching the interrelationship between fire, history, and building regulations, including Dr. Jim Mehaffey, Kin Man Wong, Harold Locke, Glenn Gibson, Greg Sereda, and Peter Senez.

Dedication

This thesis is dedicated to the memory of R. Stirling Ferguson, Margaret Law, Simon Ingberg, and James Braidwood, and others whose contributions formed the technical foundations of fire safety and its integration into building regulations, and upon whose legacy this research is built.

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List of Abbreviations

Abbreviation	Meaning
ADB V2 BR187	Approved Document B, Version 2, BRE report 187
ADV1	First advanced model
ADV2	Second advanced model
ASET	Available safe egress time
ASTM	American Society for Testing and Materials
BRE	British Research Establishment
CCBFC	Canadian Commission on Building and Fire Codes
CCR	Code change request
CFAST	Consolidated Model of Fire and Smoke Transport
DCBE	Design and Construction of Building Exits
EMTC	Encapsulated mass timber construction
EBF	Exposing building face
EVF	External venting flame
F	Functional Statement
FAST	Fire and Smoke Transport
FHF	Floor radiant heat flux
FII	Ignition of all furniture items
FLED	Fire Load Energy Density
FSCT	Fire safety concepts tree
GD	Gradient descent
GDP	Gross domestic product
GHG	Greenhouse gases
HIRF-WG	High-Intensity Residential Fires Working Group
IBC	International Building Code
ICC	International Codes Council
IRCC	Inter-Jurisdictional Regulatory Collaboration Committee

Abbreviation	Meaning
JCSS	Joint Committee on Structural Safety
JFRO	Joint Fire Research Organization
JTGS	Joint Task Group on Sprinklers
LE	Life expectancy
LM	Levenberg-Marquardt
LMFA	Levenberg-Marquardt-Fletcher-Adam
LN	Law Notional
LHS	Latin hypercube sampling
LQI	Life Quality Index
NBC	National Building Code of Canada
NBFU	National Board of Fire Underwriters
NBS	National Bureau of Standards
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NKB	Nordic Committee on Building Regulations
NR	Newton-Raphson
NRC	National Research Council of Canada
NYBFU	New York Board of Fire Underwriters
NZ C/VM2	New Zealand Building Code Verification Method 2
OP	Fire and Structural Protection of Buildings Objective
OP1	Fire Protection of the Building Subobjective
OS	Safety Objective
OS3	Safety in Use Objective
PDF	Probability distribution function
PMF	Probability mass function
RPABC	Recommended Practice for Arrangement of Building Codes
RSET	Required safe egress time
SCC	Standards Council of Canada

Abbreviation	Meaning
SWTP	Society's Willingness to Pay
ULT	Upper layer temperature
UK	United Kingdom
UPO	Permitted percentage of unprotected openings
US	United States
VBA	Visual Basic for Applications

List of Symbols

Roman Symbols

Symbol	Definition	Unit
$\sqrt{k\rho c_p}$	Thermal inertia	J/m²·s$^{1/2}$·K
$\%\mathrm{UPO}$	Percentage unprotected openings	–
A	Exposing opening area	m²
$A\sqrt{H}$	Air flow factor	kg/m²
A_f	Floor area of the compartment	m²
A_h	Area of horizontal openings	m²
A_s	Area of sprinkler operation	m²
A_T	Internal surface area of walls and ceiling	m²
A_v	Area of vertical openings	m²
A_w	Area of ventilation openings	m²
C	A factor that depends on thermal inertia	h·m$^{3/4}$/kg
d	Distance	m
E	Emissive power	cal/cm²·s
ff	Flame front factor	m
G	Guide number	–
FLED	Fire load energy density	MJ/m²
h	Exposing plane height	m
H	Height of ventilation openings	m
H_c	Compartment height	m
I	Intensity of radiation	kW/m²
I_{crit}	Critical incident heat flux	cal/cm²·s
I_r	Radiometer measurement	cal/cm²·s
$\mathcal{J}$	Jacobian matrix	–
K'	A constant close to unity	–

Symbol	Definition	Unit
k_h	A constant	min·m²/MJ
L	Fire load	kg/m²
L_s	Minimum length of sprinkler design area parallel to the branch lines	m
LD	Limiting distance	m
$\mathrm{P}(X)$	The probability distribution function (PDF) or probability mass function (PMF) of the random variable X	–
Q_f	Fuel load	MJ/m²
T	Temperature	K
w	Exposing plane width	m
X	Random variable	–
x_n	Solution vector	–
x_{n+1}	Solution vector at the next step	–

Greek Symbols

Symbol	Definition	Unit
α	Dampening factor	–
ε	Emissivity	–
ε^*	Coefficient of emission	kW/m²·K⁴
σ	Stefan-Boltzmann constant	kW/m²·K⁴
τ_e	Equivalent fire duration	h
ϕ	Configuration factor	–
ϕ_{crit}	Critical configuration factor	–
ϕ_{eff}	Effective configuration factor	–
ϕ_o	Configuration factor of the openings to the radiometer	–
ϕ_{plane}	Planar configuration factor	–
λ	Dampening factor	–
π	3.14159	–

Symbol	Definition	Unit
$\nabla f(x_n)$	Gradient of the function f evaluated at x_n	Depends on f's output
$[\nabla^2 f(x_n)]^{-1}$	Inverse of the Hessian matrix of the function f evaluated at x_n	Depends on f's output

Other Symbols

Symbol	Definition
•	"and" gate
+	"or" gate

Chapter 1
Introduction

The National Building Code of Canada (NBC) is a model code adopted by provinces and territories to regulate building design and construction to achieve a minimum level of performance in the areas of safety, health, accessibility, fire protection, and the environment. This performance is achieved through designs that comply with “acceptable solutions,” primarily consisting of prescriptive requirements, with a few that are performance-based. The acceptable solutions have a long history of development that, in some cases, predates the first edition of the NBC in 1941.

Prescriptive requirements state the details of what “shall” be done but do not state why it should be done that way. In contrast, performance-based requirements state what “shall” be achieved but not how to accomplish it. Prescriptive requirements are structured to be measurable or observable, simplifying their application and enforcement, but this limits designs to within the bounds of those measurable or observable characteristics. On the other hand, performance-based requirements allow greater design (innovation) flexibility but are more challenging to enforce without an understanding of the concepts underlying the methods for verification of their performance. In this context, designers tend to favour performance-based design for its flexibility, whereas building authorities tend to favour prescriptive design for its simplicity.

The design constraints associated with prescriptive requirements have long been recognized. In certain instances where applied through literal interpretation, prescriptive requirements have resulted in impractical and even absurd design outcomes (Figure 1-1). To address these limitations and allow greater design flexibility, earlier versions of the NBC have permitted materials and designs not regulated by the NBC, where they could be shown to have provided an “equivalent” level of performance to the prescriptive requirements. However, other than very limited explanatory notes of regulatory intent, no further criteria or guidance were provided to assess equivalent performance. To address this lack of basis information, the development and approval of “equivalent” designs required agreement between designers and building officials on the acceptable level of performance and associated methods of verification. This process was often frustrated by the perception that any design not in direct compliance with the prescriptive requirements would inherently increase fire risk, frequently necessitating additional compensatory measures to be added in order to address these concerns.

As a result, despite the inclusion of the “equivalency” provision, the predominantly prescriptive nature of the NBC's “acceptable solutions,” combined with a lack of basis information, continued to constrain innovative design approaches, even as they became increasingly necessary to address environmental factors affecting the built environment.

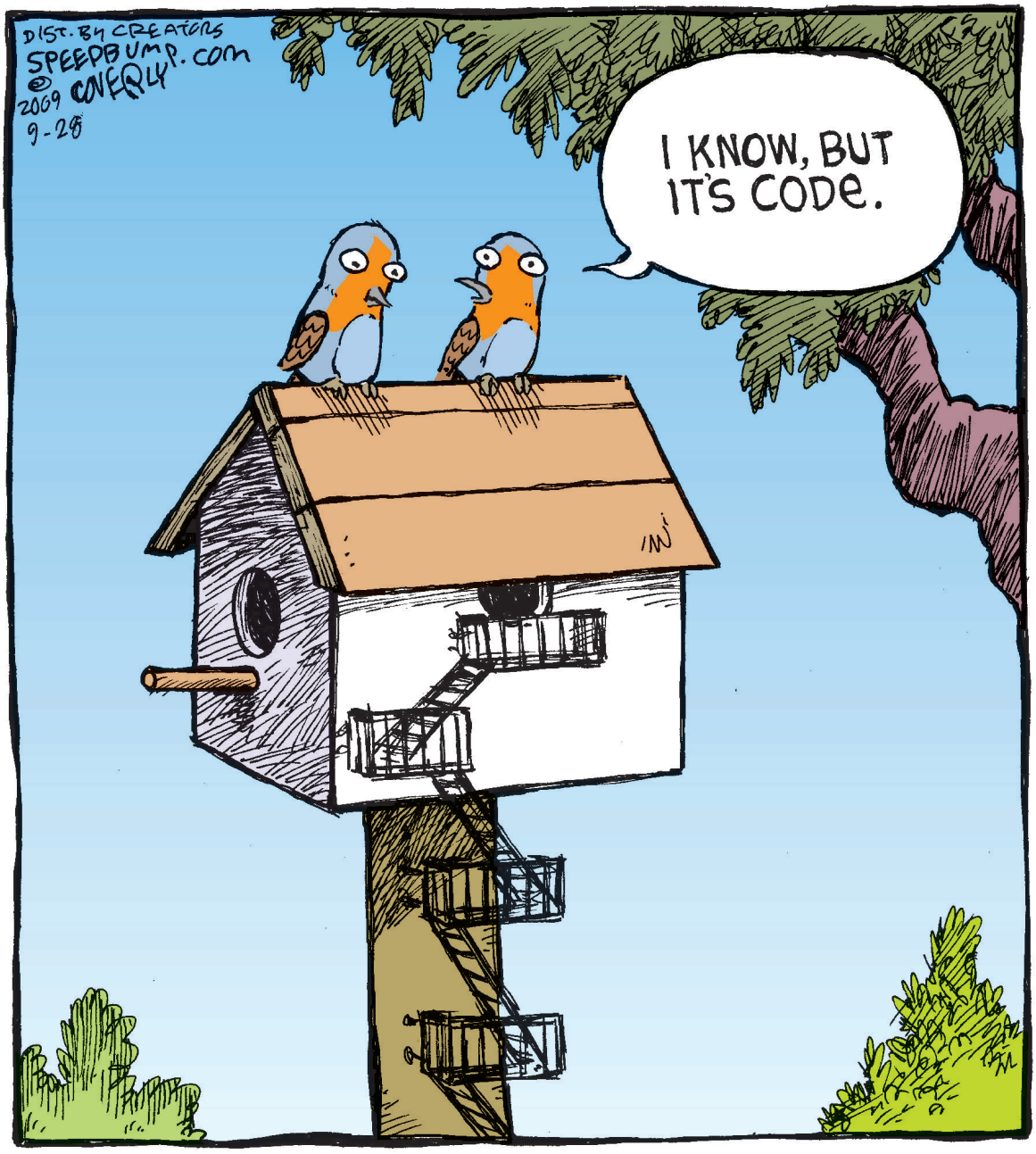


Figure 1-1: “I know, but it’s code,” by Dave Coverly [1]

To better address these evolving challenges, the framework of the 2005 NBC was restructured from primarily prescriptive-based to objective-based. Other countries prior to that time had transitioned from a primarily prescriptive-based framework for their building codes (i.e., New Zealand) to performance-based for similar reasons, but experienced challenges due to their codes only qualitatively defining the benchmarks of acceptable performance. This resulted in ambiguity and inconsistent interpretation of these benchmarks in developing appropriate designs, contributing to some notable design failures, such as New Zealand’s “leaky homes crisis.”

In recognition of these challenges and to mitigate their occurrence in Canada, the objective-based framework was structured in a similar fashion to a performance-based one, but it defined the existing "acceptable solution" requirements as the benchmark of acceptable performance. As part of this transition, qualitative performance criteria (objectives, functional statements, and intent statements), similar to those of other countries, were developed through a rudimentary top-down and bottom-up analysis of the acceptable solution requirements. The newly developed qualitative performance criteria were intended to improve upon the "equivalency" provision and, in doing so, facilitate more innovative designs through enhanced clarity of the intent of the acceptable solution requirements upon which the performance of these designs could be assessed.

Now, twenty years after the development and implementation of the objective-based framework of the NBC, the anticipated benefits have remained unrealized. Although efforts have been made to rationalize the existing requirements of the NBC to facilitate more uniform interpretation and reduce ambiguity, they have proved ineffective, providing only qualitative performance criteria. As a result, while linking the benchmark of acceptable performance to the legacy acceptable solutions may have lessened some of the challenges faced by other countries, it has ultimately continued to restrict innovative designs to be within the limits of those primarily prescriptive solutions, whose performance remains unclear. This limitation is becoming untenable in the face of significant and damaging environmental forces due to climate change, as design flexibility is increasingly necessary to address these forces.

Ideally, a present shift from the objective-based to a performance-based framework for the NBC would address yet unmet and emerging needs and enable greater design flexibility. However, achieving this shift remains challenging due to the absence of quantified "acceptable" performance criteria, as well as the lack of an appropriate framework and methods to verify the performance of alternative (innovative) designs. The primary objective of this thesis is to develop a novel framework that supports a direct shift in fire and life safety design by addressing key factors that have, up to this point, limited such a transition. These factors are examined in greater detail in the literature review presented in Chapter 3:

1. The first is the lack of quantitative performance criteria for the existing acceptable solution requirements, restricting the evaluation of alternative (innovative) designs and requiring their performance be demonstrated through a direct comparison to acceptable solution designs. Such comparisons are inherently limiting, may not adequately address fire risk, and are subject to approval from authorities having jurisdiction, who often prefer designs that more closely conform to the observable and measurable limits specified by the acceptable solution requirements.

2. The second is the long history of development of the existing acceptable solution requirements and their "test of time" performance that frustrates identification of quantifiable performance criteria. This is further exacerbated by generational amnesia, status-quo bias, the regulatory ratchet effect, and shifting baselines of performance. These factors have obfuscated and complicated the identification of the rationale underlying the development of the existing requirements that would otherwise facilitate the quantification of performance.

3. The third is the dominant approach to fire safety design through the application of the legacy acceptable solution requirements rather than fire science and fire engineering principles. This reliance is due to a lack of rationalization of the current acceptable solution requirements, imposing a more literal prescriptive application than a conceptual, performance-based one. Consequently, this approach limits innovation. In contrast, the less common approach utilizes fire science and fire safety engineering principles to accomplish designs that achieve the intent of the acceptable solution requirements. This approach provides a more direct and quantifiable link between fire risk and mitigation strategies, but requires a technical re-examination and updating of the existing acceptable solutions to achieve such a link.

In recognition of these limitations, realizing the shift from objective-based to performance-based design principles first requires a historical assessment of the existing NBC fire and life safety requirements to establish the key risk factors underlying their development. Following this, these factors need to be reconciled with modern fire science and fire engineering principles. This should be done using structured risk analysis methods that consider broader societal characteristics and provide a more optimized means to validate and evaluate acceptable performance than a more traditional “test of time” approach. The criteria derived and established from such an analysis can then be populated in a risk-structured hierarchy linking broad societal goals, such as fire safety, to detailed regulatory solutions. Devising a novel framework to: (a) conduct a historical assessment, (b) reconcile key risk factors with more modern fire science, and (c) populate the factors in a structured hierarchy that opens appropriate discussion toward overcoming these gaps forms the main objective of the present research. While it is not the intent of the framework, or this work, to define risk performance indices, use of the new framework will facilitate the transition of the NBC from objective-based to performance-based. The proposed framework is discussed in Chapter 4, with three case studies presented in Chapters 5 to 7 to demonstrate its efficacy toward this end.

Given the extensive history of development of the fire and life safety acceptable solution requirements and the importance of this history in establishing the quantitative performance criteria required for transitioning the NBC to a performance-based framework, their background is reviewed in the following chapter.

Chapter 2
Background

The fire and life safety requirements of the NBC have a long history of development that impacts their continued use and any further development, especially without an understanding of their intended level of performance. To provide background for the challenges explored in this research, the following sections outline the history and evolution of the fire and life safety requirements in the NBC, including early international influences, the limited incorporation of fire science and fire engineering concepts, and the current objective-based framework of the NBC. This historical account is not common knowledge, but is the result of extensive research conducted by the author of this thesis.

2.1 Building Code Development and History

This section explores the historical development of key fire and life safety regulatory concepts that form the basis of those in the NBC, tracing their origins from ancient Rome through London and the United States to the current Canadian regulations.

2.1.1 Early History

Archaeological evidence of humans' practical use and control of fire dates back to at least the end of the Middle Pleistocene era (approx. 500,000 years ago) [2] and played a significant role in the advancement of human evolution [3]. Fire is a beneficial and even a necessary part of our modern world. We use it to cook food, power vehicles, heat our homes, and even as a hub for social gatherings. However, when unintended and uncontrolled, fire can become a hazard with dramatic effect and significant undesirable impact (i.e., more recently the Grenfell Tower fire and the Los Angeles wildfires). We recognize the impact through injury, loss of life, and property damage (risk) and seek ways to avoid such losses in the future through building regulation (codes). Building codes are not a new concept. Many claim [4-10] The Code of Hammurabi, circa 1750 BC, was the first building code and even the first "performance-based" building code. However, while The Code of Hammurabi addresses building construction, it is more accurately characterized as a punitive (criminal) code rather than a preventive building code [11]. More preventive codes were developed later.

Several conflagrations[1] affecting significant areas of the city of Rome between 390 BC and 64 AD prompted the development of some of the earliest known building regulations [14, 15]. These early regulations were structured to control the type of construction, building size, and building separation.

[1] For purpose of regulatory development, conflagration means the burning of several buildings to almost complete city involvement in fire [12, 13].

They were developed recognizing basic fire safety principles of limiting quantity/use of combustible materials and the provision of fire containment. However, at the time, these fire safety principles were understood through experience [11], rather than more formal scientific methods [16].

Early passive fire mitigation measures were supplemented by active firefighting. Organized firefighting dates back to Ancient Egypt and Rome. The first Roman fire brigade was organized for financial gain by Marcus Licinius Crassus [17], who lived between 115 BC and 53 BC. It was a private brigade dispatched to burning buildings where a price for service was negotiated before commencing suppression activities. This concept was later developed into a public brigade called the Vigiles by Augustus in 6 AD to fight fires and limit the potential for conflagrations in Rome [18]. They were equipped with buckets, axes, hooks, and ladders. There is some indication that the Romans may also have utilized a crude form of fire pump called a sipho resembling a syringe [19] and seemingly based on a rudimentary understanding of hydraulics.

2.1.2 London

Numerous conflagrations during the early history of London prompted regulatory development, with intent to control fire growth and spread. It is interesting to note that some of these fundamental principles, building upon those developed earlier in Rome, persist in our building codes to this day.

2.1.2.1 Firewall (Partywall)

One of the earliest London conflagrations occurred in 1087 and destroyed most of the city, including St. Paul's Cathedral. Another occurred in 1135, again resulting in the destruction of most of the city [20]. Over that period of time, the buildings in the greater part of London were constructed of wood and roofed with straw or similar material [11, 20]. In response to the large conflagrations, an ordinance (Assize of Buildings) was issued by the then Mayor of London, Henry Fitz-Aylewin, in 1189 [20]. This ordinance required that houses be built of stone with tile roofs. Due to limited space to accommodate the number of houses in the city, adjacent houses were required to be separated by a stone wall three feet in thickness and sixteen feet in height (substantial barrier) [20].

Similar to Rome, the London ordinance recognized certain continuing principles of basic fire safety around limiting use of combustible materials and adding measures to promote fire containment between buildings. However, where Rome chose to contain the spread of fire primarily through building separation, London accomplished a similar intent through requirement of a substantial barrier due to space limitations. This substantial barrier is the predecessor to what the building codes today refer to as a "firewall" [21]. In addition, records of London in 1189 indicate a series of rules for preventing loss of life and destruction of property by fire. Specifically [19, p. 317]:

1. "That all persons who dwell in great houses within the ward have a ladder or two ready and prepared to assist their neighbours in case misadventure should occur by fire."

2. “That ten reputable men of the ward, with ten aldermen, provide a strong crook of iron with a wooden handle, together with two chains and two strong cords, and that the beadle has a ‘good horn, and loudly sounding’.”

Following the Great Fire of London in 1666, the requirements for firewalls (referred to as party walls at the time) evolved through subsequent building acts between 1667 and 1774 [22, 23], allowing brick as an alternative to stone, reducing the required thickness of the wall, and aligning the height to be several feet above roof height [22]. The firewall (party wall) was intended to contain fire to a single building and thus limit the occurrence of conflagrations [11]. This was practical as most domestic and business activities at the time were carried out in smaller houses [24] and a fire was contained either to the house of origin or was within the capability of the responding fire service to control it, recognizing a balance between passive and active fire mitigation measures. The practicality of the solution, however, began to change with increased population, the advent of rapid and poor construction, and building specialization (larger buildings). These resulted in larger fires that were more difficult to contain and actively control [25].

2.1.2.2 Early Performance Testing

Alternative approaches were being considered even by the 1770s to design building elements to limit fire spread and protect occupants from fire. Methods developed by Mahon and Hartley [26, 27] in the 1770s specified that protection should be applied to the underside of wood floor assemblies to limit ignition and confine a fire to one room of a house. The degree of required protection was demonstrated through experiments where the lower room of a house was filled with combustible kiln wood and shavings, and ignited to become fully involved, while the experimenter and invited guests were “coolly and securely indulging in the luxury of ice-creams in an upper apartment” [26, p. 190]. Numerous tests were conducted into the 1780s based on the concept of igniting a lower room filled with wood and limiting the spread of heat and fire to the occupied room above by using the protected wood floor assembly. In one instance during testing, Hartley entertained the royal family, several nobility, and the lord mayor of the corporation of London in the room above the test room [28]. While these appear to be precursors to more modern fire performance test methods, the amount of combustibles was not specified for any of the tests other than to describe the rooms below the test rooms as “nearly filled with combustible material” [27, p. 151], nor was the duration of the tests noted.

These early tests did recognize the merits of a rudimentary scientific approach to demonstrate the efficacy of a construction solution (protected floor assembly) to limit the impact of a severe fire (fully developed compartment fire) on persons above. As such, this example is one that signals the shift from experiential to reproducible and measurable methods of demonstrating performance solutions to mitigate the impact(s) of fire.

2.1.2.3 Building Size Limits (Cubic Capacity)

Around this same time, recognizing increases in building size, the 1774 London Building Act limited the total floor area of certain types of buildings [23]. Warehouses were permitted to be up to 35 squares in

area [23], where each "square" represented 100 square feet (3,500 ft²). The same area limit was included in a subsequent building act in 1830, which also limited building height to 60 feet [29].

The 1844 Metropolitan Act of London, a set of building requirements, introduced the "cubic capacity concept." This concept limited building size as a function of volume [30] rather than the height and area limits of the previous Acts (building regulations). The largest volume of 200,000 cubic feet was permitted for warehouses [30]. This is similar to the combined height and area of 210,000 cubic feet from the 1830 Building Act [29]. The rationale for the cubic content concept is provided by Braidwood, the first municipal fire chief for the City of London (the London Fire-engine Establishment) [31], relative to firefighting water supplies as follows [32, p. 310]:

> *If water can be obtained at an elevation, pipes with plugs or fire cocks on them[2], are preferable to any other mode at present in use. The size of the pipes will depend on the distances and elevation of the head, and also on the size of the buildings to be protected. It may be assumed as a general rule, that the intensity of a fire depends, in a great measure, on the cubic content of the buildings.*

In his comment, Braidwood was correlating fire service capability (water delivery) to fire size, which was related to building size [32]. He later drew a more direct correlation between building size and fire service capability as follows [33, p. 12]:

> *With a well organized and properly equipped fire brigade it is found that sixty feet is the greatest height at which a building can be quickly protected, and that the cube of 60, or 216,000 cubic feet, is the largest cubical capacity which can be protected with reasonable hope of success after a fire has once come to a head.*

This new, more evidence-based cubic capacity limit was included in the 1855 Metropolitan Building Act [34, 35], and is another example of the incorporation of science (hydraulics), albeit not specifically fire science, in building codes. However, these building size limits were often disregarded, resulting in buildings (typically warehouses) of larger capacity. Such buildings were of significant concern to Braidwood, who wrote letters to government officials warning of the potentially severe consequences [31]. A fire eventually occurred in a large Tooley Street warehouse building on June 22, 1861, which burned for two weeks, and resulted in Braidwood's death [36].

Following the Tooley Street fire, London insurers began to charge increased rates in the late 1860s and early 1870s as a function of cubic capacity limits exceeding those permitted by the Metropolitan Building Act; however, they allowed an increase up to a total of 300,000 cubic feet for existing buildings without a corresponding increase in insurance rates [37].

[2] Plugs and fire cocks are early versions of what today are termed fire hydrants [32].

2.1.3 United States

City populations in North America boomed throughout the nineteenth century, resulting in rapid development and densification in city centres. Despite increasing awareness of fire control overseas, building construction methods often outpaced the development of requirements intended to limit fire risk. Buildings were built in close proximity, without limit on height, area, exterior openings, materials of construction, and often with interconnecting storeys. The consequence of this was an increase in conflagrations, characterized by the burning of multiple buildings beyond the capability of the local fire department. These conflagrations had a significant economic impact on the US insurance industry, initiating the study of fire losses, fire hazard assessment, and associated systems of fire loss control and regulation. Due to their importance as a basis for the present day regulatory framework, these systems are discussed in the following sections.



Figure 2-1: Photograph showing the aftermath of the Great Chicago Fire [38]



Figure 2-2: Photograph showing the aftermath of the Great Boston Fire [39]

2.1.3.1 Insurance Rating System

Two of the most significant US conflagrations occurred just over a year apart in Chicago on October 10, 1871 (Figure 2-1), and in Boston on November 9, 1872 (Figure 2-2). The extent of damage and proximity

in time of these conflagrations had a significant economic impact on the insurance industry. With their industry-wide goal of increasing profit by reducing fire losses (conflagrations), this attracted much attention from insurers to the substandard conditions of construction in cities across the US [40]. Some key concerns were expressed by British insurers who, for this very reason, had considered withdrawing their agencies from the United States just prior to the occurrence of the Boston conflagration [40].

Following these conflagrations, and to more effectively reduce fire losses, the US insurance industry developed an insurance rating schedule (the "Schedule") based on factors considered through experience to be associated with fire risk. The Schedule was characterized as follows [41, p. 21]:

> *A schedule may be defined as a method of assessing the insurance tax by computing this tax by means of a series of charges, which charges shall have the effect of penalizing those factors in a property which are known to cause or increase the fire loss, and crediting those factors in a risk which are known to be helpful in preventing or retarding fire loss.*

This was not the first instance of charging different insurance rates as a function of building use and construction. The first fire underwriters in Europe (late 1600s) differentiated wood construction as a higher fire risk than other materials [41]. Following experience from real fires (the early 1700s), insurance companies recognized differences in fire risk as a function of building use and categorized these differences as "common," "hazardous," and "doubly hazardous," and charged rates accordingly [41]. This approach identified potentially hazardous fire properties of materials based on experience rather than an understanding of their fundamental combustibility characteristics (fire science).

The Schedule further expanded these concepts and simplified detailed consideration of the scientific complexities of fire by relations of fire hazards established through experience [42], rather than through application of any apparent fundamental understanding of fire behaviour. In this regard, the Schedule defined a "Standard Building" as a benchmark having specific characteristics representing the broad range of known fire risk factors, including building use (occupancy), type of construction (fireproof and non-fireproof), building size (height and area) and building proximity (exposure). The Schedule also recognized the benefits of certain safety features such as noncombustible (fireproof) construction, water supply, sprinklers, and fire service access to building faces [41-44]. Accordingly, building fire performance was embodied in these characteristics and quantified through comparison to the benchmark "Standard Building" performance, known through experience.

One of the first references to a "Standard Building" was by the New York Board of Fire Underwriters (NYBFU) in their rate schedule from 1873 [45]. This schedule applied specifically to "Standard Private Warehouses" and "Storage Stores" and included rate variations based on certain building height and area limits; wall, roof, cornice/gutter, parapet wall, and floor construction; provision of iron shutters; openings in floors; and width of streets, all of which remain important to fire safety in modern day buildings. The specific area and height limits were 5,000 ft^2 and 60 feet, respectively [45], combining for a cubic capacity of 300,000 cubic feet. The basis of these limits was not explicitly stated, as is the case for many requirements in our current codes. In similar fashion to the present requirements as well, it likely originated and was held over from London, given that the insurance industry in London at that time

allowed warehouses up to 300,000 cubic feet (60 feet in height) without an increase in standard insurance rates for existing buildings [37]. It was further driven by the interest from London-based insurance companies for construction reform following the Boston conflagration [40]. Additional rationale supporting the link between the London building size requirements and those of the NYBFU is detailed in a report by Calder [46]. One such example from the "Insurance Times" of New York in 1880 notes the following [47, p. 729]:

> *An architect in this city said to me not long ago, speaking of large buildings — I think it was apropos of one of these large buildings that burned here: "A building that is more than 50 by 100 feet, or 5,000 square feet on the surface, is a dangerous building to insure." That is to say, it is dangerous, for it can not be reached, and will be a total loss. He quoted the authority of the Chief of Brigade in London, for this very statement that 50 by 100 feet was as large a building as he wanted to cope with.*

Several insurance rating schedules were developed between the 1870s and early 1900s, incorporating additional industry experience with a broader range of known fire hazards [41, 42].

2.1.3.2 Standardized Performance Testing

The concept of demonstrating the performance of a system re-emerged in the late 1800s as a solution to the limitations of material specification for fire safety. This coincided approximately with the recognition that specifying fireproof construction was not the solution to limit conflagrations that it was expected to be, and outcome-based solutions were sought. Therefore, performance was demonstrated initially through outcome-based, ad-hoc testing, which evolved over a century to become more standardized (i.e., fire performance testing) in an effort to foster consistency of test results, comparisons, and interpretation.

One of the earliest examples of standardized performance testing took place in Denver, Colorado in 1881 (the "Denver Tests") during a competitive selection of a fireproof floor assembly for the Equitable Building of Denver [48]. The floor assembly proprietor, who had the highest bid, claimed that his floor assembly was the most fireproof and suggested a comparative test to other proprietor's assemblies to prove his claim. A testing regime was developed to evaluate the performance (integrity) of a floor assembly when exposed to severe fire conditions and structural loading, to the point of structural failure. The results of the testing, based on the performance criteria, confirmed the claim of the proprietor with the highest bid that his floor assembly was actually the most "fireproof."

The Denver Tests were successful in applying comparative performance testing to demonstrate achievement of an objective without specification of type or configuration of materials. This was a significant step towards facilitating greater design flexibility in an environment of increasing change. It also built upon the earlier performance testing through the consideration of a time-temperature relationship characteristic of a severe fire (i.e., fully developed compartment fire). The Denver Tests established the basis for the development of further standardized fire testing methods as a means of demonstrating fire performance. This approach evolved through the early half of the 20th century, and remains a practical and integral part of fire and life safety requirements in the NBC today.

2.1.3.3 Model Building Codes

Many cities in the US established their own building bylaws from the late 1700s to the early 1900s [49, 50], in response to significant conflagrations [51]. Over time, these bylaws were considered unsuitable [52] as they were specific to the interests, environmental conditions, and available construction materials of each city and, therefore, differed from city to city across the US. This limited uniformity and impacted manufacturing and trade [53], highlighting the need for a nationwide building code.

At the same time, the National Board of Fire Underwriters (NBFU), the first national association of insurance companies in the US [54], which had been involved with "rate-making" until 1878, shifted to become an educational and technical resource for the insurance industry [55]. One of the objectives was then to improve building construction in the United States through the development of a model building code [55]. The first model building code was specific to medium-sized cities and was published in 1893 [56]. A more general model building code was published in 1905 [57], and is considered the first model building code in North America. The 1905 NBFU Model Building Code was primarily based on specification of particular fire safety design features, with limited reference to performance testing for material strength and fire containment [57].

While not explicitly stated, there are striking similarities between the 1905 model building code and the insurance rating schedule. They both include a common relational fire hazard framework, common hazard and mitigation factors, similar building size limits, and credits for sprinklering of buildings. This is not surprising, given that both originated from the insurance industry, which had business interests in reducing large fire losses ("fire-waste"), as well as a significant technical and experiential knowledge base associated with fire losses and building construction. At a time when only one-sixth of buildings in large cities were rated using an insurance schedule [55], it was expected that the industry would benefit from a model building code that would apply to all buildings, whether insured or not, and bring about more uniform construction, and thus reduce fire losses. However, the requirements of the NBFU model codes really were primarily based on fire loss experience, since they closely followed the intent in development of the insurance rating schedules and associated "standard building" concept.

This began to change in the 1915 edition of the NBFU model building code that incorporated explanatory notes providing a rationale for certain requirements that, in some cases, aligned with earlier more scientifically-based principles [58]. One such note specific to a 55 feet height limit and 5,000 ft² area limit for a building of "ordinary" construction stated the following [58, p. 52]:

> *It is generally conceded that five stories is the maximum height to which water can be thrown effectively by a fire department from the street level, and that 50 feet is the maximum distance inside a building which can be reached by a stream through a window.*

The building size limits in the 1915 NBFU model code are consistent with those from London in the 1870s, and those of the NYBFU insurance rating schedule from the same time period. Subsequent editions of the NBFU model building code were published until 1955 [58-63], incrementally recognizing the need for broader performance-based testing but maintaining the primarily prescriptive legacy requirements.

The NBFU model building code was intended as a guide to the drafting of local ordinances. Being insurance-based, it primarily addressed matters of insurance interest, and not necessarily all matters of interest to cities, including such subjects as sanitation [58]. In addition, the First World War caused disruption of the building industry and a subsequent housing shortage[3], partly due to federal government intervention impacting transportation, fuel and labour availability [53]. This disruption was studied by a US Senate Committee [53] and one of the key observations and recommendations was [64, pp. 2, 57]:

> *The building codes of the country have **not been developed upon scientific data [emphasis added]**, but rather on compromises; they are not uniform in principle and in many instances involve an additional cost of-construction without assuring more useful or more durable buildings.*
>
> *…*
>
> *At the present time there is a great variety of requirements in the building codes of the different cities and States. A study of these codes and experience under them would be of great service in preparing the material for the drafting of a building code which would be as nearly uniform as the varying conditions in the different cities would permit.*

Following this recommendation, the US federal government, through the Department of Commerce and the National Bureau of Standards (NBS), formed a Building Code Committee. This Committee was charged with the development of a set of model building regulations, the "Elimination of Waste Series" [65-72], intended to realize efficiencies from consistency in construction, materials, and regulation throughout the country [66]. One of the tasks of the NBS Building Code Committee was to study existing building codes, including the NBFU model code, relying on past experience to address future incidents and undesirable conditions.

To this end, many of the requirements in the Elimination of Waste Series are similar to those of the NBFU model code (and other similar codes at the time). This lack of change is not surprising given the chair of the NBS Building Code Committee, Ira Woolson, was significantly involved with the development of the NBFU model building code requirements [73] as well as participating in the development of other codes and standards. Many others involved in the process were also prominent fire insurance representatives.

The NBS Elimination of Waste Series included a publication of "Recommended Practice for Arrangement of Building Codes," (the RPABC) based on a detailed review of the content and structure of many existing building codes throughout the US at the time (early 1920s) [71]. The RPABC made two notable recommendations to address challenges experienced with the application of prescriptive requirements. The first recognized the inflexible nature of these requirements, noting that [71, p. 16]:

> *A code, no matter how carefully prepared, will need further interpretation…The Department of Commerce building code committee advocates publication of an appendix*

[3] The housing shortage in the US at that time is not dissimilar to what Canada is experiencing today.

with all codes, which will provide in part for such interpretation and aid in supplying the data upon which changes should be based.

To overcome this inflexibility, the second recommendation promoted the concept of performance in how requirements are structured [71, pp. 19, 20]:

It is recommended that whenever possible requirements take the form of prohibitions forbidding the dangerous practices it is desired to prevent, rather than directions for the methods or materials deemed satisfactory.

…

[w]herever possible, requirements should be stated in terms of performance, based upon test results or service conditions, rather than in dimensions, detailed methods, or specific materials. Otherwise new materials, or new assemblies of common materials, which would meet construction demands satisfactorily and economically, might be restricted from use, thus obstructing progress in the industry. It is desirable that opportunity exist for establishing the merits of new or untried forms of construction. Compliance may be established by tests made under the building official's supervision, or by presenting evidence that the prescribed standards of performance have been met elsewhere under competent disinterested control.

The practical application of these recommendations in subsequent model building codes in the US allowed building officials to accept "new materials or modes of construction" [62, p. 5], that are demonstrated to provide an "equivalent" level of performance (achieve the intent) as the code [62, 74-76], and also brought about an increased reference to performance tests.

2.1.3.4 Fire Load and Containment

The term "fireproof" was used in insurance rating schedules, early city building ordinances, and the first editions of the NBFU Model Building Code to describe assemblies of noncombustible materials. The 1905 NBFU Model Building Code included the following description of fireproof construction [57, p. 141]:

constructed with walls of brick, stone, Portland cement concrete, iron or steel in which wood beams or lintels shall not be placed, and in which the floors and roofs shall be constructed with rolled wrought iron or steel floor beams.

At the same time, the concept of "fire-resistance" was being developed, and was based more on fire performance than on material properties. This concept was originally considered in London in the 1870s, but evolved significantly in the US between 1880 (Denver Tests) [48] and the 1920s [77-79]. In the US, this was driven, at least in part, by a large conflagration that occurred in Baltimore on February 7 and 8, 1904. Investigations of fire-damaged buildings were conducted by the Committee on Fire-Resistive Construction of the National Fire Protection Association (NFPA) [80]. Due to combustible contents [80], fire was observed to have spread between buildings of construction that, at the time, was deemed to be fireproof. From this, the committee concluded that [80] fireproof construction is a "misnomer" and highlighted the

importance of fire-resistive construction, which was intended to provide a performance-based (by testing) physical barrier to limit fire spread.

The degree of fire-resistance of a building element was determined, through testing, by its ability to support a load and limit the passage of flame for a certain period of time when exposed to increasing temperature (time-temperature curve). The time-temperature curve was intended to represent severe fire conditions, and evolved over several years, with a more standard version established in 1916 and published in a test standard by the American Society for Testing and Materials (ASTM) in 1918 [81]. This time-temperature curve has remained unchanged since that time, and still remains in the current editions of the US E-119 test standard [82], and the Canadian CAN/ULC-S101 test standard [83]. The time-temperature curve is arbitrary, and not directly representative of the time-temperature behaviour of actual fires understood today. Instead, it has become a means to establish the comparable performance of different building construction and assemblies [82].

The fire-resistance test was one of the earliest attempts to incorporate fire performance in building regulations beyond a reliance on basic material properties. The combination of fire-resistant floor and wall assemblies (barriers) allowed for the development of the "fire compartment concept" to provide a measured region of containment of fire and limit its growth and spread within a building.

Studies conducted by S.H. Ingberg at the National Bureau of Standards in the United States between the 1920s and 1940s identified that the temperature histories of actual room fires differed from the standard time-temperature curve [84, 85]. To overcome this, Ingberg related the "burn-out" of varying quantities of combustible fuel (contents) to times associated with the standard time-temperature curve through fire tests [84]. For this, he conducted numerous complete burn-out fire tests of varying fire load quantities and correlated the results of those tests with the standard time-temperature curve through an equal area comparison. The equal-area fire-severity hypothesis proposed that the area beneath a time-temperature exposure curve was a measure of the intensity or severity of a fire, and all fires with equal-area exposures were equally severe [79]. Ingberg's results are summarized in Table 2-1.

Table 2-1: Complete Burn-out Correlation Results [84]

Fire Load (lbs/ft^2)	**Equivalent Fire Resistance Test Time (hours)**
10	1
20	2
30	3

Ingberg continued his research into the 1950s through additional fire tests and surveys of the combustible fuel load of certain occupancies [86]. He provided a basic correlation between combustible fire load and fire-resistance (severity), rather than a direct comparison between the time-temperature curve and temperatures of actual fires. This research enhanced the fire-resistance performance test by forming a relationship between the fire hazard, as correlated to combustible content of major occupancies

(risk characterization), and the degree of fire-resistance required to contain burn-out of those contents, and thus prevent fire spread to adjacent areas (risk mitigation). This is one of the earliest fire models, utilizing a basic understanding of fire behaviour to predict outcomes.

2.1.3.5 Life Safety

Up to the early 1900s, with the exception of theatres, building codes were primarily concerned with property protection rather than life safety. This was likely an artifact of the origins from the insurance industry with consequent focus on property protection in both model and city building codes of the time.

Life safety became a more significant factor following the Triangle Shirtwaist Factory fire that occurred on March 25, 1911, resulting in 146 deaths (Figure 2-3). A Factory Investigation Commission was established on August 17, 1911, in part to examine [87, p. 14]:

> *the character of the buildings and structures in which [sic] manufacturing and business takes place, and the laws and ordinances regulating their erection.*

The Commission's attention was substantially focused on fire and life safety in factory (manufacturing) buildings, and part of their mandate was to "compel the attendance of witnesses and the production of books and papers" [87, p. 11]. Expert witnesses were deposed, as well as the commissioning of papers, including several by H.F.J. Porter, who had firsthand knowledge of occupant evacuation dynamics based on his experience conducting fire drills and staged evacuations of factory buildings in the City of New York, among other cities, the decade leading up to, and following the Shirtwaist Fire [88-92].

The NFPA approved the formation of a Committee on the Safety to Life (the "Committee") on June 23, 1913 [93]. One of the primary purposes of the Committee was to "consider additional standards on safety to life with particular reference to exit facilities and housekeeping methods" [93, p. 66], and develop associated regulations. The formation of this Committee followed the Triangle Shirtwaist Factory fire by less than 2 years, and initially focused on life safety in factories. Though not explicitly stated in the NFPA committee minutes, it is assumed that the Life Safety Committee was formed in response to the Factory Investigation Commission's report of a lack of adequate exit facilities in buildings.

The NFPA Life Safety Committee worked for 10 years to develop the first tentative edition of the NFPA "Building Exits Code," which was published in 1924 [94]. The scope of this NFPA Building Exits Code is stated as follows [94, p. 4]:

> *This Code covers the construction, arrangement and use of exit facilities necessary to provide safe means of egress from structures, together with such features of construction and protection as have bearing on safety of egress.*

In the early 1930s, the NBS Building Code Committee, responsible for the Elimination of Waste Series, undertook a study of exit requirements in cooperation with the NFPA Life Safety Committee [70]. The NBS Building Code Committee also conducted studies of existing exit facilities and statistical analyses of the exit flow rate of persons [70]. This is an early example of the consideration of human anthropometrics to inform building code development. The last of the Elimination of Waste Series, "Design and Construction

of Building Exits," was published by the NBS in 1935 [70] and incorporated many of the same requirements as the NFPA Building Exits Code of that time [95], including explanatory notes on the rationale for many of the requirements as well.

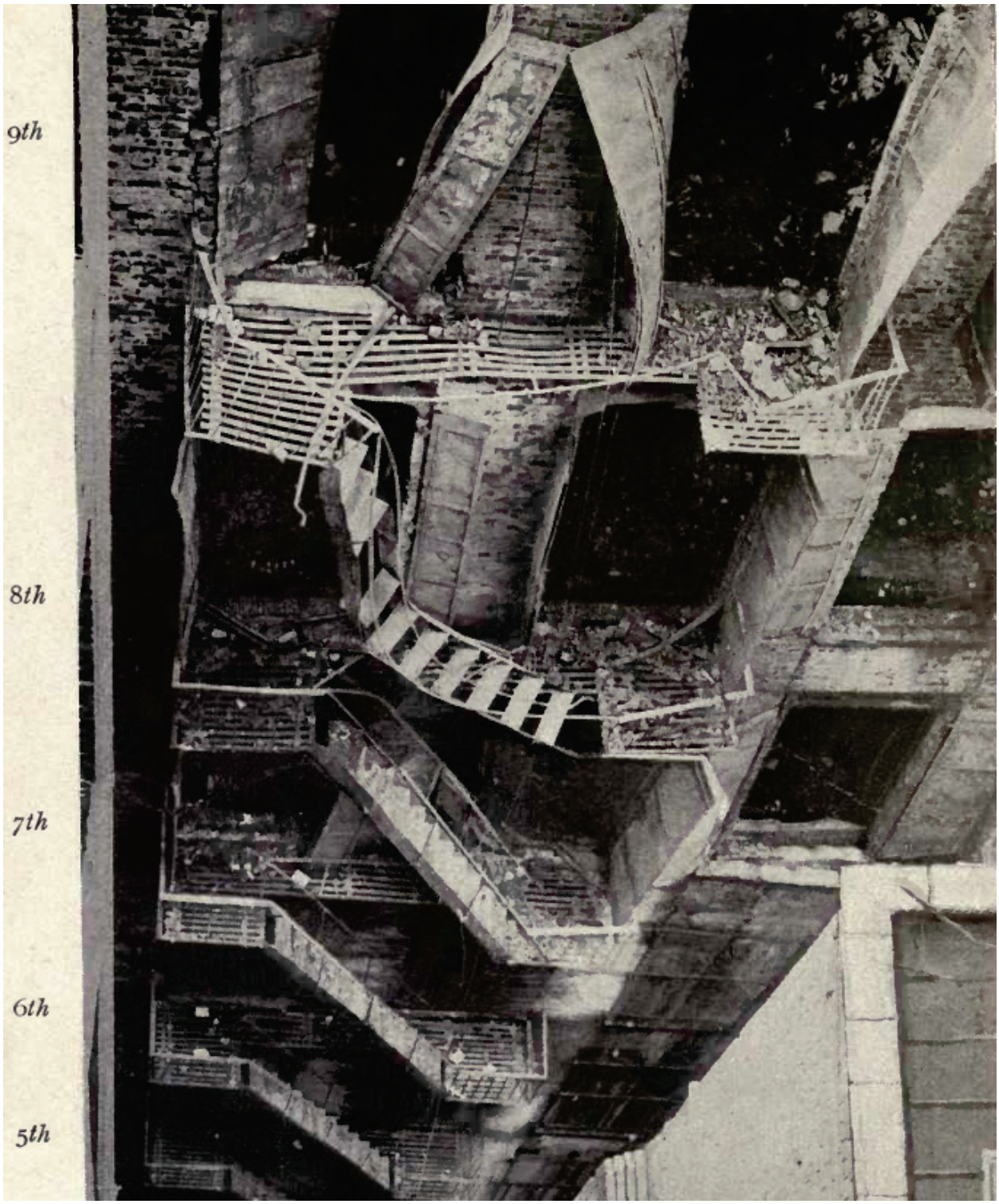


Figure 2-3: Photograph showing the collapsed fire escape on the Asch building [96]

Since then, the NFPA Buildings Exits Code has evolved through numerous iterations and published editions, and is used throughout the US today as the 2024 edition of NFPA 101, the “Life Safety Code” [97]. It has also informed the development of the exiting requirements in the NBC.

2.1.4 Evolution of Canadian Building Codes

Similar to the US, before the first edition of the NBC, building construction was largely governed by city building codes [98-100]. This resulted in non-uniform building regulations across Canada, making it difficult for the construction industry to adapt construction methods and materials for each jurisdiction. The solution was to develop a model building code that could be adopted across Canada to bring about more uniform regulation.

Canada had originally considered developing a model building code in the 1920s, at the same time as the US. However, this effort was abandoned, as there was no Canadian organization at that time in a position to write suitable specifications [101]. A model building code was reconsidered again in the 1930s, commencing with the formation of an Administrative Committee by the National Research Council in 1933 [102]. One of the mandates of this committee was “the consideration of standards and work in connection with the unifying of building codes throughout the country” [101, p. 1].

The National Research Council organized a conference on December 10, 1937, inviting many construction industry stakeholders having an interest in the development of a National Model Building Code [103]. Mr. A.F. Gill of the NRC presented a paper titled "A National Building Code" [104], outlining work at that time and recommending an approach to bring such a code document together. Gill identified the large amount of work completed in the United States with respect to their model codes and suggested that given the similarities between the United States and Canada that [104, p. 8]:

> *any building code authority in Canada could do no better than adhere to the procedure followed by American authorities and take advantage of their recommendations.*

Gill was referring to the "Elimination of Waste Series" [65-72], model building code discussed in the previous section. A similar recommendation was made by J. Grove Smith, Dominion Fire Commissioner, but in reference to the model code of the NBFU, noting that [103, p. 3]:

> *the committee on fire protection could probably do no better than to make use of the code of the National Board of Fire Underwriters.*

The first national building code, 1941 NBC, was published in 1942 [105] by the Administrative Committee and was substantially based on the content of the Elimination of Waste Series and NBFU model building codes [62, 65-72]. Therefore, it shared the same historical basis and primarily prescriptive and experiential-based requirements as those codes.

At approximately the time of development of the 1941 NBC [105], efforts were also underway to unify fire performance testing through the Canadian Standards Association [106]. At the conference initiating

development of the 1941 NBC, the performance approach was one of the key concepts considered for adoption as follows [107, p. 4]:

> *The specification type of code is definitely a deterrent to improved methods of construction and it can be avoided only if each building authority has access to technical information in a form in which it can be used…Furthermore, if the code is truly a performance code and not one of a specification type, the difficulties once more are minimized.*

Following this, the 1941 NBC included references to several performance tests and performance specifications, facilitating greater design flexibility than existed in the primarily prescriptive-based city building laws. In addition, similar to the US model codes, the 1941 NBC permitted [105, p. 45] "new materials and methods of construction not specifically regulated" by the code, based on their suitability demonstrated through laboratory testing. However, this was primarily intended to apply to new materials.

Due to personnel limits during the Second World War, it was not possible for the Administrative Committee to continue active development of the NBC [102]. Once the war ended, an Associate Committee was formed by the NRC in 1948 to continue the work of the Administrative Committee in the further development of the NBC [101]. The 1953 NBC was published in 1954 and was claimed to be a complete overhaul of the 1941 NBC in terms of arrangement and "scientific principles" underlying the fire and life safety requirements [108]. Despite this claim, examination of this version of the code illustrates that many of the requirements originally adopted from the US model building codes remained without further scientific support, except for the incorporation of Ingberg's correlation between fire load and fire-resistance [84] and research from the UK on fire spread between buildings [109].

The third and fourth editions of the NBC were published in 1960 [110] and 1965 [111] respectively. In an effort to address the challenges in regulating rapid advancements in technology, building design and construction, discussion of broader performance concepts began to emerge in Canada in the 1960s [112-115]. Through these, other methods were sought to demonstrate performance beyond just standard tests.

Part 9, "Housing" of the 1965 NBC included high level performance objectives without listing any specific performance criteria or verification methods, but referenced the "Residential Standards," which were primarily specification-based, as an acceptable means of designing for compliance [116]. At that time, the Residential Standards were published under separate cover. However, without performance criteria, or verification methods, the performance requirements in Part 9 were not enforceable. Eventually, the specifications in the Residential Standard were incorporated into Part 9 in place of the performance requirements, which essentially eliminated the original concept for a performance-based approach. As a result, the code shifted to a specification-based regulatory model for Part 9 of the NBC as well.

The fifth edition of the NBC, published in 1970 [117], redefined the provision for "new materials and methods of construction" as "equivalents," allowing new materials as well as designs not specifically addressed by the NBC that can be shown to "provide the level of performance required by [the Code]" [117, p. 7]. Equivalents were developed by those seeking to use innovative designs, subject to approval by local authorities having jurisdiction. However, the prescriptive nature of the existing requirements that focused on material and dimensional specifications for building elements without providing a rationale,

limited the flexibility of alternative designs within the constraints of those specifications. This was due to the lack of a rationale to explain the intent of the requirements and to allow the demonstration of equivalent performance in a manner acceptable to an authority having jurisdiction. This continued into the 1990s with subsequent editions of the NBC, which were also prescriptive-based and structured with a focus on specifying technical requirements for the design of building elements, but without providing the underlying rationale.

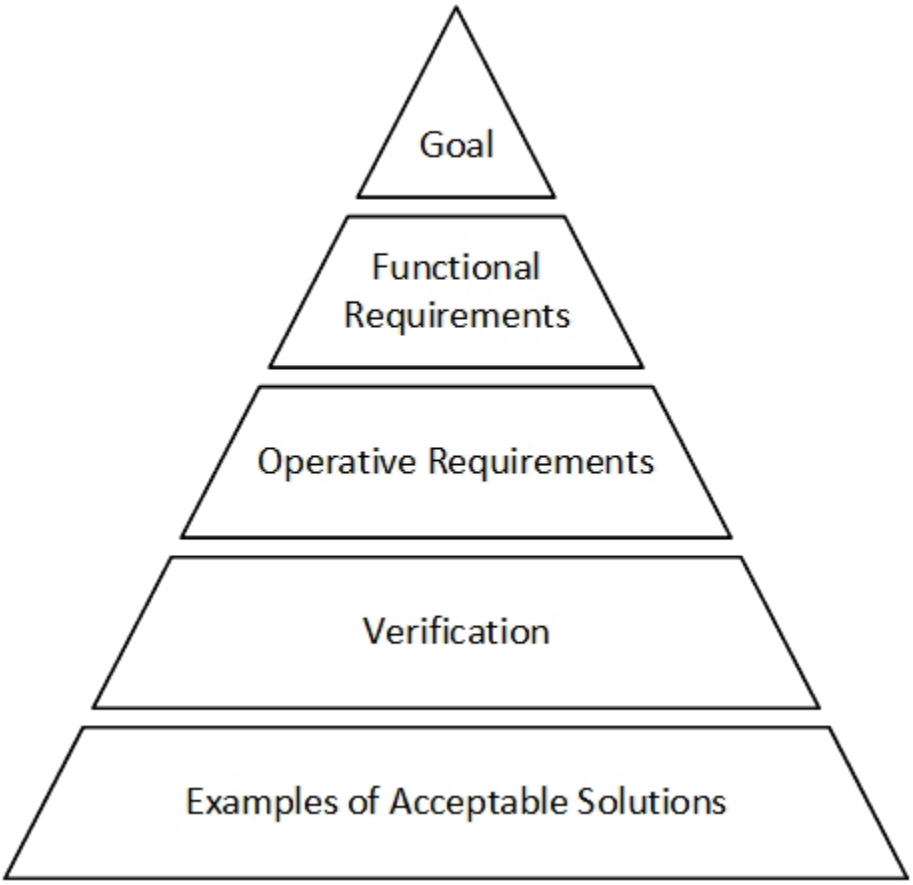


Figure 2-4: A modified version of the NKB hierarchy

This structure became quite complex to address the numerous potential designs, construction configurations, and materials, as they changed and evolved over time. In the early 1990s, the Canadian Commission on Building and Fire Codes (CCBFC)[4] began studying the feasibility of implementing a performance-based framework to address the limitations of the primarily prescriptive-structured NBC [118, 119]. Research by Oleszkiewicz [120] recommended that Canada utilize a framework developed by the Nordic Committee on Building Regulations (NKB), published in a 1978 report, as part of an effort to harmonize building regulations in the Nordic countries [120, 121]. This same framework had been utilized by other countries [120, 122, 123] in the 1980s and 1990s to transition their building codes from primarily

[4] The Associate Committee of the NBC became the Canadian Commission on Building and Fire Codes in 1992 [118].

prescriptive-based to performance-based. The tiered NKB framework, illustrated in Figure 2-4, includes the following levels [120, 121]:

Level 1: OVERALL GOALS - The statement of the properties of a building, phrased as objectives, important from the point of view of society and individuals.

Level 2: FUNCTIONAL AREAS - Functional requirements of buildings and building subsystems that are to be attained to meet the Level 1 objectives.

Level 3: OPERATIVE REQUIREMENTS - Specific requirements to effect the functional requirements identified in Level 2 may be applied in the design and construction of buildings.

Level 4: VERIFICATION - Instructions or guidelines for evaluation and verification of compliance.

Level 5: EXAMPLES OF ACCEPTABLE SOLUTIONS – Supplement to the regulations with examples of solutions deemed to satisfy the fire and life safety objectives embodied in the regulations.

The NKB framework provides a link between the objectives of a building code and its technical solutions in an effort to facilitate uniformity amongst countries with different systems of building code administration [121]. Such a framework was considered to be [120, p. 3]:

> *well defined, transparent, hierarchical and objective-oriented. One can trace a path from a particular requirement to the objectives of the regulations and tell the function that meeting this criterion has in meeting the objectives of the regulations.*

Oleszkiewicz examined the experience in the UK, Australia and New Zealand following their implementation of performance-based frameworks [120], which generally provided two paths to demonstrate compliance. The first was by designs that followed primarily prescriptive “deemed-to-satisfy” (acceptable) solutions. The second was by alternative solution designs that achieved certain performance criteria, which were almost entirely qualitative. This reliance on qualitative criteria led to ambiguity and inconsistent interpretation in developing appropriate designs, contributing to notable failures, such as New Zealand’s “leaky homes crisis” [124-126]. To address these challenges, Oleszkiewicz recommended that the Canadian framework focus on the legacy-based and primarily prescriptive requirements (“acceptable solutions”) as defining the acceptable level of performance for innovative (alternative) designs [120, 127], rather than qualitative performance criteria.

The new Canadian framework populated Levels 1 and 2 of the NKB framework through a bottom-up analysis of the acceptable solution requirements [128] (Level 5). This analysis also focused on identifying the intended outcomes of these requirements, which were then documented in “intent statements.” Defining acceptable performance in the new “objective-based” Canadian framework using the existing acceptable solution requirements was viewed as an intermediate step toward a fully performance-based framework [119], while acknowledging the acceptable performance of these requirements that had been demonstrated over time. The new framework was intended to:

- provide clarity of intent of the existing acceptable solutions, thereby reducing the complexity of the code [128];

- facilitate the development and acceptance of innovative designs [119];
- facilitate the development of performance requirements [119], including the introduction of performance criteria;
- lead to a "dual path" framework that allows either prescriptive or performance solutions to achieve an objective [119].

The CCBFC, Standing Committees, and associated Task Groups worked from 1995 to the early 2000s to develop the objective-based framework, which was eventually implemented in the 2005 edition of the NBC [129] and exists today in the 2020 NBC [21]. Since the existing objective-based framework of the NBC forms the starting point of the present research, it is discussed in more depth in the following section.

2.2 Objective-Based Framework of the NBC

The 2020 NBC is the fifteenth and current edition, published in December 2022 [21], and is the fourth iteration of the objective-based format of the code. The NBC is organized in a simple primarily specification-based framework intended to facilitate achieving certain objectives while allowing "alternatives" to those specifications to allow innovative design as detailed in the following sections.

2.2.1 Structure

The objective-based structure of the 2020 NBC is composed of three divisions [21]:

- **Division A:** defines the scope of the code and includes objectives that the code addresses and the functions the building must perform to satisfy those objectives.
- **Division B:** contains the acceptable solutions of the Code in 9 parts, which are deemed to achieve the objectives included in Division A.
- **Division C:** contains administrative provisions relating to the application of the code.

Division B and the acceptable solutions will be discussed first as these were the set of requirements that were the main body of the earlier (legacy) versions of the NBC.

2.2.2 Acceptable Solutions

The Division B acceptable solutions are divided into 9 parts. Part 1 addresses general requirements and Parts 2 to 9 address specific types of buildings or aspects of building design and construction. This thesis is specific to Part 3, "Fire Protection, Occupant Safety and Accessibility." The acceptable solutions of Part 3 were adopted as the requirements from earlier codes, partly developed through a consensus process to address fire and life safety risks related to the design and construction of buildings. The intent of the application of the acceptable solutions is to limit those risks to a level considered by consensus of the code-development body to be acceptable to the general public. The NBC uses the term "acceptable," whereas others have used the term "tolerable" [130], implying that society may not actually accept the

resulting level of risk but may tolerate it. The term “acceptable” is used in this thesis rather than “tolerable” to be consistent with the language in the NBC.

The acceptable solutions of the NBC are primarily expressed in a prescriptive format with few being performance-based. Prescriptive specifications provide an explicit method, measurement, or materials by which to achieve an end goal (performance), whereas performance-based specifications identify the end goal and allow any solution that achieves that goal. For purposes of simplification [21], the performance intended by the application of a prescriptive requirement is not typically expressed as part of that requirement, but is instead implicitly satisfied when the details of the requirement are appropriately applied during the course of the building design and construction. This limits the application of prescriptive requirements to the range of fundamental design conditions that form the basis for their original development. Where those fundamental conditions are known or readily inferred, the prescriptive requirement can therefore be applied as intended.

An example of a prescriptive requirement is the requirement in the NBC that, if access is provided to a storage garage through a vestibule, the vestibule is required to [Sentence 3.3.5.7.(4)] [21, Div. B, p. 3-137]:

a) be not less than 1.8 m long,

b) be ventilated

i) naturally to outside air by a vent that has an unobstructed area of not less than 0.1 m^2 for each door that opens into the vestibule but not less than 0.4 m^2,or

ii) mechanically at a rate of 14 m^3/h for each square metre of vestibule floor surface area, and

c) *have openings between the vestibule and an adjoining occupancy provided with self-closing doors with no hold-open devices.*

This requirement provides a detailed solution but does not explicitly state the intended performance (intent) of the requirement, which is to limit the probability that gas and exhaust fumes will migrate from storage garages (parkades) into other areas of the building [131]. This solution is measurable and, therefore, easy to incorporate into a design and to confirm compliance with the requirement. However, the solution does not explicitly indicate that it is related to gas and exhaust fumes, nor does it specify the type of gas and exhaust fumes intended to be addressed, or to what level the solution needs to limit those gases. This lack of explicit intent can lead to misinterpretation and disagreement when applied to design in a local context, limiting the flexibility of that design.

Similar to prescriptive requirements, performance-based requirements are intended to control building design to limit undesirable events. However, performance-based requirements identify a performance objective, but do not stipulate the means to achieve that objective. This allows greater design flexibility than prescriptive requirements, but less simplicity in terms of application, interpretation and enforcement. Development or evaluation of designs advanced to meet performance-based requirements requires specialized knowledge of the physical principles associated with the performance objective and method(s) of verification from both the designer and the enforcer.

An example of a performance requirement intended to limit the impact of harmful gases, similar to the one used above, is the requirement that rooms such as operating rooms, recovery rooms, delivery rooms, and intensive care units, from which it is impracticable to move patients in an emergency, are required to be provided with a mechanical air supply. The intent is that, during a period of "2 h after the start of a fire in another space, the compartments [rooms] will not contain more than 1% by volume of contaminated air from the fire area" [21, Div. B, p. 3-133] [Subclause 3.3.3.6.(1)(b)].

This requirement provides an expected level of performance (i.e., 1% by volume of contaminated air), identifies the harmful element (smoke), and allows any design that achieves that performance. As a result, it allows greater design flexibility, but is more difficult to implement and more challenging for an authority to confirm whether the design achieves the prescribed performance without specialized knowledge of the hazard (smoke), the key technical attributes of the various solutions (such as ventilation systems), and the relationship among them necessary to verify performance.

2.2.3 Objectives, Functional Statements and Intent Statements

Prior to the 2005 edition of the NBC, objectives, functional statements, and intent statements were not explicitly written. They were considered implicit to the existing acceptable solution (primarily prescriptive) requirements, and it was through a bottom-up analysis [127] of these requirements that objectives, functional statements, and intent statements in the then new 2005 NBC were derived.

The purpose in defining objectives, functional statements, and intent statements was to simplify the application of the NBC by clearly stating the high-level societal goals that the acceptable solution requirements are intended to achieve. The objectives are located in Division A, Section 2.2 of the NBC, and are expressed in a way that "describe undesirable situations and their consequences, which the Code aims to prevent from occurring in buildings" [21, p. viii], thereby establishing the scope of the subject matter addressed by the NBC. The NBC defines five primary objectives and corresponding sub-objectives. The primary objectives are [21]:

- safety,
- health,
- accessibility,
- fire and structural protection of buildings, and
- environment.

The objectives are entirely qualitative and are formulated to state what the code is intending to limit. Specifically, the "fire and structural protection of buildings" objective is specified as follows [21, Div. A, p. 2-4]:

> ***OP Fire and Structural Protection of Buildings***
>
> *An objective of this Code is to limit the probability that, as a result of the design, construction or demolition of the building, the building or adjacent buildings will be exposed to an unacceptable risk of damage due to fire or structural insufficiency, or the*

building or part thereof will be exposed to an unacceptable risk of loss of use also due to structural insufficiency.

As noted above, the Code is intended to limit the "unacceptable risk of loss" in the "construction or demolition of the building." The "unacceptable risk" is limited through the application of the acceptable solutions or the performance targets implicit to these solutions. In contrast to what would be expected for a full performance-based code, the objective statements are qualitative, and no performance measures are provided to quantify the intended outcomes.

The primary objectives are divided into sub-objectives that more specifically describe their intended goals. The following shows the sub-objectives associated with "fire protection of the building" (OP1), which is itself part of the broader objective of "fire and structural protection of buildings" (OP) [21, Div. A, p. 2-5]:

OP1 Fire Protection of the Building

An objective of this Code is to limit the probability that, as a result of its design or construction, the building will be exposed to an unacceptable risk of damage due to fire. The risks of damage due to fire addressed in this Code are those caused by—

OP1.1 – fire or explosion occurring

OP1.2 – fire or explosion impacting areas beyond its point of origin

OP1.3 – collapse of physical elements due to a fire or explosion

OP1.4 – fire safety systems failing to function as expected

The objectives are linked to functional statements, which act to further clarify the goals of the code and [21, p. viii] "describe the conditions in the building that help satisfy the objectives". Similar to objectives, functional statements are entirely qualitative with no threshold values or other evaluation criterion provided. An example of a functional statement is as follows [21, Div. A, p. 3-1]:

F02 *To limit the severity and effects of fire or explosions.*

There may be more than one functional statement for an objective, and a single functional statement may describe the conditions necessary to satisfy more than one objective.

Each acceptable solution within the NBC is attributed to one or more objectives and functional statements, which identify the goal(s) of the specific acceptable solution. The following is an example of an acceptable solution with the attributed objective(s) and functional statement(s):

Acceptable Solution [21, Div. B, p. 3-144]:

3.4.3.2. Exit Width

1) … the minimum aggregate required width of exits serving floor areas intended for assembly occupancies, residential occupancies, business and personal services

occupancies, mercantile occupancies, and industrial occupancies shall be determined by multiplying the occupant load of the area served by

…

c) 9.2 mm per person for

i) ramps with a slope of more than 1 in 8, or

ii) stairs, other than stairs conforming to Clause (b).

Objective and Functional Statements [21, Div A., pp. 2-2, 3-2]:

[F10-OS3.7]

OS3 – An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this Code are those caused by

OS3.7 – persons being delayed in or impeded from moving to a safe place during an emergency.

F10 – To facilitate the timely movement of persons to a safe place in an emergency.

Intent statements explain how each acceptable solution achieves its objectives and functional statements, but in plain language [21]. An example of an intent statement for the exit width is as follows [131, p. 533]:

To limit the probability that exits will be of insufficient width to permit efficient egress in an emergency situation, which could lead to delays in the evacuation or movement of persons to a safe place, which could lead to harm to persons.

Intent statements are not a mandatory aspect of the NBC but are intended to clarify the application of the acceptable solutions to facilitate compliant design and the development of alternative solutions.

The objectives, functional statements and intent statements were developed to facilitate compliance in general, and specifically where an alternative design does not directly comply with the acceptable solutions of the NBC. Methods of compliance with the NBC are discussed in the next section.

2.2.4 Compliance

The NBC defines two paths of compliance. The first path involves direct adherence to the Division B "acceptable solution" requirements. However, given their prescriptive nature, they can be challenging to apply to basic building designs, and more so to innovative designs. Such cases are often best addressed through the second compliance path, which allows for "alternative solution" designs that can be shown to perform at least as well as a design that complies with the otherwise applicable acceptable solution requirement(s) in the areas defined by the objectives and functional statements [21].

Compliance by alternative solutions replaced the previous “equivalency” provision as the primary means to allow consideration of materials and designs not directly compliant with the acceptable solution requirements. As previously discussed, the objectives, functional statements, and intent statements established during the development of the objective-based framework of the NBC were intended to provide clarity of intent of the benchmark acceptable solution requirements, thereby facilitating the demonstration of performance for alternative solutions. However, this goal has not been fully realized for reasons explored in the following chapter through literature review of factors and challenges that have limited the acceptance of alternative solutions and the intended shift to a performance-based framework. Key elements related to the impact of time on building code development, the need to integrate fire science and fire safety engineering principles into design practice, and methods for risk assessment and use of risk in fire safety design performance and acceptance frameworks are also reviewed.

Chapter 3
Literature Review

Nearly two decades after the NBC incorporated an objective-based framework, its intended benefits remain largely unrealized. The framework was intended to clarify regulatory intent, facilitate the development and acceptance of innovative designs, and ultimately serve as a stepping stone toward a fully performance-based framework. However, building authorities and code development groups are reluctant to accept movement to such a framework without sufficient evidence that the new framework will not foster designs that supplant the performance implicit to the “tried and true” methods [132], which have become deeply ingrained in industry practice and, to some extent, are relied upon. Consequently, the Canadian construction industry continues to operate within the confines of the legacy, prescriptive-based framework, which stifles the innovation necessary for adopting more creative and sustainable practices.

The following sections review existing literature and experience to further discuss the original intent and the ongoing urgent need to shift to a performance-based framework for the regulation of building fire and life safety design in Canada. Also outlined is how the impact of time on building code development is one major factor at the root of the challenges in applying the present NBC to achieve acceptable innovative designs (alternative solutions) and to facilitate the shift to a performance-based framework. Finally, important background information required to facilitate such a shift, including key concepts and principles from fire science and fire engineering, and the development of risk frameworks and use of risk as a means to quantify performance are also examined.

3.1 Alternative (Innovative) Solutions

The prescriptive nature of the NBC's acceptable solutions has historically limited, and continues to limit, the adoption of innovative designs. Prior to the 2005 NBC, this limitation had been addressed through the “equivalency” provision, which allowed the performance of innovative designs to be benchmarked against the performance of the acceptable solutions. However, due to the lack of defined performance criteria and a framework to verifying equivalent performance, this approach required agreement between design proponents and building authorities regarding the appropriate level of performance, a process often frustrated by ambiguity and inconsistent interpretations.

The objective-based framework that was introduced in the 2005 NBC aimed to address these limitations by establishing an “alternative solution” compliance methodology. This approach was intended to provide the missing performance information and associated framework through a bottom-up analysis of the existing acceptable solution requirements. The analysis sought to trace the origins of these requirements to define high-level objectives, functional statements, and intended performance (intent statements).

However, key quantitative criteria for the assessment of performance have remained and continue to remain elusive, as discussed below.

3.1.1 Rationale and Intent

During the development of the objective-based framework, understanding the rationale behind the existing predominantly prescriptive requirements was identified as a crucial factor for the framework's success. This was recognized early in the process during strategic planning sessions, which defined a key goal as stated in [133, p. F-80]:

> *the underlying principle of code requirements being clearly stated and communicated to the users. Success or failure of objective based codes hinge on this issue. In other words, the intent and the reasons behind a given regulation must be understood by the users of the code.*

The absence of such information was identified as a key factor limiting the earlier "equivalency" provision from effectively supporting innovative designs, highlighting the need for inclusion within an objective-based framework. This focus is warranted, given the earlier recognition of ambiguity and interpretation challenges associated with the prescriptive requirements, which specified materials, measurements, and configurations without explicitly defining the intended outcomes. Such foundational information enables a more principled, rather than literal, interpretation of the requirements, aligning designs with their original intent and facilitating consistent interpretation while reducing ambiguity and speculation.

Identifying the rationale behind the fire and life safety requirements in the NBC was an ambitious goal, given their extensive, yet only partially understood, history of development. A bottom-up analysis strategy was utilized to review the requirements, with the purpose of determining the high-level objectives they were intended to achieve and the means by which they were to achieve them. This information was to be drawn from explanatory appendix notes, committee meeting records (minutes), and the "best understanding" of committee members, staff, and other experts conducting the review, with the goal of capturing the committee's original intent behind the requirements at the time of their development [134]. However, after years of analysis and review, the resulting objectives, functional statements and intent statements were entirely qualitative. The NBC itself acknowledges this limitation, noting [21, Div. A, p. 1-18]:

> *The objectives and functional statements are entirely qualitative…In many cases, [the quantitative performance targets] are not defined very precisely by the acceptable solutions-certainly far less precisely than would be the case with a true performance code, which would have quantitative performance targets and prescribed methods of performance measurement for all aspects of building performance.*

While the qualitative information provided some high-level guidance for applying the fire and life safety requirements to design, it proved insufficient to resolve the longstanding issues of ambiguity and

inconsistent interpretation. These challenges remain, continuing to limit the acceptance of innovative designs and even increasing the administrative burden of documenting alternative solutions beyond what was expected for the previous equivalency approach. As a result, the new “alternative solution” compliance option is proving to be just as limiting as the equivalency provision it was meant to replace.

Therefore, without quantitative performance criteria or verification methods, demonstrating equivalent performance of innovative designs relies primarily on comparative assessments against acceptable solution designs. While these assessments enable direct performance comparisons of specific design aspects, they present challenges, including limited guidance on the appropriate selection and evaluation of scenarios. The next section explores the limitations further and the associated issues in evaluating acceptable performance of a design.

3.1.2 Limitations of the Comparative Approach to Compliance

In the absence of clear performance criteria or a documented technical basis for the acceptable solutions in the NBC, demonstrating equivalent and acceptable performance for an alternative (innovative) solution design is significantly restricted to comparative approaches [127]. These approaches rely on an analogous acceptable solution compliant (reference) design as the benchmark for comparison. In doing this in a consistent fashion, both designs have to be based on the same assumptions, models, calculations, and input data (i.e., occupant walking speed) [135], which also requires acceptance by the authority having jurisdiction who may not have a technical understanding of the complex methods and interacting factors involved in such an analysis. The validity of this approach, therefore, relies on there being an appropriate and close match between the actual design and the comparable reference design [136]. Even if this is the case, it has been found that such an approach may not result in a design solution that in practice meets even a qualitative acceptable level of performance [123, 137-139].

Lundin [123] investigated the impact of changes in the Swedish Building Code from a prescriptive to a performance-based framework, 10 years following its enactment. Similar to the NBC today, the Swedish framework included acceptable, mostly prescriptive, solutions and permitted alternative methods. Evaluation of alternatives was based on verification, at the component and system level, of these methods relative to the acceptable solution requirements. In his thesis, Lundin examined [123]:

- The level of risk resulting from using the acceptable prescriptive design options in the code by conducting a risk analysis on a reference design.
- The validity of several fire safety approaches with supporting analyses from forty-six real design projects that had been completed since enactment of the new building code.
- The rigor of various analytic design approaches that had been used to verify performance in achieving the objectives of the building code.

Lundin generally concluded that, under the Swedish framework, the level of risk resulting from the application of the acceptable solution design methods significantly varied even within a single class of building, i.e. assembly halls. Further, in some cases, the actual level of risk, determined using fundamental

risk assessment methods, was found to exceed the acceptable level intended by the Building Code. The following were identified as key factors contributing to this result [123]:

- The Building Code does not provide recommendations regarding the choice of a reference building (or design) for purposes of comparison. This allows selective minimization of fire safety measures and correspondingly higher levels of acceptable risk than what was intended by the application of the prescriptive requirements on an averaged national level.
- The Building Code does not explicitly state acceptance criteria (acceptable levels of risk), nor provide guidance on comparison or methods for verification of comparative risk amongst different fire safety approaches, which can result in disagreement between stakeholders. Decisions regarding the acceptable levels of risk tend to shift from building authority to designer, and the analytical methods used to establish these acceptable levels is highly arbitrary.
- A "paradigmatic shift" in fire safety design to effect performance-based requirements resulted in changes in the traditional roles of stakeholders and required increased coordination amongst stakeholders due to increased demands in verification of performance-based solutions. It further required consideration of the building as a system, and drove the need for broader design approaches and design evaluation methods (primarily risk assessment methods).

The factors outlined by Lundin highlight the challenges associated with a lack of clear performance targets, as well as the limited applicability and appropriateness of comparative assessments, without guidance, as a means of validation that a building meets acceptable fire and life safety targets. Lundin's criticisms of the appropriateness of comparative assessments have been supported more recently by others [138, 140], leading to the question of what might be a more appropriate approach.

Lundin recommends that, to rectify this situation [123]:

- There is a need for development of explicit acceptance criteria and appropriate procedures for verification of safety in alternative designs, correlated to the existing requirements.
- The level of safety (acceptable risk) should be established from the application of the prescriptive requirements to suitable building designs.
- Risk analysis methods should be used to examine the impact of changes to prescriptive requirements for classes of buildings.
- Guidance and control measures should be defined for the selection of reference buildings (design) for purposes of comparative analysis (verification), such that the resulting residual risk be equivalent to the mean acceptable risk for a specific class of buildings.

The first three recommendations are important to provide the clarity intended by a true performance-based code [120]. However, the last of Lundin's recommendations is important, and potentially more significant than anticipated. It highlights the concept that the prescriptive requirements are intended to be applicable across a majority of buildings in bringing about an acceptable level of risk. However, some buildings fall outside the range of applicability, and the risk resulting from application of the prescriptive requirements in these cases will be higher or lower than anticipated. This is partially addressed in some building codes, such as those in Sweden and New Zealand, by limiting the scope of their prescriptive

(acceptable solution) requirements to buildings that do not have complex features, such as atriums, intermediate floors, significant height, or design elements requiring fire safety engineering analysis [141]. This is not the case in Canada where the NBC applies to almost all buildings and building design features. Here, even though the acceptable solutions may be applicable to certain assembly halls, the application of the acceptable solutions to other assembly hall designs will not result in the intended acceptable level of risk (performance) [11]. In its present form, the NBC still permits a design fraught with an "unacceptable" risk level to be used as a comparative basis for justification of other, alternative (innovative) solutions.

Similar challenges with the comparative approach have more recently been identified by Bjelland relative to the building code of Norway [137-139]. Bjelland notes that the choice of a comparative analysis is due to a lack of explicit acceptance criteria and is a [138, p. 2] "mere thought construct" that does not provide any insight into issues that actually affect the level of safety or performance in fire, but instead limits the responsibility of the fire safety engineer [138]. Important fire safety issues are not considered in conducting a comparative analysis and similar to Lundin, Bjelland found that the performance associated with the acceptable solutions does not provide a single consistent level of safety [138]. Bjelland argues that the acceptable solutions will have limitations with respect to their application to complex buildings of the future [138]. These same challenges apply to acceptable and alternative solutions in the context of the NBC [142, 143].

Similar to that found by Lundin, Bjelland, and also by Law [144], the acceptable solutions of the NBC do not provide a single consistent level of safety. This is identified in an appendix note to alternative solutions in the NBC and potential variance of implicit levels of performance [21, Div. A, pp. 1-18, 1-19]:

> *Where Division B [the acceptable solutions] offers a choice between several possible designs, it is likely that these designs may not all provide exactly the same level of performance. Among a number of possible designs satisfying acceptable solutions in Division B, the design providing the lowest level of performance should generally be considered to establish the minimum acceptable level of performance to be used in evaluating alternative solutions for compliance with the Code.*

It is important to note that Lundin's and Bjelland's research is germane to the Swedish and Norwegian Building Codes, which have similar structures as the NBC, but differ in terms of the specific acceptable solution (prescriptive) requirements for a given building design. Thus, while it is anticipated that Lundin's and Bjelland's research methods could be applied to analyze the NBC, the results are expected to differ due to differences in the acceptable solution requirements and the structure of those requirements as applied within the separate regulatory documents. However, similar ideas identified by Lundin and Bjelland in their examinations of acceptable and comparative performance have been expressed by Bergeron relative to the research necessary to progress the objective-based codes in Canada to be performance-based [145, p. 108]:

> *The implicit level of performance embedded in the acceptable solutions can be viewed as representing society's expectations of building performance. Converting this implicit level*

of performance into quantitative terms is a critical first step in the development of measurable and verifiable performance criteria that closely reflect society's expectations – the performance criteria that are essential to true performance-based codes. ***This is an area where research is needed to develop tools and methods that allow the quantification of the implicit level of performance of acceptable solutions [emphasis added]****.*

In addition to the challenges in application of the "comparative approach" to assess fire performance and safety of an alternative design, are challenges around the nature of comparison expected by building authorities who, in the end, approve the design for construction but who may not have the technical background to comprehend methods of comparative assessment. These officials frequently favour the comparison of individual material or design characteristics over discussion of the holistic performance of the building as a system. The result is that they expect a reduction in any perceived important characteristic or requirement of a particular acceptable solution to be addressed through provision of a corresponding, or even superfluous, design feature or characteristic that is known through (often their) experience to enhance fire safety. This "trade-off" mindset often leads to design compromises that may appease perceived material or design imbalances, but expend unnecessary resources with limited, if any, benefit to the final performance. In some cases, certain required design characteristics are considered to be so critical that acceptable trade-offs are rarely permitted. An important example is the use of combustible construction in a building required to be of noncombustible construction. This creates an apparent imbalance of material fire characteristics upon which acceptance can be judged, even where it can be demonstrated that the combustible material does not contribute to fire growth and spread. In simple terms, combustible material burns and noncombustible material does not; therefore, in order to allow the use of combustible material, there is often an expectation, not always appropriate, that a significant compensating measure (or measures) must be provided (i.e., a sprinkler system).

In contrast to a comparative approach, an evidence-based or "first-principles" approach allows for more in-depth assessment of an alternative solution, typically using fundamental fire science and fire engineering principles. With such an approach, the results must be assessed against defined objectives, performance requirements, and criteria [135]. This approach requires acceptance and use of a performance-based framework and therefore, does not rely on the specification-based acceptable solutions to define acceptable performance [135]. An appropriate performance-based framework would allow use of scientific principles in an integrated first-principles approach. Since the scientific principles, and surrounding considerations, are constantly evolving, they can be updated within such a performance-based framework without impacting its structure. This is not the case for the present objective-based framework that, for purposes of simplicity, relies on the legacy specification-based requirements of the NBC, limiting alternative design practices to a comparative approach and use of artificial "acceptable" risk constructs. In reality, the formulation of the current objective-based NBC, itself, continues to limit any shift to a performance-based framework. At the same time, there are many who favour the current comparative approach, even with the resulting discrepancy in risk levels, because they feel that they capture consensus and principles that have stood the test of time. At the same time, recognizing the limitations that the

current code places on innovation in use of materials, technologies, and design in the broader sense highlights the urgent need to transition to a performance-based framework, allowing a first principles approach to design. The next section examines this necessity and the factors driving it.

3.1.3 Necessity for a Performance-Based Framework

At present, there are compelling reasons to transition the NBC from its existing objective-based framework to a fully performance-based framework. Beyond the current framework's failure to achieve its original goal of fostering innovation in design, this shift is essential to support novel solutions that address the increasingly severe environmental challenges affecting the built environment.

Interestingly, an objective entitled “Environment” was added to the 2010 NBC. This was to address excessive energy use that is considered to have an unacceptable effect on the environment [146]. A new sub-objective of the Environment objective has been proposed for the yet to be published 2025 version of the NBC. This is intended to address excessive emissions of greenhouse gases (GHG) [147]. The purpose of adding this objective is to allow for the development of requirements to [147, p. 2]:

> *meet provincial, territorial and federal GHG emissions reduction targets and climate action plans, including Canada’s goal to reduce Canada's total GHG emissions to 40 to 45% below 2005 levels by 2030 and to reach net-zero by 2050.*

The importance of a flexible regulatory system arises because many of the solutions needed to achieve energy efficiency and embodied carbon may also precipitate changes to, or even increase, fire hazards [148, 149] as outlined in the examples (not all inclusive) and their associated potential fire hazards below:

- Mass timber construction: a combustible material that can increase the potential for fire growth and spread.
- High Efficiency Insulation: typically, a combustible material that can increase the potential for fire growth and spread.
- Battery Energy Storage Systems: potential ignition source, potential for thermal runaway, with combustible components with potential generation of new toxic fire products.
- Building Tightness: potential for ventilation limited environments with increased toxic fire products and increased compartment pressure (increased door opening forces) that limit egress.
- Photovoltaic Panel Arrays: potential ignition source and combustible material with potential generation of new toxic fire products.
- Centralized Energy Recovery Ventilators: potential exacerbation of smoke spread.

Integrating new solutions for these kinds of fire safety challenges into the NBC, or allowing consideration of these types of complex situations in alternative solutions, while also minimizing the potential increase

in fire risks, is a challenge that requires an in-depth understanding of fire dynamics, as well as the basis and interrelationship of the current fire and life safety requirements with other aspects of the NBC.

Complicating this situation is the recognition that to achieve GHG emission reduction targets, associated requirements will need to apply not only to new buildings, but also to existing ones [150]. In this respect, the NBC provides limited guidance on how to apply the existing acceptable solution requirements to changes in existing buildings. Thus, efforts are underway to develop a building code for alterations to existing buildings [150]. These are currently focused on energy efficiency but will eventually have to address fire and life safety for similar reasons detailed above for new buildings. This will be a complex endeavour given the period of time over which the existing specification-based requirements of the NBC have been developed, and how they relate to the age range of existing building stock. A solution to all of these complexities is not possible within the limits of the current NBC objective-based framework, primarily due to the lack of quantified performance targets upon which the alternative solutions necessary to address these complexities can be evaluated.

This was highlighted in a recent series of consultation workshops conducted by the National Research Council of Canada (NRC) through their "Platform to Decarbonize the Construction Sector at Scale" and in collaboration with the Standards Council of Canada (SCC) [151]. The consultations gathered input and recommendations from stakeholders to guide research and development necessary to transition the NBC to be performance-based in an effort to better achieve new environmental goals. Several recommendations that resulted from the consultations are summarized as follows [151]:

- Clear and quantified performance targets are needed for the acceptable solutions of the NBC, along with historical context and better documentation of evaluation methods.
- Clarifying the NBC's objectives, functional statements, and the history behind their development would provide insight into how these objectives were originally perceived and how societal risk tolerance has evolved over time.
- An updated Part 3 user's guide that includes the rationale behind the acceptable solution requirements would facilitate the development of performance-based alternative solutions.
- A comprehensive framework should be developed to guide in the development of alternative solutions and to assist authorities in their evaluation.

A central theme in these recommendations is the emphasis on understanding and documenting historical and background information, aligning with Bergeron's earlier suggestion that "research is needed to develop tools and methods that allow the quantification of the implicit level of performance of acceptable solutions" [145, p. 108]. As noted, this information is critical to transitioning the NBC to a performance-based framework, which is essential for enabling the design flexibility required to achieve the environmental goals.

Understanding the historical development of the NBC's acceptable solutions is therefore essential and will form one key element of the present research. In this context, the next section explores how time-

related factors have obscured this understanding and reviews the compounding factors that limit the acceptance of alternative solutions that have impeded the transition to a performance-based framework.

3.2 The Impact of Time on Building Code Development

Fire safety regulations have a long history of development that predates there being a specific discipline of fire safety engineering [46]. As discussed earlier, these regulations have evolved in response to incidents of significant scale or impact that drew attention to specific building design issues. Investigation and analysis followed such events, to establish the conditions that led to the incident, and solutions were developed to limit the occurrence or impact of such events in the future. Early solutions, such as the 3 foot thick stone firewall used to limit fire spread between houses in London in 1189 [20], were based on a rudimentary and experiential understanding of the fire behaviour [11] observed during those events. The performance of such solutions was then confirmed over time and altered where necessary or warranted (i.e., the refinement of the firewall requirements to allow brick) through primarily an iterative, trial and error process.

As fire science emerged and evolved, it was utilized to better inform the alteration of existing fire safety requirements and development of new ones [27, 31, 32, 73, 84, 86-92]. This still only took place on a limited basis. Over time, memory of the origins of many requirements and the methods or level of incorporation of fire science has faded. This complicates understanding of the interrelations between a given requirement and its scientific basis, if there ever was a scientific basis. While the knowledge of the background of a given requirement diminishes over time, the requirements remain and become entrenched in traditional practice [11]. The following sections review the impact of time on the development and application of building code requirements and the forces, in this context, that limit the change necessary to realize evidence-based updates and establish a framework that allows, and even fosters, innovative design.

3.2.1 Acceptable Performance and the “Test of Time”

Each of the “eras” of regulatory development discussed in Section 2.1 included identifying hazards (conflagrations, significant fires), identifying the exposed (property and people), and developing solutions (fireproof construction, building size limits, exit capacity, etc.) intended to limit the impact of the hazards of that era on the exposed. These solutions were primarily developed from the experience of those participating in the code development process, but with limited and inconsistent incorporation of fire science and fire engineering principles.

The solutions were then abridged into a concise specification-based format to facilitate more general application to, and enforcement of, building design. However, the abridgment process inevitably resulted in the diminution of the detailed basis for the original solution and a potential loss of effectiveness in achieving the intended performance. In some cases, errors were also made during the abridgement process and these were then included in the regulatory specifications, which replaced the original solution.

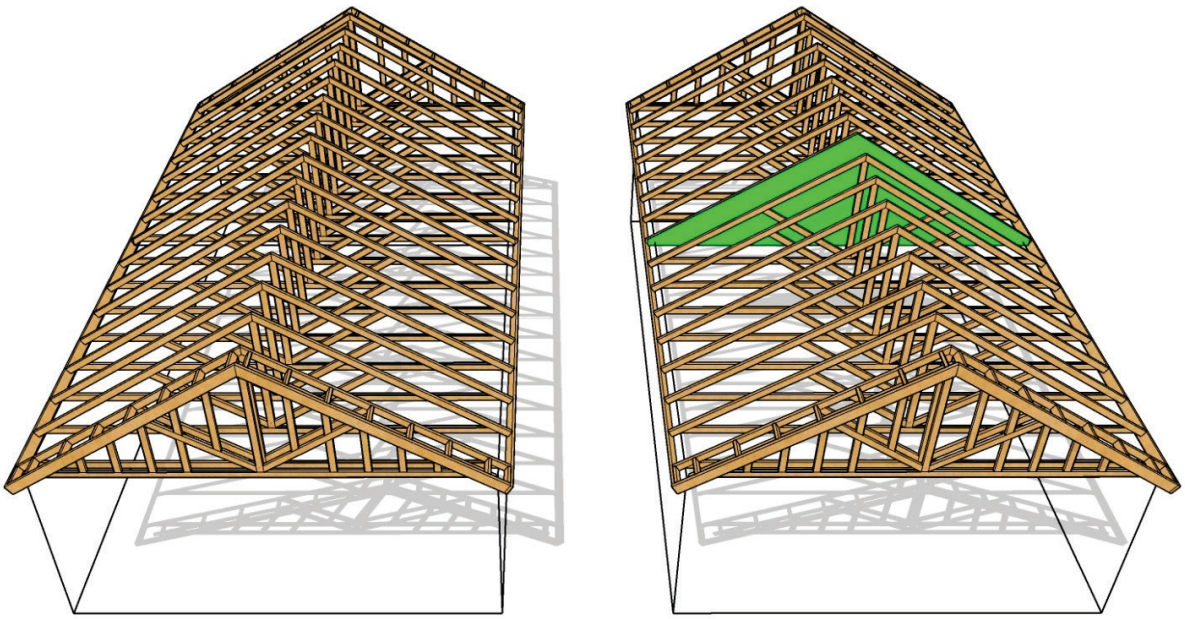
The measurable performance of a given regulatory requirement was typically not known at the time of its initial development, due to the limited understanding of fire behaviour and its impact on life and property. The test of performance has historically been the demonstrable limitation or absence of the hazard over time, as intended by the regulatory requirement (the outcome). However, this was prolonged by the time frames required to implement new regulatory requirements in design and construction, coupled with the general infrequency of fires, and in particular specific fire events. Following these time frames, where the outcome was judged to be acceptable (tolerable), the regulatory requirement was considered to have performed acceptably and remained an "acceptable solution" as intended at the time of its development. Where the outcome was judged to be unacceptable, modifications or additions to the original solution and associated regulatory requirement were necessary to achieve a better, more acceptable outcome. This iterative process often spans extended periods until acceptable performance can be demonstrably achieved.

A particularly striking example of this process is the introduction of regulatory specifications to the 1970 NBC [117] to limit the size of concealed combustible attic spaces (the "attic fire example"). This came about in response to fire losses experienced primarily in residential buildings built before the late 1960s. The key factors considered at the time of development of the requirements are summarized as follows [152]:

Hazard: fires occur within and involve a large combustible, concealed attic space and grow undetected to a size beyond the capability of a responding fire service to control quickly.

Exposed: building occupants and building structure.

Solution: limit fire size to within the capability of a responding fire service to quickly gain control by limiting the size of concealed combustible attic space. This will limit fire damage and provide occupants with adequate time to evacuate the building.



(a) (b)

Figure 3-1: (a) No fire stopping, (b) fire stopping included

The resulting regulatory specifications in the 1970 NBC required that an attic space in wood-framed buildings be separated by "fire stops" which divided the space into compartments no larger than 3,000 ft² or with no single dimension larger than 150 ft [117]. An attic fire stop is illustrated by the green barrier in Figure 3-1(b), and was required to be a solid barrier of one of the following materials [117]:

- approved noncombustible material such as sheet steel, asbestos board or gypsum board,
- solid lumber not less than 2 in. (51 mm) nominal thickness or
- 1/2-in.-thick (13 mm) plywood with joints backed with like material, or two thicknesses of lumber not less than 1 in. (25 mm) nominal in thickness with joints staggered, where the width or height of the opening or space to be fire stopped is such that more than one piece of 2-in.-thick (51 mm) lumber is necessary.

No rationale underlying the attic fire stop requirements was detailed in the NBC. Given the limited understanding of fire spread in concealed spaces in the late 1960s (and even to present day), these specifications instead were based primarily on experience and "expert judgement" of members of the committee involved in their development. Consequently, the effectiveness of the requirements in controlling attic fires was not known at the time of development; instead the actual performance had to be evaluated and demonstrated over time through assessment of the outcomes in related fire events.

Unfortunately, the solution did not perform as intended. Thus, it required re-examination following a subsequent fire at the Fairlane Meadow apartment (a row housing complex) on May 20, 1980 [153] (Fairlane Fire). The Fairlane building was two storeys with a common attic space. The fire occurred at night, initiated by a hot barbecue in a combustible storage shed in an exterior passageway. It spread along the face of the building and into the attic via the soffits. From there, the fire spread through the attic, involving the entire building within approximately 12 minutes, and resulted in the loss of 32 residential units. The combustible soffits and attic space were identified as the key modes of fire spread that led to the involvement of the entire building. More specifically, this was a result of [153, p. 2]:

> *the ease with which the fire could enter the roof space through the overhanging roof soffit, traverse the width of the roof space and emerge on the other side of the building to involve units on the far side. The soffit vents no doubt assisted this process.*

Although fire stopping, as described in the previous section, was required in the attic space of the Fairlane building, the fire stops were not effective [153, p. 4]:

> *Although the NBC requires that combustible attic or roof spaces be separated by fire stops into 300 m² compartments, this was not sufficient to prevent the spread across the roof space and being one of the major contributing factors to the speed of the fire spread. This vulnerability of roof soffits to fire entry has been illustrated on a number of occasions in other multiple unit fires.*

The fire stops alone were considered ineffective in achieving their original intended performance, and the soffits were identified as a key mode of fire spread resulting in significant building fire damage;

therefore, the soffits became the focus of additional regulatory development [153]. This resulted in a reconsideration of the original hazard, which had been characterized as a fire occurring within the concealed space without considering external fire exposure and entry through the soffits. Therefore, the key recommendation following the analysis of the Fairlane Fire was that [153, p. 7]:

> *[a] new Code rule should be developed to require soffit vents on roof overhangs to be fitted with fire-stop flaps, and the soffits constructed as fire separations.*

Based on this recommendation, a requirement was added to the 1985 NBC [154] for buildings with a common attic space above more than 2 suites, which required that the soffit of a roof overhang in proximity to an opening in the exterior wall of the building (i.e., door, window, etc.) be protected by:

- noncombustible material having a minimum thickness of at least 0.38 mm and having a melting point of at least 650°C,
- not less than 11 mm thick plywood,
- not less than 12.7 mm thick waferboard, or
- not less than 11 mm thick lumber.

The rationale for the addition of this requirement to the 1985 NBC was as follows [153, p. 44]:

> ***Experience has shown [emphasis added]*** *that fire can enter roof soffits fairly easily and can expose simultaneously the suites below. This negates the fire separation provided between the suites. The proposed revision is intended to provide additional fire protection for the soffit and make it more difficult for fire to enter the roof space.*

Thus, the attic fire stopping and soffit protection became a combined solution (second iteration) to address the hazard of large combustible attic space fires. This requirement was added to the 1985 NBC based on the assumption (driven by the Fairlane fire) that fire exposure to the soffit would occur as a result of flames issuing from an opening in the exterior wall of a building (compartment fire) and still did not consider additional hazards of potential exposure, such as from an exterior (balcony) fire. Similar to the initial attic fire stop solution, the actual performance of this new combined solution would not be known without demonstration, via real fire events, of the actual performance over time.

As with the original fire stop solution, the limitations in breadth of applicability of this new combined solution became evident as large loss fires in which concealed spaces were a major contributing factor continued to occur. A High-Intensity Residential Fires Working Group (HIRF-WG) was formed in June 2007 as an internal Government of Alberta committee to study large-loss building fires and to make recommendations to the Minister of Municipal Affairs and Housing on ways to reduce the occurrence and severity of such fire events in the future. The HIRF-WG specifically noted that “fires are extremely difficult to extinguish once they enter an unsprinklered concealed roof or attic space and become established” [155, p. 17].

To understand the source of these fires, the HIRF-WG examined fire loss statistics from 1996 to 2005 for fires that had entered concealed spaces within buildings. From these, two key findings drove further

reconsideration of the hazard associated with attic space fires and thus the next iteration of requirements. First, the HIRF-WG found that 567 fires originated on an exterior balcony. Of these, 248 (44%) were attributed to smokers' materials, more specifically involving cigarettes or matches improperly discarded into planters containing combustible materials such as peat moss, and had resulted in $14.7 million worth of property loss [155]. Further, they found that 218 (38%) of the fires spread beyond the balcony of origin and resulted in $26.6 million worth of property loss which constituted 90% of the total property loss for all of the fires (i.e., 567) that had originated on a balcony [155]. The report also noted that scientific research up to that time had focused on how individual materials and assemblies of materials performed under test conditions that simulated fires originating in an occupied interior space and had not considered exterior or attic fires.

Indeed, the NBC at the time permitted wood frame buildings up to four storeys to be sprinklered in conformance with NFPA 13R, but did not require sprinklers in attic spaces or over exterior balconies. The HIRF-WG recommended that sprinklers be installed in concealed, unprotected attic spaces, and over balconies, on the basis that the sprinklers would greatly improve protection against fire spreading from exterior exposures, as had been the case in the events that had historically led to large losses. Nonetheless, the recommendation was not immediately adopted for all buildings since the current edition of the NBC (2020) [21] only requires attic and balcony sprinklers for higher wood-frame residential buildings (i.e., 5 and 6 storeys), but not lower wood-frame residential buildings. Some provinces have more recently superseded the NBC by requiring balcony sprinklers in almost all wood-framed residential buildings [156, 157]. Given that these changes are very recent, sufficient time has not yet passed to establish whether this increased use of sprinklers has achieved the original intent of limiting the size of attic fires. In contrast, the increased prevalence of exterior sprinklers introduces potential unintended consequences, such as damage or failure due to freezing, the long-term effects of which may also become evident over time.

As demonstrated by this example, requirements to limit attic fire size were developed across several distinct "eras," driven by reconsideration of an original hazard following fire losses that occurred between eras of regulatory development. New or modified solutions were developed to address the updated hazard in an attempt to reduce further harm. However, each new solution was added to the previous solution(s) without assessing the holistic impact of the complete set of solutions on limiting fire spread in attic spaces. Further, the actual effectiveness (intended performance) of the new requirements in limiting the impact of the hazard was not evident without the [158] "test of time," which is still unfolding in Canada in the context of attic fires.

The iterative and prolonged approach to regulatory development, as illustrated by the attic example, underlies many of the fire and life safety requirements of the NBC. It primarily relies on "absence-based inference" to demonstrate acceptable performance. This is due to a limited understanding of the impact of fire safety strategies on the relationship between fire hazards and the exposed. A clear limitation in relying on this approach is that direct causality is not established to validate acceptable performance. In fact, even in the case where a reduction of the impact of fire hazard is established, there is also the possibility that it could be due to other independent influences (i.e., materials, methods, and

configurations) that are part of traditional building construction practice, but whose contribution to acceptable performance was not recognized at the time of solution development.

Changes to these practices can result in reductions of expected performance, but manifest over time through unintended outcomes. A recent example of this is the recognition that changes from traditional residential floor assembly construction (I-Joists used instead of solid wood joists) resulted in a reduction of the "implicit" fire-resistance and subsequent stability of these assemblies under fire exposure. Use of this new construction method led to earlier collapse under loading by firefighting activity than had been provided by more traditional construction. The premature failures have resulted in significant research [159] and recommendations to regulate the fire-resistance of residential floor assemblies [160], which are currently relied upon for both occupant and responder safety, but are otherwise not currently regulated. Where I-joists are used, this would require an additional layer of drywall to delay the charring and failure of the I-joist webbing to maintain the original expected level of performance.

To reduce the prolonged process associated with validating the performance of regulatory requirements, building code committees (groups) often apply multiple strategies (the "shotgun" or "belts and suspenders" approaches) during the initial stage of regulatory development to maximize the chance of success in achieving acceptable performance. However, while this method generally seems to be effective, it tends to obfuscate the particular aspects of each of the combined strategies that contribute most to achieving acceptable performance from those that do not.

It is clear, then, from the regulatory development and performance validation process discussed above, why quantitative performance targets have not been established and, indeed, are difficult to establish for the fire and life safety acceptable solutions in the NBC. Key reasons include:

- The acceptable solution requirements are based more on experience than science, without any complete understanding of the impact of fire hazards on the exposed.
- The acceptable performance of these solutions has primarily been validated through the test of time and, in some cases, due to an absence of the hazards which they were intended to limit.
- The actual performance of a given acceptable solution requirement may be attributed to certain aspects of that solution more than others, some aspects may not contribute to its performance at all, or may even be attributed to factors of design and construction unrelated to the application of the requirement.

A further danger with "test of time" processes for regulatory development lies in the inconsistency with which resulting regulatory requirements and the original performance expectations of solutions are recorded and maintained. This can lead to loss of key information over time. The lack of historical information then makes it challenging to evaluate the continued applicability of the requirements as building design and construction practices evolve and new materials are introduced. Another primary contributor to the loss of historical context is generational amnesia. The next section examines the impact of generational amnesia on the retention of critical regulatory knowledge.

3.2.2 Generational Amnesia

A key factor in the loss of historical basis for building code requirements arises due to the finite nature of "memory," whether individual, social, political, or cultural [161]. Individual memory is one's own recollection of personal events and observations such that, as members circulate through the building code consensus committees, a certain portion of the memories of these individual members can be lost if not appropriately recorded. Since codes are developed and reviewed by committees, social (communicative) memory could potentially overcome some of the individual memory loss. However, the horizon of recollection for professional cohorts is still only about 30 to 40 years [162] due to average retirement ages. Beyond this time horizon, memory is said to become political and cultural, which is transgenerational but straddles the line between remembering and forgetting [161], referred to as the "floating gap" [163, 164]. Political memory usually relates to political events and figures that are deemed important, and are enshrined in symbols and practices [161], rather than to more detailed requirements as might be found in a building code. For example, although his ideas were foundational to the original building codes, the following "symbolic" inscription is found on the statue of James Braidwood (Section 2.1.2.3) located in Edinburgh Scotland [165]:

> *This statue is dedicated to the memory of James Braidwood, a pioneer of the scientific approach to fire-fighting. It also recognizes the courage and sacrifice of fire-fighters, not only in Lothian & Borders Fire and Rescue Service, but all over the world.*

Cultural (archival) [164] memory relates to broader historical events preserved in archives that "are neither actively remembered nor totally forgotten" [161, p. 220]. However, when the information is not maintained or exhibited in a public realm, it is gradually removed from common knowledge and, where archived, is generally accessible only to specialists [161]. In the case of an ever-evolving regulatory document such as a building code, these elements lead naturally to a type of generational amnesia whereby information that is not within recent memory becomes "forgotten." It either no longer exists in the public realm or has been archived and is time-consuming and challenging for members of consensus committees or committee staff to retrieve.

The development of the combined set of solutions in the expanded attic fire example spanned nearly 50 years, with approximately 15 to 30 years between each iteration of solution and regulatory development. In this case, the relatively short time frame between iterations might allow for more immediate recollection and reconsideration of the basis for previous solutions since they would be within the time period associated with individual or social memory. However, where the timeframes of regulatory development exceed recent memory, older solutions and their fundamental bases are generally forgotten, complicating reflection and reconsideration during the next impetus for change. This is important in understanding the fundamental and intended interrelationships between specified hazards and protections of the exposed in any portion of the building code. Law describes the impact of "forgetting" in a regulatory context as follows [144, p. 78]:

When there are simple and arbitrary rules, there are always more arguments and disputes than when an engineering approach is adopted, because the underlying technical assumptions are forgotten or not understood.

Thus, updates to, or the post facto incorporation of, fire safety engineering concepts into the requirements that govern fire safety design require an understanding of the historical development of the requirements. However, this is difficult where the development of the requirements predates recent memory and requires archival recovery and analysis, which is complex given the broad timeframe over which regulatory development takes place.

The negative impact of generational amnesia was recently demonstrated during a proposed change to occupant load factors in office buildings in the 2012 Life Safety Code [166]. An occupant load factor is used for building design by US and Canadian building codes to establish the number of occupants as a function of use (i.e., office) and on the basis of floor area. The number of occupants is then used for sizing of exit facilities and other associated design features. The occupant load factor for offices in both the US and Canada[5] at the time was 9.3 m²/Person (100 ft²/Person) [21]. The proposed change was to modify the office occupant load factor in the 2012 Life Safety Code from 100 ft²/Person to 150 ft²/Person. A research report [167] which analyzed the history of the existing occupant load factor and included more current statistical surveys of office occupant loads was submitted in support of the proposed change. The report concluded that "there is no formal record indicating the basis of the occupant load factors" [167, p. 3]; however, it was speculated that it originated from the 1934 edition of the Building Exits Code [168]. Even though the research report included some historical context and a much more current survey of actual office occupant loads, the proposed change was rejected, in part, due to a lack of data (historical and statistical) [169].

This example highlights several key factors associated with how generational amnesia, timeframes, and complexity of code requirements are interrelated. The period between when the occupant load factor was assumed to have originally been developed (1930s) and the year the historical research of the occupant load factor was conducted (1996) is on the cusp of the timeframe for social memory. Therefore, it is implausible that the original information, which was deemed as necessary in support of the change, could be readily retrieved from living memory. It was more likely only available through a search of archival information. As noted in the research report [167], a review of the archival information yielded limited results, which implies that the information was either not initially recorded, not available, or that the search was limited due to complexity. Therefore, no matter how technically robust the newly proposed and statistically determined occupant load factors actually were, the lack of ability to compare the new values to the original technical basis for the existing factor raised doubt in the minds of the modern era technical committee of the need for change and even precipitated fear that change could result in catastrophic consequences[6].

[5] The office occupant load factor in the current NBC has remained unchanged since the 1941 NBC and was adopted from the US model building codes as discussed in Section 2.1.4.

[6] Due to their "test of time" approach (discussed above) and status quo bias (discussed below).

As such, loss of records in support of past decisions (generational amnesia) can have a significant impact on regulatory reform particularly when the information underlying those requirements is not known or is considered too complex to obtain or interpret. This loss of historical context is further complicated by factors such as status quo bias and adherence to traditional practices. The following section examines how these biases hinder regulatory evolution as well.

3.2.3 Status Quo Bias and Traditional Practice

In response to the proposed office occupant load factor code change example above, one of the commenters who voted against the change noted that [170, p. 101-61]:

> *The current Occupant Load Factor, which has proved to be adequate for 75 years, should not be changed in the absence of sound technical justification.*

This is an excellent example of the status quo bias, which "is the belief that it is beneficial to remain in the current state, even when more—or similar—value from change is obtained" [171, p. 2]. Status quo bias can greatly impact decision-making as is further supported by Hofman who found that the building sector is a conservative industry when faced with the adoption of innovative and sustainable technologies [171]. The key factors limiting the adoption of these technologies are status quo bias and confirmation bias, which are exacerbated by lack of continuously updated knowledge and the imposition of increasingly complex information (hassle) [171]. Confirmation bias is "an inclination to interpret information in support of current beliefs" [171, p. 2]. Hofman notes that [171, p. 14]:

> *As information about innovative technologies is increasingly seen as complex, it tends to be perceived as a hassle and avoided more often, [which] increases the chance of biased behavior.*

Hofman's findings equally apply to changes to the existing acceptable solution requirements, and the limitations in the adoption of fire and life safety performance concepts and performance-based frameworks [172]. These are exacerbated by the current situation in which fire safety design is predominantly governed by the application of fire safety requirements as opposed to being based on a strong foundation of the principles of fire safety engineering. While some fire safety requirements have a basis in fire science, the science is not explicit in the requirements, nor is an understanding of that science needed to apply the requirements to building design. Much of what may have originally existed has now been "forgotten" (Section 3.2.2) over time. Thus, where regulatory practitioners, often without fire safety engineering background, are faced with the complexities of obtaining and understanding the information required to support alternative solutions and performance-based design, their tendency is to rely on the existing requirements and framework as the performance benchmark (the comparative approach). This tendency was noted by Bergeron [127] relative to Canada's selection of their acceptable solution benchmarked objective-based framework over a full performance-based framework [127, p. 1]:

> *enforcement officials…feared that the introduction of performance-based codes would create an "anything goes" atmosphere.*

This apprehension is one of the primary forces that led to the deliberate focus of the NBC objective-based framework on the "status quo" and primarily prescriptive and legacy acceptable solution requirements to define performance. This was a key factor limiting a full transition to a performance-based framework and effectively maintained the existing regulatory content, albeit with a slightly different structure.

The tendency to maintain the status quo in the absence of accessible, sufficient, or readily comprehensible information arises, at least in part, as a somewhat circular artifact of the approach used in the historical development of fire and life safety requirements. Due to the inherent focus on limiting undesirable events that have occurred in the past, risk-based decision-making, referred to as "bootstrapping" [173], can easily drive the final outcomes. Those who utilize this approach consider that [173, p. 50]:

> *Society achieves an acceptable tradeoff between risks and benefits only through a protracted period of hands-on experience that allows for trial-and-error learning. ['test of time' or 'tried and true']… The safety levels achieved with old risks provide the best guide as to how to manage new risks.*

Unfortunately, however, a "bootstrapping" approach assumes that methods derived from past experience are effective and equally apply to future situations. Rather than freely considering potential advances in scientific knowledge or changes in materials or practice that might improve a requirement, this approach relies on past policies and requirements to prescribe future actions. This fosters status quo bias, which tends to limit the acceptance of alternatives [173], and encourages conservative decision-making even when it may be misguided. As a result, the desire to hold on to conventional (traditional) practice is so strong that it becomes a hinderance to innovation [11, 144]. Any effort to improve upon the existing regulatory framework is seen as too complex, and even too disruptive, by those responsible for the regulations [172]. The continuation of the status quo limits change within the bounds of existing systems and practices without acknowledgement of any new knowledge of fire science or fire engineering. The result is that new requirements are built upon the existing ones regardless of their actual effectiveness, which as noted earlier, may not be known.

This accumulation of requirements without adequate reflection leads to a phenomenon known as the regulatory ratchet effect, which contributes to the rigidity of the current framework. The next section explores how this effect also limits acceptance of alternative solutions and the transition to a performance-based framework.

3.2.4 The Regulatory Ratchet Effect

Catastrophic fire events that result in harm are often considered to be a failure of regulations or of the responsible agencies whose duty is to protect the public from harm. The consequence is pressure to identify further hazards, close gaps in existing regulations, and draft new regulations [174]. To compound this situation, bad actors find and exploit regulatory loopholes to make arguments related to the event,

which result in further harm and criticism, drawing focus toward these agencies and prompting continued upward regulatory reform. Even without ongoing major fire events, reminders of past failures are strong motivators for continued reform.

Since regulatory agencies for fire and life safety are charged with making regulations to protect the exposed against hazards and consequent harm, it could be said that "[i]f the only tool you have is a hammer, it is tempting to treat everything as if it were a nail" [175, p. x]. Added to this is an underlying perception or belief that regulatory expansion and upward reform is synonymous with enhanced safety. In reverse, this belief is reinforced by the notion that, if not for the current regulations, safety would be compromised, a view that is further strengthened by the recollection of past catastrophic events and associated regulatory failures. This permeates our regulatory systems to the extent that any proposed, or perceived, roll-back of regulations is seen as an affront to safety. This inherently imbues a type of "attribution" bias whereby a lack of harm is attributed to a solution and removal of the solution is believed to lead to the harm, despite whether the solution is actually effective in reducing the harm[7]. This is also the process, as discussed earlier, primarily used to validate acceptable performance of solutions by inference through absence.

The net result is a regulatory process that is continuously expanding and reforming upward, with little, if any, reduction, re-evaluation, or downward reform. This is called the [174] "regulatory ratchet effect," through comparison to a ratchet that moves incrementally in one direction and locks, limiting backward movement. The regulatory ratchet effect is evident in the attic fire example. Following the original analysis that required fire blocks in attic spaces, further reflection was not conducted at each subsequent "era" of analysis to establish whether the new requirements were supplementary to, or superseded, the original solutions that were already embodied in the requirements to limit ultimate fire size. Ferguson describes this same effect in the context of the development of the NBC [11, p. 51]:

> *The development of building regulations today is an aimless process…In the broadest sense, building regulations develop from contingency to contingency. Each one represents an emergency measure taken with very little or no study. As the emergency recedes, the regulation tends to form part of traditional practice. It is added to the pile, which grows and grows.*

The regulatory ratchet effect then restricts regulations such as the NBC to be primarily additive, without regular reflection or correction. As a result, regulation rarely recedes even though the current reasonableness of most regulations has not been analyzed to any great extent [175]. This may not even be due to lack of trying by certain proponents, but instead can be via delays and apparent lack of progress due to prolonged processes, frustrated by bureaucratic policies and procedures [175], all further exacerbated by limited availability of information required to support change (i.e., generational amnesia). The result is avoidance of changes considered substantial, regardless of their potential benefits, and a

[7] Note that the opposite effect has also been observed where a certain harm has been reduced by a solution, but the relationship between harm and solution has been forgotten, resulting in an abandonment of the solution and a resurgence of the harm [176].

focus instead on limited and incremental variations to existing regulations. The resulting slow and restrictive process significantly lags behind the pace of change in building design, materials, and construction that the building code is intended to address.

Even when a regulation is not under dispute and regulatory flexibility is sought through alternative solutions, which are permitted by the NBC at the discretion of the enforcement authority, similar forces work against the proponents of a novel solution. In general, enforcement officials are instructed to take the conservative approach to enforcement which is to "go by the book" (the NBC acceptable solutions in this case) to limit liability and the potential for public criticism. An issue arises, however, in that enforcement officials know the "book," study it, are proficient with its application to building design and construction, but they may not understand, or even have access to, the technical background and reasons for many of the requirements. Consequently, when assessing any deviation from a specified solution, no matter how technically robust it may be, they often perceive the new solution as falling short of ensuring an equivalent level of safety. Given the potential consequences of catastrophic harm associated with fire events, enforcement authorities are more likely to be held liable for harmful regulatory failures due to perceived lax enforcement than to be blamed for enforcing inflexible and costly measures [174], thus also reinforcing status quo bias discussed earlier.

The result is a building code system that purports flexibility but is inflexible in its implementation. Flexible regulatory frameworks, such as performance-based codes, are complex and challenging to develop, implement, and administer. They largely benefit the regulated entities and not the regulatory or enforcement agencies [174]. Enforcement officials would require a higher level of technical sophistication, combined with broader documentation of decision-making processes, in order to facilitate more discretionary application of the regulations [174]. This is a significant departure from the current enforcement regime. It would require significant resources with little perceived benefit to either the regulatory agencies or enforcement officials who govern the current regulatory framework of the NBC.

The longer the cycle of regulatory ratchet effect continues to drive evolution of the NBC, the more complex and unwieldly the NBC becomes. Tradition is being frozen in regulation [11], and the regulations are becoming increasingly detached from the knowledge and experience upon which they were, or should be, based. As the NBC becomes entrenched, it is also becoming increasingly difficult to roll back, even for those portions that are outdated or no longer necessary. Thus, our current rigid regulatory framework, bogged down in bureaucracy and resistant to change, is a major factor in limiting acceptance of alternative solutions and limiting any shift to a performance-based framework that would allow the building construction innovation that is increasingly becoming necessary to achieve current and future objectives. In this, the lack of quantifiable performance criteria limits the ability to objectively assess fire safety solutions, suggesting the need for a risk-based approach. Compounding these challenges is the issue of shifting baselines of acceptable performance and risk. The next section discusses how shifting baselines further complicate the establishment of consistent performance metrics.

3.2.5 Acceptable Performance (Risk) and Shifting Baselines

Transitioning from the current inflexible system to more performance-based approaches will rely on designers, regulators, and enforcement agencies reaching a consensus on a set of baseline values against which to judge performance. As discussed earlier, the performance of acceptable solution designs serves as the baseline against which alternative designs are currently measured. However, the levels of performance of these are not static; they tend to shift over time. This effect has been recognized in other disciplines, such as fisheries conservation, as the "shifting baseline syndrome" [177]. Pauly contends that researchers accept fishery stock size and species composition at the start of their career as representing the baseline by which future change is assessed. Each subsequent generation of researchers develops a new (reduced) baseline. The result is a gradual shifting of the baseline that, when paired with generational "forgetting," limits understanding of long-term consequences (or lack thereof). The shifting baseline concept has been characterized in other disciplines as well:

- Kahn identified a shifting baseline of pollution levels in cities in the US where the question of "[h]ow could children who know about pollution in general and live in a polluted city be unaware of their own city's pollution?" [178, p. 106] The conclusion was that "if one's only experience is with a certain amount of pollution, then that amount becomes not pollution but the norm against which more (or less) polluted states can be measured at a later time" [178, p. 106].
- Spennemann identified that "shifting baselines in heritage studies are real and have a significant effect on the validity of the outcomes of these studies" [179, p. 5].
- Craig noted that the shifting baseline syndrome "arises when a long-existing public legal regime so successfully eliminates a societal problem that citizens, politicians, and lawmakers forget that the regime is in fact still working to keep that problem at bay" [176, p. 2].
- Rost considered the shifting baseline syndrome in an interdisciplinary context and relates the shifting baseline syndrome to generational amnesia (Section 3.2.2), emphasizing that it emerges from generational "forgetting" [164].

While these observations of shifting baselines are negatively correlated to the desired outcomes (i.e., a gradual degradation), the shift in the acceptable baseline level of fire safety performance would be positively correlated (i.e., perception of increased safety). This means that the level of fire and life safety each generation experiences in their youth is the baseline by which future incidents that reflect negatively on that baseline are judged, studied, and new requirements are developed to limit future occurrences. This cycle continues through incremental changes to ostensibly improve fire and life safety performance and reduce risk, which then becomes the new and acceptable baseline level of performance (risk) for each new generation.

An example of the shifting baseline for acceptable level of performance is the requirement of sprinkler protection over time. The first successful commercial automatic sprinkler was patented by Henry Parmelee in 1874 [180]. Voluntary use of sprinkler protection allowed for an increase in building area by 50% to

66.7% in the 1905 NBFU Model Building Code [57]. Similar building area increases were permitted in the 1941 NBC where sprinkler protection was provided [105]. The benefits of sprinkler protection were recognized then as an optional and added benefit to improve life safety and property protection, but were not well quantified and were not yet a required measure.

Mandatory sprinkler protection was eventually incorporated in the 1953 NBC for certain high hazard locations, but not for whole buildings. This was discussed during a committee meeting where it was noted that "it was beyond the scope of the code to require sprinklers in any occupancy" [181, p. 6]. However, this changed in the 1960 and 1965 NBC [110, 111] that required sprinkler protection of some school buildings and large retail buildings. This gradual shift to mandatory sprinkler protection was recognized in a negative context by Ferguson as a ratcheting of the existing measures (Section 3.2.4) with little reflection [182, p. 11]:

> *Despite the higher factor of safety in larger buildings it is the practice in many building by-laws to take further precautions by restricting the combustible load and requiring non-bearing partitions, interior trim and even furniture to be non-combustible and* ***sometimes sprinklers are required on top of all this [emphasis added]****. To the author of this paper this appears to be a malpractice.*

Between the 1970 and 1990 NBC [117, 154, 183-186], several additional building types required mandatory sprinklering; however, this was more of an exception than a rule. Mandatory sprinklering was eventually required more universally in the 1995 NBC [187] for all buildings over approximately 3 storeys in building height. Mandatory sprinklering would have applied to all building types if not for concerns over water supply in smaller towns and remote locations [188]. At approximately the same time, all buildings in the city of Vancouver were required to be sprinklered [189], regardless of building size.

The sprinkler protection example illustrates the gradual shift of acceptable performance (acceptable risk) that has characterized the evolution of the NBC. Similar acceptable performance (acceptable risk) baseline shifts have been observed in the development of other aspects of the NBC. Raising the baseline of acceptable performance in building regulations (resulting in risk reduction) may seem like a positive outcome. However, the shifting baseline can also result in negative outcomes. When the basis of requirements is forgotten (generational amnesia), baseline shift amplifies the status quo bias and by doing so, indirectly contributes to the ratchet effect. Ferguson describes this phenomena noting that [11, p. 34]:

> *[t]he way buildings look becomes the way they ought to look, [and] [i]t is, in effect, what the individual has got used to that forms the norm that is the basis for his judgement.*

The combined effects of generational amnesia, status quo bias, and the ratchet effect, amplified by upward shifting baselines of performance, taken together, greatly impede the change necessary to transition the NBC from objective-based to performance-based. Instead, they maintain a more traditional than progressive approach to fire safety design. Understanding these impediments is key to recognizing why two distinct approaches to fire and life safety design have emerged in Canada and possibly other countries. The next section discusses these two approaches and their implications for the future of fire safety engineering design.

3.2.6 Two Approaches to Fire and Life Safety Design

In addition to the biases and other factors listed above, the lack of movement to performance-based codes in Canada has been attributed, in part, to the lack of maturity of fire safety engineering as a discipline. This limitation is compounded by an education system that focuses on training fire safety technicians rather than educating engineers in fire science [190]. At the same time, fire engineering has been recognized elsewhere as a discipline since at least the 1880s [191], with establishment of the first post-secondary four year course in fire protection engineering in the US in 1903 [192]. Other arguments are circular to this and claim that the maturity of fire safety engineering and associated acceptance of performance-based design has been constrained by [140, 190, 193]:

- Reliance on prescriptive solutions.
- Limited means to quantify acceptable levels of performance.
- A focus on comparative analysis over holistic solutions.
- Limited guidance on the appropriate application of, or framework under which to apply, fire safety engineering analyses.

All of these points have been discussed above, with particular emphasis on the reliance on prescriptive solutions as the benchmark of acceptable performance. It has been suggested that part of the issue is that more traditional engineering disciplines have matured through professional reform that follows a cycle of "failure-concern-response" but that fire safety failures have more often led to regulatory reform than professional reform [140]. Requirements that follow the most current principles of engineering practice are by necessity performance-based to facilitate the evolution and application of the best practice of the discipline (see Part 5 of the NBC and building envelope engineering), which would otherwise be limited by specification-based requirements. In contrast, when engineering practice follows regulatory development, such as the present case for fire safety engineering under the NBC, it is governed by the application of the requirements and is not grounded in the practice of, and science behind, fire safety engineering. Therefore, it is unduly limited by the constraints of the requirements and the attitudes of those who practice within them.

Deakin makes a similar claim [194] that building regulations are not based on engineering, but a set of "prescriptive" requirements. Further, he notes that had fire safety design developed in the 20th century (much like building envelope engineering), the regulations would have an engineering base [194]. The present exception to this situation arises when a particular aspect of a design does not directly comply with the regulations; in such cases, fire safety engineering design becomes the only means of rationalizing an alternative solution. This will, however, not typically be a holistic solution [144] but instead will be justified by a comparative approach. The implication is that fire safety design is governed by two approaches [172, 195]:

1. the application of fire safety regulations (i.e., building code consulting) for design, and

2. the use of fire safety engineering principles to accomplish a design that meets a set of performance criteria.

The more predominant and established of these approaches is the first, the application of fire safety regulations as a basis for fire safe design, which may involve fire safety engineers but mostly employs other practitioners and authorities who do not necessarily have background and understanding of the principles of fire science or fire engineering in the application of these regulations. At present, it is possible to practice “fire safety design” without any knowledge of fire science or fire safety engineering.

This has led to a focus on training technicians in support of the industry. In fact, whole industries and organizations have been established in response to and in support of undertaking fire safety design according to the current primarily specification-based regulatory framework. This has occurred because the framework is assumed to lead to fire safe building designs without any clear understanding of the implicit technical foundation on which it is based. While some aspects of a building design may actually be fire safe in spite of the regulations, designs are often accomplished through strict use of materials [11] and methods that are claimed to have instead stood the test of time [158] for fire safety, enforced by statements that promote fear that any change in that system will result in catastrophe, reflecting status-quo bias and regulatory ratchet effect.

Consequently, there is limited desire for change and even concern that change could bring about unsafe buildings, particularly in the absence of an “acceptable” or better, superior alternative, to the existing regulatory-based practice of fire safety design. This ultimately limits acceptance of alternative solutions and the ability to transition the current system to a performance-based framework that facilitates more flexible “first-principles” analyses.

To overcome these challenges, it is important to holistically and consistently integrate fire science and fire safety engineering concepts into the regulations governing fire safety design. This integration not only addresses current challenges but also establishes a basis for future advancements. Achieving this without supplanting the existing “tried and true” methods, which have demonstrated acceptable performance over time [158], is critical for such an integration. While this may be difficult for those unfamiliar with the link between current requirements and fire science principles, similar shifts have succeeded in other disciplines, such as structural engineering. Importantly, it would allow fire safety engineers to more holistically practice fire safety engineering, allow further evolution and maturation of the discipline, and facilitate the development of a next generation building code with a scientific and performance-based framework.

It is clear from the review in this chapter that bridging the gap between traditional practices and engineering principles requires a detailed historical analysis of the acceptable solutions of the NBC. Identifying initiating fire hazards and evaluating mitigation strategies to limit their impact allows for a better understand their effectiveness. This requires a comprehensive characterization of fire risk to quantify how well solutions mitigate impacts on people and property. The present research aims to develop and validate a methodology by which to address these challenges. As necessary background, the next section delves into risk concepts, assessment methodologies, and analytical frameworks essential for

enabling this analysis within a regulatory context, and to realize a performance-based framework for the NBC.

3.3 Risk as a Measure of Performance

Despite numerous innovative approaches and new frameworks [195-202] proposed over the last 20 to 30 years to facilitate the adoption of performance-based methods in building codes, a significant barrier remains. These approaches, while important to the development and adoption of performance-based concepts, have not fully addressed the key issue limiting their acceptance in Canada, which is the reliance on specification-based practices developed through the "test of time" and the absence of fire hazards to confirm acceptable performance. This approach is protracted and offers little empirical validation of actual performance. Central to advancing and implementing a next-generation performance-based framework for the NBC is the ability to scientifically reconcile historical regulatory requirements with modern fire science and fire engineering principles. A critical element in this reconciliation is defining and verifying acceptability in terms of risk.

This section focuses on the technical aspects of risk assessment, reviewing key scientific principles and risk-informed methods fundamental to the development of a robust performance-based framework that forms the essence of this research. To support the shift from the current "test of time" and "absence-based inference" methods of performance assessment to one that quantitatively defines acceptable performance in terms of risk, it is important to develop methodologies that integrate quantitative risk analysis into the NBC. This integration requires not only the development of new performance-based design approaches, as noted above, but also a critical evaluation of existing regulatory requirements within a risk context. To this end, the following sections review the extent to which risk has been incorporated into the current NBC and examine an approach to risk characterization in the context of regulatory development. They also present a risk-structured framework that facilitates the development of performance-based design solutions aligned with objectives and acceptable risk levels at a societal scale.

3.3.1 Risk in the NBC

The development of the objective-based framework of the 2005 NBC introduced risk terminology fundamental to the specification of the objectives, functional statements, and intent statements. As an example of their use, Sentence 3.1.3.1.(1) of the NBC [21] requires that major occupancies be fire separated from other adjoining major occupancies to achieve the following (risk-related terms are emphasized in bold):

- Objectives [21, Div. A, pp. 2-2, 2-5]:
    - "OS1 Fire Safety: An objective of this Code is to limit the **probability** that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable **risk** of **injury** due to fire. The **risks** of **injury** due to fire

addressed in this Code are those caused by—OS1.2 - fire or explosion impacting areas beyond its point of origin."

- "OP1 Fire Protection of Buildings: An objective of this Code is to limit the **probability** that, as a result of its design or construction, the building will be exposed to an unacceptable **risk** of **damage** due to fire. The **risks** of **damage** due to fire addressed in this Code are those caused by— OP1.2 - fire or explosion impacting areas beyond its point of origin."

- Functional statement [21, Div. A, p. 3-1]:
  - "F03 To retard the **effects** of fire on areas beyond its point of origin."
- Intent statement [131, p. 2]:
  - "To limit the **probability** that a fire will spread from one major occupancy to an adjacent major occupancy having a different degree of fire **risk**, which could lead to **harm** to persons [or] **damage** to the building."

The objectives, functional statements, and intent statements in this example are attributed to the acceptable solutions, intended to reduce the impact (consequence) of a hazard. In this instance, it is done by provision of a fire separation with a certain fire-resistance rating designed as a function of the major occupancies that are separated. While some explanation of the addressed risk is provided, the information is wholly qualitative. However, without a common means to quantify key risk factors and acceptability criteria, subjective and artificial representations of risk can result.

As discussed earlier, application of, or comparison against, the acceptable solutions in the NBC is intended to bring about safe buildings by reducing what would otherwise be unmitigated risk. The NBC characterizes this process of risk mitigation as follows [21, Div. A, p. 1-18]:

> *The risk remaining once the applicable acceptable solutions in Division B have been implemented represents the residual level of risk deemed to be acceptable by the broad base of Canadians who have taken part in the consensus process used to develop the Code.*

This description implies that risk is quantifiable and that acceptable risk is judged through a political balance of social values [173, 203, 204]. These factors embody the concept of "safety," a subjective term used throughout the NBC to describe a desirable attribute of the built environment and listed as a prime objective of the Code. It also serves as a fundamental descriptor of the acceptable outcome of risk mitigation (e.g., fire and life **safety**). Two key elements are required to establish safety [203]:

- assessing (measuring) risk, and
- judging the acceptability of risk.

The first element is an empirical and sometimes a probabilistic exercise [203] that informs the second element, which is a contextual value judgement of the acceptability of that risk [173, 203, 204]. This is a decision-making process, as discussed earlier, whose actual outcomes are fully realized only over extended periods (i.e., through performance evaluation over time). Risk-informed solution development, however, can expedite the confirmation of acceptable performance and, through quantification, more effectively support decision-making on acceptable risk within the consensus process.

To support this assessment methodology, the following section reviews methods for characterizing risk within a regulatory development context. This review is critical for translating the qualitative risk concepts embedded in the NBC into quantifiable metrics that can then be systematically evaluated.

3.3.2 Fire Risk Characterization (Quantifying Risk)

The absence of rationale and quantitative performance criteria associated with the fire and life safety acceptable solutions in the NBC has been identified as a significant barrier to the adoption of alternative design solutions. However, this issue alone does not fully capture the scope of the challenge. Contemporary understanding [205] defines "performance criteria" as threshold values for evaluating outcomes but typically excludes critical elements of fire risk that influence those outcomes, such as fire size, location, and smoke toxicity (hazard); the number and movement of people (exposed); and the relationship between them (relationship). This gap has been addressed in other jurisdictions, such as New Zealand [206], that have begun to incorporate such pre-approved criteria and methods into their building codes to characterize these elements. Therefore, facilitating alternative designs and transitioning to a performance-based framework requires not only the identification of quantitative performance criteria but also the characterization of these key risk elements.

Risk characterization is challenging since risk is a complex concept not defined by any particular unit of measurement, analytical method, or degree of quantification. Application of the concept enables the evaluation of potential harm and damage that could result from exposure to a hazard. This information can then be used to facilitate decision-making amid uncertainty and in various contexts. There is no one common definition of risk. Instead, there are multiple definitions (at least 13 [207]) depending on the specific context in which it is examined, the factors important to its application, and the nature of the expected outcomes. Meacham provides a definition of risk in a regulatory context as [201, p. 50] (restructured as a list):

> *the possibility of an unwanted outcome in an uncertain situation, where the possibility of the unwanted outcome is a function of three factors:*
>
> 1. ***loss** or **harm** to something that is valued,*
> 2. *the **event** or **hazard** that may occasion the loss or harm, and*
> 3. *a judgement about the **likelihood** that the loss or harm will occur.*

These (risk) elements can be expressed in various ways and with differing terminology [204] depending on the context in which risk is being examined. These risk elements correspond to the terminology used in the SFPE Handbook of Fire Protection Engineering [204, p. 2820]:

- Hazard (event): "any situation that has the potential for causing injury to life or damage to property and the environment" (something that is valued).
- Consequence (loss or harm): a measure of the impact of a hazard (event) to life, property or the environment (something that is valued).

- Probability (likelihood): has the following governing approaches
    - Frequentist: probability is the proportion of the time a hazard (event) will occur in the long run.
    - Subjective: a measure of the strength of belief concerning the occurrence or non-occurrence of a hazard (event).

The intent statement from earlier, associated with the separation of major occupancies by a fire-resistive barrier, is shown below with the three key elements of risk identified by Meacham [201], highlighted in bold [131, p. 2]:

> *To **limit the probability [Factor 3]** that a **fire will spread from one major occupancy to an adjacent major occupancy having a different degree of fire risk [Factor 2]**, which could lead to **harm to persons [or] damage to the building [Factor 1]**.*

While the key elements of risk are identified and linked in the intent statement, there is no quantification of these elements to facilitate understanding of the level of performance of the associated acceptable solution. Risk characterization is essential for addressing this challenge and translating the qualitative risk concepts embedded in the NBC into quantifiable metrics that can be systematically assessed. By quantifying the risk associated with existing acceptable solutions, their actual effectiveness in mitigating fire hazards can be evaluated more efficiently than relying on the traditional performance confirmation obtained via "test of time" and "absence of impact" methods. Quantitative assessment not only validates the adequacy of the existing requirements but also identifies areas where improvements may be needed. Furthermore, risk characterization is key to the development of future requirements, as it provides a data-driven basis for incorporating new technologies, materials, and design practices into the NBC.

The following sections present and review important concepts toward multi-step approaches to risk characterization in fire safety. In general, they include: identifying key fire hazards; characterizing the people and property exposed to these hazards; understanding the empirical relationships between fire hazards and those exposed; the process of developing and assessing solutions to mitigate risk; and considering the acceptability of regulatory solutions in reducing the impact of fire hazards on people and property.

3.3.2.1 Characterization of the Fire Hazard

According to a quote often attributed to Albert Einstein, "the formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill." Appropriately defining the hazards (the problem in this case) is therefore a crucial step in designing effective strategies to mitigate fire risk[8], as was demonstrated in the attic example. This is vital not only for the development of new strategies, but also in review of existing strategies in light of a more current

[8] The implications of not accurately characterizing the hazard(s) were illustrated in the attic fire example in Section 3.2.1.

understanding of fire science and fire engineering. To this end, fire hazard can be subcategorized as follows:

1. Magnitude of fire including fire ignition, fire growth and spread, and
2. Impact Phenomena: heat and products of combustion.

In the context of performance-based design, fire can be considered as an escalating hazard that is characterized as a function of stages of development within, and spread between, buildings. Thus, key elements of each of these sub-categories are discussed briefly here for context, though in reality each of these comprise whole subdisciplines of fire science and fire safety engineering.

Fire initiates and grows through distinct stages as a function of the surrounding environment. Fire characteristics in each of the stages are used to better define hazards and potential impacts related to a given building design.

Ignition and the subsequent incipient sustained burning (fire) are a result of the following combination of factors [208]:

- **Ignition Source:** source of energy able to cause sustained combustion of a material in the surrounding air.
- **Combustible Material:** the type and form of material (fuel) that the ignition energy comes into contact with.
- **Circumstances:** the circumstance, activity, failure that bring the above factors together to allow a fire to occur.

There are numerous possible combinations of these factors that exist within buildings, presenting the designer with a challenging task, and one that is exacerbated by the fact that the nature of these factors constantly evolves with changing technologies, occupant behaviour, and material properties.

Once ignition has taken place, it can lead to incipient burning and fire growth given an appropriate combination of the key elements that govern the combustion reaction including availability of combustible fuel, heat feedback from flames, and supply of oxygen (air). The combination of these factors is often represented by the fire triangle [6]. The absence of any one or more of them interrupts the combustion process. Thus, mitigation of a fire can be achieved through provision of strategies that result in such an interruption, leading to the eventual extinguishment (i.e., sprinklers). On the other hand, the enhancement of any of these factors can result in increased fire growth. Thus, the environment surrounding a fire can have a significant impact on fire growth. A fire located in an open (unconstrained) environment can be characterized by basic diffusion flame behaviour, illustrated in Figure 3-2. This involves pyrolysis of a combustible surface by heat from the flame above, and then mixing (diffusion) of the pyrolyzed fuel and air (oxygen) to react at an optimum ratio to produce heat, light (flame), and reactants (byproducts). The byproducts of this combustion reaction, along with unreacted fuel and air, then rise buoyantly away from the flame, entraining additional air as they rise. The flame flow dynamics shift from laminar to turbulent with increasing involved fuel diameter and height above the fuel surface.

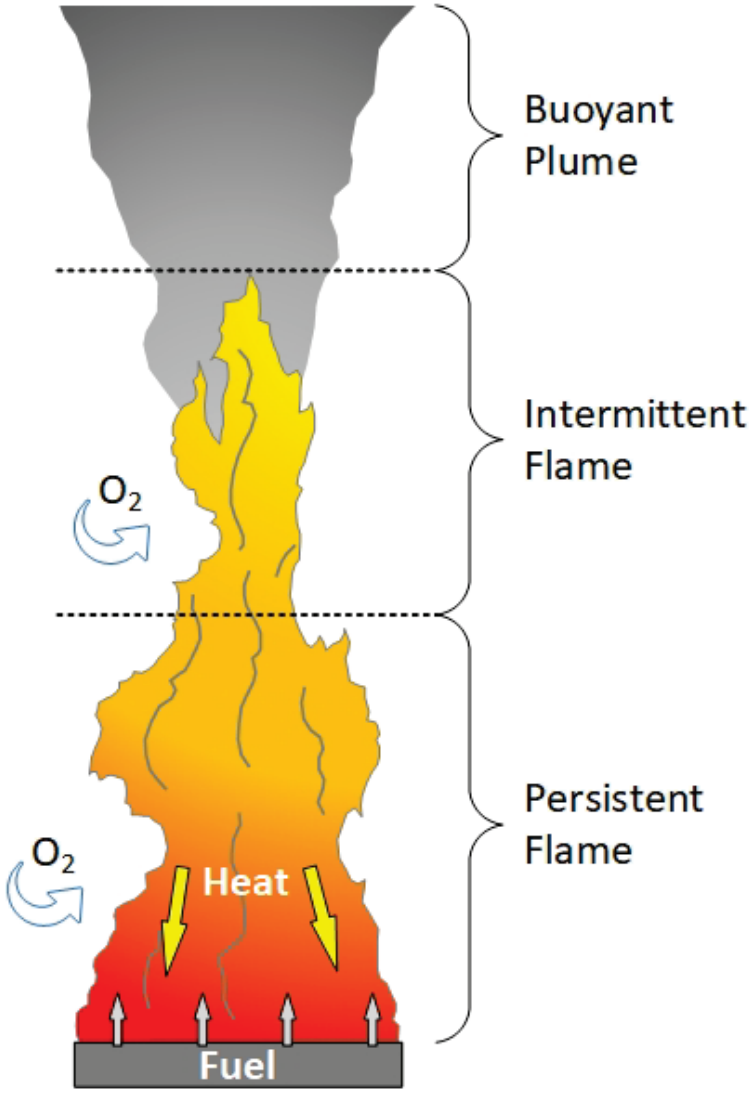


Figure 3-2: Diffusion flame schematic

In an interior situation, the dynamics of such a free burning fire are impacted by boundaries such as compartment walls and ceilings, which lead to much more complex compartment fire dynamics. In the early stages, a compartment fire follows the above description with the free burning fire established on the item first ignited as the fuel source. As the fire grows, the plume becomes constrained by the compartment boundaries and forms a heated upper layer below the ceiling. This layer descends at the same time as the flame height increases and begins to spread along the ceiling. Radiation heat transfer from the growing fire results in heating and ignition of additional combustible items (furniture) and materials (wall linings) within the compartment remote from the item first ignited, further increasing the fire size and potentially resulting in flashover within the compartment. Flashover is a dangerous and rapid transition in fire behaviour from localized burning to full compartment involvement caused by progressive ignition of all combustibles within a compartment. The important transition in fire behaviour through flashover depends on the following factors:

- **Combustible material:**
    - **Quantity and energy density:** The quantity and energy density is specified via the fuel load of a compartment associated with its occupancy classification, typically expressed in kg/m² or MJ/m². A higher energy density increases the probability of fire growth and transition through flashover, as well as the duration of full compartment involvement, as addressed by Ingberg in his correlation [79], which was incorporated into the 1953 NBC [108].
    - **Configuration:** The distribution of combustible material within a compartment can have an impact on fire growth and transition. The more evenly distributed the fuel load, the higher the probability of fire growth and spread. This is particularly the case for combustible compartment lining materials on the upper walls and ceiling, which are currently regulated by the NBC. The area of exposed fuel surfaces can also have an impact on the rate of burning.
- **Ventilation (height and area):** The height and total area of ventilation openings (i.e., windows and doors) can have an impact on the rate of fuel consumption if the fuel burning rate is not already limited by the fuel surface area. The greater the height and area of ventilation openings, the greater the supply of air (oxygen) to the compartment to fuel the combustion reaction. Ventilation is not currently incorporated in the NBC fire and life safety requirements.
- **Compartment size and configuration:** The larger a floor area and higher the ceiling, the longer it takes for development of a comparable/significant heated upper layer, reducing radiant heat transfer to lower-level fuel surfaces. This can prolong localized burning within a compartment. This is also not currently incorporated in the NBC fire and life safety requirements.
- **Compartment boundary thermal properties:** The greater the insulating properties of the compartment boundaries, the greater the heat buildup within the compartment and temperature of the compartment boundary materials with increased burning rates, probability to ignite combustible boundary materials and/or for a fire to transition through flashover. This is not currently addressed in the NBC fire and life safety requirements. However, this effect may be exacerbated as buildings are required by the NBC to be designed for greater energy efficiency through enhanced thermal performance and higher-effective R-value exterior wall assemblies [147].

A dangerous combination of these factors in a given fire situation can result in full compartment involvement, which is a near-steady and continued burning of all combustibles until substantial depletion occurs. Full compartment involvement is the hazard that was intended to be addressed through Ingberg's development of the fire load and containment of burn-out concepts, including the fire-resistance of fire compartment boundaries. However, this was at a time when the influence of the key factors noted above was not as fully understood as it is today.

Full compartment involvement is characterized by a high, relatively uniform temperature throughout the fire compartment with a rate of burning that is governed by the more restrictive factor of either fuel burning surface area or available ventilation. During this stage, heat, flames, and products of combustion

can extend through compartment openings, potentially leading to further spread of the fire depending on configuration of adjacent compartments and location within a building.

Once the combustible contents within a compartment are almost completely depleted, the fire begins to decay. This will result in a reduction in temperature and eventual cessation of combustion. A simplified time temperature curve schematically illustrating the progression of these various stages of compartment fire growth is included in Figure 3-3.

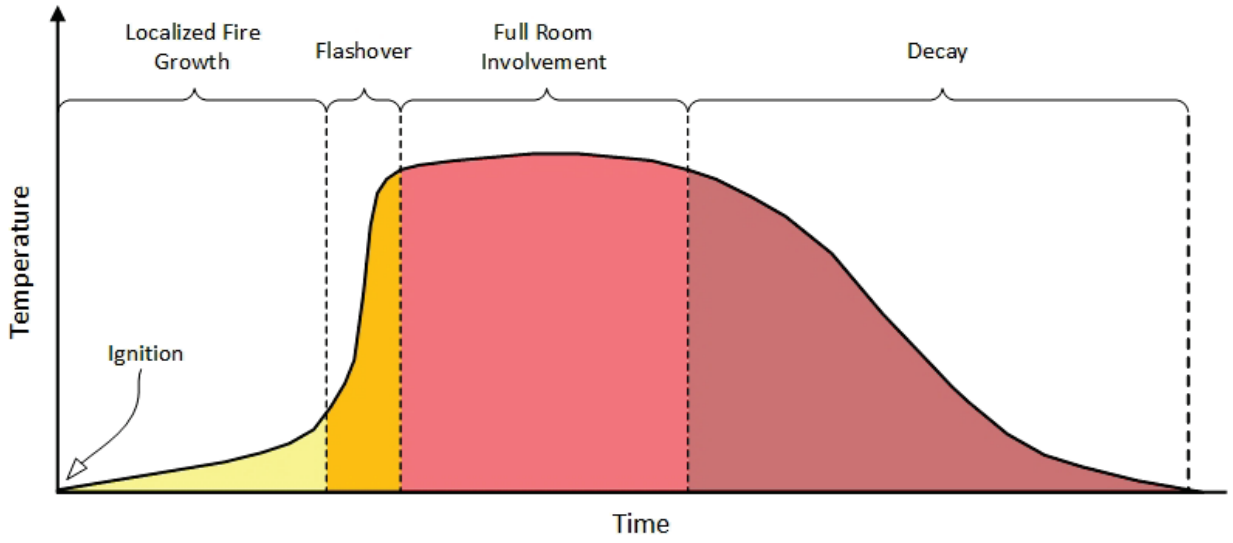


Figure 3-3: Schematic of compartment fire growth temperature history

A fire may remain largely contained within the compartment of origin (burn-out) or it may contribute to fire spread to adjacent areas. Building fire spread involves a complex set of events beginning with the manner of growth of the fire. Depending on the location of the initial fire and the sequence of fire spread, three key fire scenarios have been observed: fire development within a compartment, fire spread through a concealed space, and fire encroachment on the building exterior [209, 210]. These scenarios, influenced by the location and sequence of fire spread, are detailed as follows [210]:

- **Compartment:** Compartment fire development is the mode of fire growth and the main scenario traditionally considered in fire and life safety regulatory development (i.e., fire containment to burn-out).
- **Concealed Space:** Fire development in concealed spaces depends on the size and configuration of the concealed space and can range from compartment-like development for larger concealed spaces (i.e., attic space) or can be significantly constrained and ventilation limited for smaller concealed spaces (i.e., wall stud space). Like compartment fire spread, fire spread in concealed spaces has been considered during regulatory development, but to a lesser extent than compartment fire situations and often in response to specific fire incidents (attic fire example).
- **Exterior:** Fire that encroaches a building exterior typically develops in an unconstrained or partly constrained fashion depending on the fire location. Unconstrained fire development could occur immediately adjacent to a building exterior wall or from a fire in an adjacent area. Partly constrained fires can occur on exterior balconies or alcoves and depending on the degree of

enclosure may or may not follow the trajectories commonly associated with compartment fire growth. Exterior fire spread has not been considered in regulatory development until recently (i.e., approx. 30 to 40 years), for example in the third regulatory development context of the attic fire example.

Each mode of fire spread can be amplified by the presence of combustible surfaces, which can be interior finish for compartments, the surface of framing and sheathing materials in concealed spaces, or cladding on exterior building spaces. Where such surfaces are noncombustible, the degree of fire development and spread is limited for many concealed space and exterior fires, since those areas typically contain only minimal combustible contents. This is not the case for compartments, which by nature of their use are expected to have combustible contents, as was earlier quantified by Ingberg [84, 86].

Fire spread from the initial fire typically occurs through openings to adjacent locations. For instance, fire can propagate in the following ways:

1. to other compartments through open doors or other openings/penetrations between compartments,
2. to or from concealed spaces through openings in a wall, ceiling or floor due to electrical outlets, light fixtures or similar penetrations, and
3. to or from the exterior of the building through window and door openings.

The sequence and degree of fire spread during a building fire depends on factors such as the condition of the openings (i.e., open or closed) and degree of interconnection between building spaces; the quantity and configuration of combustible contents and building materials; and the location of initial development. All other things being equal, fire tends to spread to a greater extent if it occurs on a lower level of a building due to upward movement of hot fire gases driven by buoyancy. The extent of fire spread also increases in buildings with combustible contents, combustible lining materials (both interior and exterior), and a higher degree of interconnectedness between compartments, concealed spaces, and the exterior. Depending on these factors, a fire may be contained to its point of origin, spread to involve the entire building, or result in any of a wide array of intermediate levels of involvement.

Fire development on or within a building can also result in ignition and spread to adjacent buildings by direct flame impingement for closely spaced buildings, or via radiant heating and brand spotting[9] for more spatially separated buildings. Similar to spread within a building, fire can continue to spread to adjacent buildings as a function of various exterior spread mechanisms, which can escalate into a conflagration, serving as one of the key hazards considered in the early development of building regulations.

Where fire poses no impact to people or property, there is no associated risk and, consequently, no need for regulatory solutions. However, due to its destructive nature, fire typically affects the immediate environment and those within it, with its impact increasing as it grows and spreads. This impact is

[9] Brand spotting is where smaller burning debris is lofted into the air by buoyant forces from a fire and carried over distances to land upon and ignite combustible surfaces under favourable conditions.

characterized by a range of fire effects that can cause harm to people and damage to buildings and contents. These effects include heat, smoke, and a variety of other gaseous emissions. Heat can cause thermal damage (melting, charring, etc.), ignition of additional materials, and burns. Smoke can cause staining, lung irritation/damage, and obscured vision. Fire gases can cause varying degrees of physiological and cognitive incapacitation, irritation to eyes and lungs, and asphyxiation.

Thus, the effects of fire are associated with a wide range of factors that adversely impact people and property (the "exposed"). It is these fire effects that form the basis for establishing performance criteria that regulatory solutions seek to mitigate. As such, fire hazard characterization requires knowledge of these effects and their potential impact on persons or property. For example, light is an effect of fire, but light from a fire does not generally negatively impact either persons or property. At the same time, heat is also an effect of fire but does result in negative impacts, since it can cause burns to skin (impact to persons), promote ignition and fire spread (impact to property), and facilitates charring of wood and other materials (impact to property).

The magnitude of fire effects generally increases as a fire grows and spreads. However, the impacts also depend on the characteristics of the fire scenario and on the characteristics and response of the exposed, whether they are people, property, or both. These aspects are discussed further in the following section in the context of the impact of fire effects on the "exposed."

3.3.2.2 Characterization of the Exposed

The "exposed" are the things that are valued [201] and thus need to be protected from the hazards of fire. These are expressly stated in the objectives of the NBC to be people and property[10].

People includes all those who may occupy a building, on a regular or temporary basis, as related to the design, function, or fire event. They may be impacted by the heat, smoke, or gases from a fire. In the context of a building code, the important characteristics of the exposed people include:

- **Number:** A large number of persons require adequate evacuation facilities to move, unimpeded, to a place of safety.
- **Location:** The location of persons in a building could change their ability to reach a place of safety before being impacted by the effects of fire.
- **Response:** Persons may or may not have a delayed response to a fire event due to their current state including, awake, sleeping, unconscious or unaware.
- **Ability:** A person's physical and cognitive abilities can impact their capability to move away from the effects of a fire or toward a place of safety.
- **Attributes:** A person's attributes, such as resistance to heat or tolerance to carbon monoxide, can impact their response if exposed to the effects of fire.

[10] These are not static entities, as the environment is more recently recognized as a thing of value that is negatively impacted by fire (i.e., wildfires) and may eventually be a third item included in the NBC's objectives with respect to fire.

An example of a quantitative physical risk factor that could be used to characterize the difference between harm and no harm due to fire exposure is critical heat flux. For an incident heat flux from the fire to exposed below a value of 1.7 kW/m² [211], no pain is experienced for an infinite duration of exposure. Note that this value is slightly higher than the heat flux from the sun on a sunny summer day (approximately 1.2 kW/m² [212]). Therefore, it is reasonable to utilize this heat flux exposure value as a measure of acceptable performance with respect to limiting harm to people during a fire, and as discussed above, the degree of exposure is expected to increase with fire escalation.

Property has not been defined clearly in the context of regulatory development. Property has traditionally included both building structure and contents, likely as an artifact of the insurance origins of fire safety regulations. The range of different materials that make up the building and its contents are extensive. Heat and smoke, more than fire gases, are considered the key fire effects that impact property. The resulting impact is a function of both thermal and physical properties of the materials and assemblies involved:

- **Thermal properties:** These include thermal conductivity, heat capacity, heat of vapourization, melting temperature, thermal damage threshold, ignition temperature or heat flux (pilot or auto).
- **Physical properties:** These include thickness, porosity, density, orientation and configuration.

The combined properties determine the response of a material to heat and smoke and the potential for damage. An example of a quantitative risk factor related to material performance in fire is, once again, the incident heat flux. Of interest this time is the value needed to cause ignition of wood over time. This generally is considered to be 12.5 kW/m² with a piloted ignition source and 33.5 kW/m² for autoignition of the material [213]. Therefore, as discussed above, it may be reasonable to utilize these heat flux exposure values as a measure of acceptable performance with respect to limiting damage to the wood within a building and its contents during a fire. At the same time, caution must be exercised in choosing the value for regulatory purposes since values of critical heat flux for ignition can vary significantly across types, density, and moisture content in wood as well [214].

By understanding and quantifying the characteristics of the fire hazard in combination with those of the people and property most affected, it becomes possible to define empirical relationships between these elements, which enables quantification of the degree to which the hazard impacts the exposed entities. These types of relationships are discussed in the next section.

3.3.2.3 Hazard-Exposed Relationship (Risk Assessment)

Early building code development relied on basic risk assessment processes, with fire safety strategies developed primarily through experience and expert judgment rather than being based on scientific principles. The effectiveness of this approach was uncertain until validated over time, leading to prolonged cycles between the implementation of solutions and the realization (or not) of their intended outcomes. The long verification cycles, driven also by a limited understanding of the quantifiable relationship between hazards and those exposed, have resulted in solutions that often lag behind advancements in design, construction methods, and technologies. Given the evolving and urgent need for innovative and

even basic alternative solutions, this approach, as discussed earlier, is no longer an effective way to verify acceptable performance.

At the same time, advancements in fire science and fire engineering have led to a better and more precise understanding of fire hazards and their impact on people and property, with these relationships becoming more quantitatively defined in recent years. Integrating these concepts into current regulatory requirements, or reviewing where they were originally applied, and re-examining those concepts in a current context, would facilitate more quantifiable relationships between specific hazards and their impact on the exposed, and thus reduce the time associated with verification of the performance of solutions. This would also enable the development of measurable criteria to more effectively assess the performance of regulatory requirements in limiting the impact of fire hazards on the exposed. However, as previously discussed, the information needed for this (i.e., that supporting the development of regulatory solutions), has often been distilled into precise regulatory language, and is typically only accessible through a historical (and archival) analysis.

A historical analysis of the regulatory requirements, then, could reveal where experience, rather than fire science and fire engineering concepts, had shaped the relationship between fire hazards and exposed people or property, as well as where outdated concepts were applied and need updating. Solutions can then be updated to incorporate more current fire science and fire engineering principles, expressed in a risk-based context. This approach could take several forms and span a range of complexity, from simple deterministic models to complex stochastic methods. An example of a simple deterministic relationship is the point source radiant heat transfer model [215], which represents a fire as a point source of energy and calculates the incident heat flux as inversely proportional to the square of the distance from the source. In contrast, a more complex stochastic model might involve a Monte Carlo analysis of fire spread potential under uncertainty, using computational fluid dynamics-based fire models that numerically solve the conservation equations of mass, momentum, and energy.

Thus, characterizing the fire hazard and the exposed people and property, followed by development of a clearer understanding of the relationship between them, enables the assessment of existing solutions or development of newer and more effective solutions to reduce harm and damage from fire as discussed in the following section.

3.3.2.4 Solution Development

The primary goal of many regulatory solutions is to limit fire growth and contain it at the earliest stage to minimize its impact on people and property. This has historically been achieved through a combination of passive and active strategies, which were primarily developed through trial and error experience over time with only a rudimentary understanding of the science of fire growth and spread. Key passive strategies have historically involved fire barriers (i.e., firewall), building size limits, and type of construction (i.e., noncombustible construction); key active strategies have involved detection and notification systems (i.e., smoke/heat detectors, fire alarms) and suppression systems (i.e., sprinklers). The strategies have also relied on fire service response and capability to limit further fire growth and spread. However, the extent

to which these strategies have limited the impact of fire on people and property (risk), or their reliance on fire service capability, is not currently quantified in the NBC.

As was illustrated in the attic fire example, the initial strategy to limit fire spread throughout an attic space was the provision of a passive barrier of specific configuration and materials, based primarily on experience. Over time and with the occurrence of further fire incidents, this strategy was recognized to be unsuccessful in achieving the intended performance due to mischaracterization of the original hazard (i.e., location of fire initiation and development). A further strategy was developed in light of experience from the additional fire incidents that occurred. The subsequent strategy involved the added provision of a passive "soffit" barrier to limit fire spread in to an attic space. Years later, these combined solutions were also deemed unsuccessful for similar reasons (i.e., mischaracterization of the hazard), and a third strategy developed involving provision of an active system (i.e., sprinklers) on balconies. Whether or not this latter strategy provides acceptable performance is yet to be confirmed.

The above stepwise approach to solution development, involving the "test of time" confirmation of performance, is clearly very cumbersome and no longer viable. In contrast, a more recent analysis of fire spread and damage in apartment buildings, conducted in the same context as the attic example, characterized and quantified fire hazard based on the location of fire initiation and ensuing fire development [210]. The analysis identified sprinklering of balconies as a key strategy expected to limit the extent of building fire damage. At the same time, the new analysis considered the effectiveness of combined fire safety strategies. Such an approach is rare in the development of the NBC fire and life safety requirements, which more often follow the shotgun approach to solution development, obfuscated by generational amnesia and the regulatory ratchet effect, and with limited reconsideration of whether a combined set of mitigation strategies actually achieves an acceptable level of performance. The final requirement thus worsens with each "era" of regulatory development despite the fact that it is intended to further reduce risk. Ferguson characterizes this process of regulatory development as [182] "malpractice" and suggests the following [182, p. 11]:

> *The correct way to regulate is to assess the risk and apply regulations accordingly. It should be unnecessary as a sequel to apply further requirements to diminish the risk. If it is necessary, these further regulations should have been considered as part of the initial risk.*

Ferguson suggests that a holistic evaluation of the risk reduction impact of the combined fire safety strategies, developed over multiple eras, is essential for developing an appropriate regulatory requirement or set of requirements, rather than a regulatory ratchet-based approach. This is exemplified by Bardach and Kagan in their book, "Going by the Book: The Problem of Regulatory Unreasonableness," where they note that [174, p. 186]:

> *Fire codes typically have called first for the installation of fire doors, then sprinkler systems, then one set of fire-retardant construction materials, then another—all without seriously considering whether the addition of each new requirement would justify elimination of some of the old ones under certain circumstances.*

The necessary more holistic analysis can be conducted by utilizing existing tools such as the fire safety concepts tree (FSCT) [216], which is a relational risk framework (reliability block diagram) built on traditional fire safety strategies. The tree allows for more holistic assessment of the impact of individual or combined (redundant) fire safety strategies on the reduction of fire risk. The tree is structured to assess fire safety objectives (strategies) that are connected to lower-level sub-objectives by “and” or “or” gates, represented by the symbols (•) and (+) respectively. The gates provide a logical connection between strategies. An “and” gate signifies that the top-level strategy is achieved only by achieving all of the sub-strategies. An “or” gate signifies that the top-level strategy is achieved by achieving any one or more of the sub-strategies. In this way, the gates differentiate dependant (“and”) from independent (“or”) strategies. The FSCT allows for a structured assessment of the relationships among a system of fire strategies and their combined impact on the reliability of the solution. This approach alleviates the challenges with iterative and shotgun approaches to fire safety solutions, by allowing the identification and quantification of those strategies that are most effective from those that have limited to no effectiveness in achieving the intended overall objective.

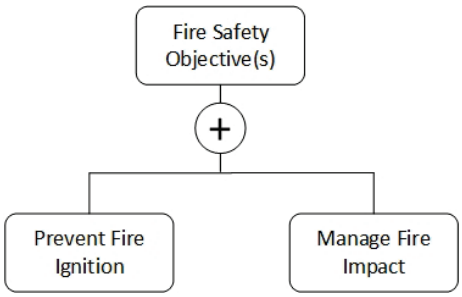


Figure 3-4: A version of the top level of the fire safety concepts tree

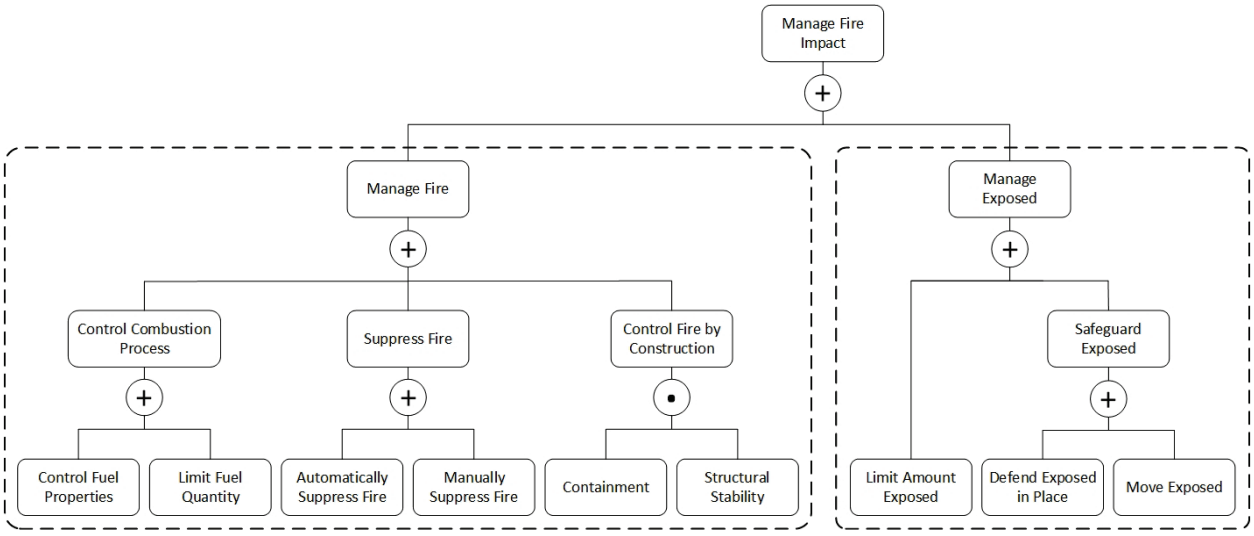


Figure 3-5: A version of the Manage Fire Impact tree

The top level of the FSCT, illustrated in Figure 3-4, branches into “Prevent fire ignition” and “Manage fire impact,” joined by an “or” gate. The implication of the “or” gate between “Prevent Fire Ignition” and “Manage Fire Impact” strategies is that the impact of fire can be limited by either preventing fire from

igniting or managing fire impact. Thus, where a solution exists that can completely prevent ignition from occurring, there would be no need to manage the impact of a fire because the fire is not expected to occur. However, preventing ignition is not yet a broadly practical regulatory solution. Therefore, while "Prevent Fire Ignition" is a key strategy in the fire safety concepts tree, it is not addressed in this thesis, which is focused on the historical development of the current regulations to "Manage Fire Impact." Future changes could consider the prevention of fire ignition where such a strategy becomes more practical, and factor this aspect of the fire safety concepts tree into a truly holistic assessment of fire risk. Instead, the focus here is on the "Manage Fire Impact" strategy of the fire safety concepts tree, illustrated in Figure 3-5.

The "Manage Fire Impact" strategy branches into "Manage fire" and "Manage Exposed." The "Manage Fire" strategy relates to sub-strategies intended to the limit fire growth and spread, which constitute the fire hazard as discussed earlier. The "Manage Exposed" strategy relates to the protection of people and contents, which constitute the exposed as discussed earlier. The "Manage Fire" branch of the fire safety concepts tree is further divided into "Control Combustion Process," "Suppress Fire" and "Control Fire by Construction" all connected by an "or" gate. This means that the objective of "Manage Fire" can be achieved through use of any one of these sub-strategies. However, the strategies are often considered together to ensure effective management of the fire, or as a set of redundant or "backup" solutions (i.e., shotgun approach) when developing measures to manage, and thus limit, the risk of fire growth and spread.

The combined approach to characterizing the hazard and the exposed using a tool like the FSCT, then establishing their empirical relationship, and assessing the effectiveness of strategies to limit the respective impact, provides an assessment of the fire risk. Furthermore, shifting the assessment from being primarily experiential to technical (i.e., fire science and fire engineering based) can address the current lag in time for confirmation of acceptable performance. An assessment in such a risk-based framework then further addresses uncertainties while allowing for the quantification of risk criteria, and in doing so, facilitates the decision-making necessary to confirm whether regulatory strategies achieve acceptable performance by reducing risk to an acceptable level.

3.3.2.5 Acceptable Risk (Performance)

At the foundation of any risk assessment is an understanding of what constitutes acceptable risk. In terms of the acceptable level of performance of the current regulatory requirements, the NBC notes that [21, Div. A, pp. viii and 1-18]:

> *the NBC cannot eliminate all risk…The risk remaining once the applicable acceptable solutions in Division B have been implemented represents the residual level of risk deemed to be acceptable by the broad base of Canadians who have taken part in the consensus process used to develop the Code.*

This indicates that the NBC is not structured with an intent to eliminate all fire risk, as this is impractical; instead, it acknowledges that a certain level of residual risk remains even after application of the acceptable solution requirements to building design and construction. This residual risk is deemed

acceptable by a diverse group of stakeholders, whose perspectives reflect varying levels of knowledge, experience, and sometimes political interests, all of which contribute to the consensus-based code development process. The judgement has not traditionally been based on quantitative performance criteria but on indirect measures of performance (i.e., absence of fire hazards) as discussed earlier. Therefore, acceptable risk in the NBC is not something that can be established by any one person. Instead, it is a qualitative, social and even political accord [203], attributed to a set of regulatory specifications that are considered to have stood the [158] "test of time" in limiting the impact of undesirable fire outcomes. In this respect, while this research provides technical foundations for risk characterization, it does not attempt to quantitatively define acceptable risk levels or provide tools to inform the determination of acceptable risk for future fire and life safety regulatory development. These must instead be recognized as policy decisions requiring broader stakeholder input.

Further, the objectives of the NBC describe undesirable impacts of fire hazards (consequences) on people and buildings using terms such as "injury" and "damage;" however, the level to which these consequences are accepted is not quantified. Attempts have been made to attribute monetary value to human life and cost to injury or damage for purposes of differentiating "acceptable" from "unacceptable" performance (risk) in terms of harm to people and damage to property, through cost benefit studies and regulatory decision-making [217, 218]. Quantifying risk to life remains an inherently abstract process that has historically required some level of assigning value to human life [219, 220], which has raised significant questions of morality and whether it is ethical to place a value on life [218]. Estimating property damage due to fire as a function of dollar losses is less controversial; however, it is still a complex exercise for non-economists [218]. Given the ethical complexities and the lack of explicit quantitative criteria, relying on individual assessments or cost-benefit analyses is insufficient for establishing acceptable risk levels. Consequently, a more holistic approach is required, one that considers the broader societal context and the variability inherent in the Canadian building stock to which the NBC must be applied.

To address the complexities inherent in performance-based fire safety design, it is important to develop risk assessment methodologies that incorporate a broad societal perspective. Quantifying performance through risk characterization and assessment, using the methods discussed above, would significantly facilitate the development and acceptance of alternative solutions and performance-based specifications. However, in doing this, it is important to establish clear, measurable criteria for what constitutes acceptable levels of risk/performance. Defining these criteria enables the objective evaluation of alternative solutions in alignment with the objectives of the NBC. Without explicit quantitative criteria, the process of risk assessment cannot effectively guide the development and acceptance of performance-based designs. For this as well, a societal-level approach enables better accommodation of the uncertainties and variability of fire events across a broad range of building types and methods of construction. This may facilitate development of more consistent and widely accepted performance criteria and provide a foundation for scientifically-based and adaptable requirements that more effectively address the complexities of buildings on a broader societal level.

3.3.3 Societal Level Risk Assessment

Due to the randomness of building fire events and an incomplete knowledge of the phenomena underlying fire growth and spread, there is inherent uncertainty in the assessment of fire safety [196]. This is exacerbated by the individual or limited number of past events that are studied in pursuit of regulatory development and the tendency to utilize the characteristics of the designs of buildings involved in those events as reference designs, although they may not be representative of the "portfolio of buildings" [196] to which the regulations are intended to apply. The result, discussed earlier in the comparative assessment method, is that the regulatory requirements may not adequately mitigate fire risk to the level intended, which is then further aggravated by the impact of time.

A risk assessment framework that addresses the uncertainty inherent in fire safety, considers the broad range of building designs and characteristics, and is structured in a generic manner to allow updating based on new information or advances in knowledge, would provide a means to optimize fire safety strategies and reduce fire risk to an acceptable level.

Fischer [196] developed such a framework to optimize the investment in fire safety measures. The framework utilizes a generic risk assessment model to determine the quantitative impact of those measures on the reduction of risk to an acceptable societal level. To address the challenges associated with quantifying risk to life, Fischer [196] and De Sanctis [197] utilize Society's Willingness to Pay (SWTP) method and the Life Quality Index (LQI) to quantify the reduction of risk to life based on the provision of fire safety features [196, 197, 221, 222]. The SWTP method [196, 197] and LQI [221] support social-level quantitative decision-making relative to life safety. The LQI is established as a function of social indicators, gross domestic product (GDP), and life expectancy (LE), to estimate SWTP for decision making at a social level. This framework was built upon by De Sanctis [197], who further developed the generic risk assessment model and validation of the SWTP and LQI methods.

Fischer identified that the challenge with optimization of fire safety measures at a societal level is establishing a means to quantify risk across a group of buildings as opposed to just an individual building. This is also the case when utilizing a reference design, as was done by Lundin [123]. For this, Fischer utilized a generic risk assessment framework, illustrated in Figure 3-6 and Figure 3-7, which was originally developed by the Joint Committee on Structural Safety (JCSS) for risk assessment in structural design [223].

The generic risk assessment framework, illustrated in Figure 3-6, focuses on the risk assessment process rather than a project flow for risk assessment [223]. As such, the framework is applied to estimate the risk of a system as a function of "risk indicators" and "safety measures," which requires knowledge of the interrelation of the individual components that characterize the overall performance of the system relative to defined risks. Risk indicators include those factors that are measurable or observable and characterize the exposure, vulnerability, and robustness of a system [197]. For example, ignition represents an exposure, fire development within a room represents vulnerability, and spread beyond a fire compartment represents robustness. Safety measures are strategies aimed at influencing building characteristics and thereby impacting the risk indicators.

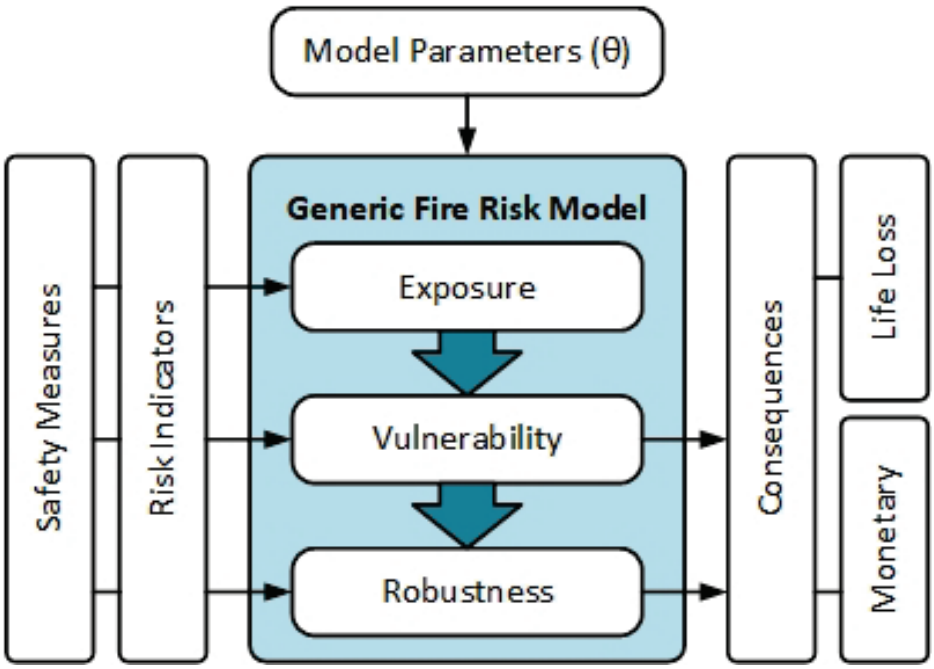


Figure 3-6: The conceptual generic risk framework – object level

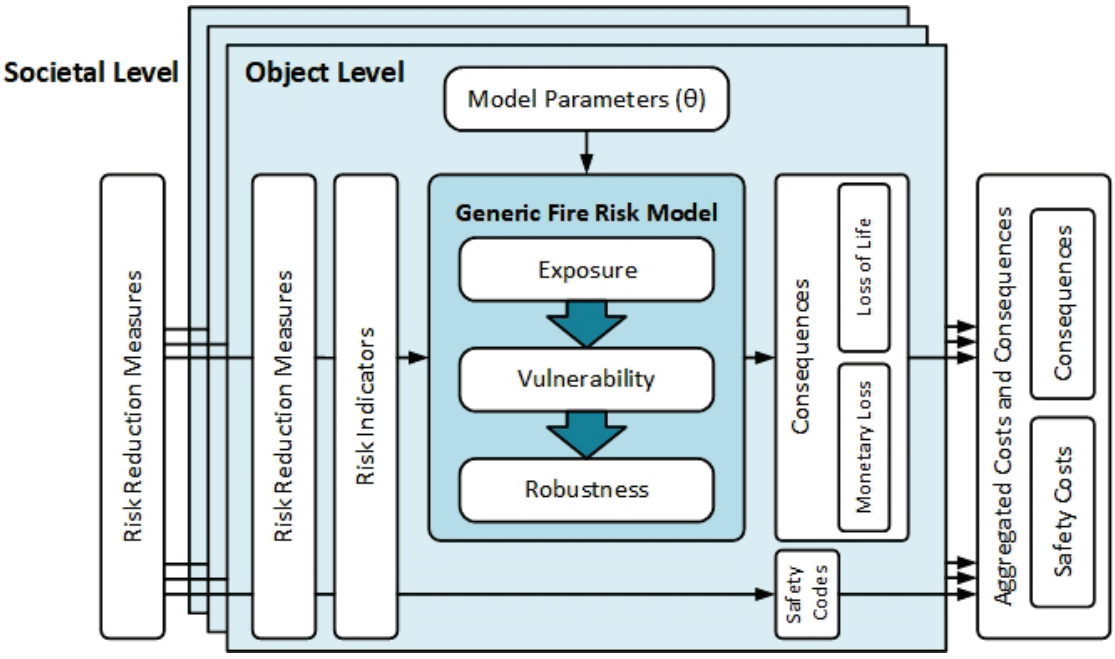


Figure 3-7: The conceptual generic risk framework – societal level

The blue box in the framework in Figure 3-6 represents a generic risk model that can be used to estimate the consequences of exposure to a fire hazard as a function of the risk indicators with consideration of the safety measures. The model includes non-observable, deterministic, or uncertain parameters that are estimated from statistical data or based on engineering knowledge [196] and analysis. These parameters define mathematical relationships integral to the risk model [197], such as relationships for fire growth in a scenario under evaluation.

The generic risk assessment framework can be used to assess fire risk in an individual building (i.e., object level) or a set of buildings (i.e., at a societal level). The societal level representation of the framework is illustrated in Figure 3-7. It allows for the quantification of consequences, which can be aggregated over the group of buildings. However, this is possible only if the risk indicators are common to the set of objects [196]. This scaled-up model enables the evaluation of the effectiveness of fire safety measures at a societal level, a critical consideration for developing model building codes like the NBC.

A generic fire risk framework such as that presented by Fischer also facilitates various techniques to address uncertain parameters. The most common of these include [197] logic trees, approximation methods, simulation methods, and graphical networks (Bayesian networks or Markov random fields).

The FSCT detailed above is an example of a logic tree. Approximation methods estimate the reliability of a system using First or Second Order Reliability Methods, which are primarily limited to linear-based systems [197]. Simulation methods estimate system behaviour and uncertainties through numerous iterations of engineering-based model assessments with random samples of key variables (Monte Carlo analysis). Graphical networks, such as a Bayesian network, allow for the assessment of causal relationship between risk indicators in complex systems. The Bayesian approach enables utilization of risk indicators defined via probability distributions and reduction of uncertainty through calibration (Bayesian inference) with statistical fire loss data. The Bayesian approach has been gaining momentum in fire research, particularly for estimations of fire growth and spread [224-226] and in fire investigation [227-229], likely as a result of only needing limited quantities of statistical data coupled with the flexibility of the approach to incorporate new data within an existing analysis framework. Both logic tree and Bayesian approaches are limited by availability of event probabilities, which can be supplemented by empirical data or fundamental engineering relationships. In this respect Fischer sought to further reduce uncertainty in the generic risk model output by comparison and calibration to Swiss statistical fire loss data [196].

Three case studies were presented by Fischer [196] and built upon by De Sanctis [197] to demonstrate the application of their generic risk assessment framework to regulatory challenges in a Swiss context. In the first case study, Fischer [196] assessed the risk to life safety for travel distances to an exit that was located at a distance exceeding those required by the Swiss Building Code for a single office building (design scenario) with an automatic fire alarm system. The relative risk due to fire in the office building was determined through comparison of the available times for egress with a reference building having travel distances to an exit that complied with the Swiss Building Code, but without an automatic fire alarm system. The application of the SWTP and LQI principles was not possible for this case, as the absolute risk was not determined for either scenario. The relative risk to life was determined using probabilistic models of fire growth, fire detection, occupant response time, and occupant travel time [196]. The results were verified through the outcomes of the comparative probabilistic risk analysis that indicated that provision of an automatic fire alarm system in the design scenario does not increase the risk to life beyond that in the reference “compliant” design. The approach used by Fischer [196] for this case study is similar to that used by Lundin [123], and as a result has corresponding limitations noted as follows:

1. The approach assumes that the risk implicit in the application of the acceptable solution requirements for travel distance to an exit in the Swiss Building Code is inherently acceptable. However, as noted earlier, this may no longer be the case (i.e., shifting baseline of performance).
2. The results do not identify the implicit performance/risk of the requirements in the Swiss Building Code in limiting the travel distance to an exit.
3. The case study was specific to egress in office buildings with low occupant load and certain room areas and heights. The results may not be applicable to other occupancies, or even other office occupancies with differing characteristics such as room area/height.

De Sanctis [197] examined a different aspect of egress route design, but advanced the principles used by Fischer. De Sanctis looked to optimize the required door width in the Swiss Building Code for retail occupancies using absolute risk assessment (similar probabilistic models used by Fischer [196]) and principles of SWTP with LQI criteria for life safety. Changes to door width were considered a risk reduction measure with respect to the risk to life from occupant exposure to fire conditions (ASET and RSET). Based on the results, De Sanctis [197] concluded that the required door width in the Swiss Building Code is not optimal at a societal level and that a reduced width is optimal. De Sanctis' approach addresses the first of the three limitations identified above from Fischer's research, but does not address the other two. The second limitation would be addressed by a historical analysis of the regulatory requirements related to current door width requirements in the code and the third limitation could be addressed by expanding the analysis to consider additional random variables that play a role in the fire scenario of interest.

In the second case study, Both Fischer and De Sanctis [196, 197] examined structural fire safety in the context of the Swiss Building Code and Eurocodes, which include requirements and calculation methods [230] that have no equivalent with respect to the NBC. Therefore, the results of their respective analyses are not directly applicable in a Canadian context. However, the application of generic risk assessment to establish the probability of failure of structural elements exposed to "real fire" conditions, based on the Swiss Building Code requirements and the Eurocode alternative design methods, is informative in demonstrating the feasibility of adapting the framework proposed by Fischer and De Sanctis for application in a Canadian context. The key results of the analyses for this case study conclude that:

1. The analysis framework can be used to quantify difference in the probability of failure of structural elements exposed to fire for standard design conditions (e.g., prescriptive requirements or alternative Eurocode methods) relative to designs incorporating additional mitigation measures such as sprinklers or enhanced fire brigade intervention. This result supports the application of the generic risk assessment model to innovative approaches considering the interrelation of components of systems.
2. There is a significant dependence between failure probability and specific building indicators such as floor area and ventilation, resulting in a broad range of failure probabilities for prescriptive designs which are applied independent of building properties. This broad range of failure probabilities complicates the appropriate selection of comparable prescriptive design approaches to demonstrate equivalence of an alternative design, consistent with the limitations to the comparative approach identified by Lundin [123] and Bjelland [137-139]. In such cases, knowledge

of the historical development of the prescriptive requirements for structural fire protection could facilitate narrowing the range of probabilities by identifying the key risk indicators upon which the prescriptive requirements were developed.

In a third case study, Fischer and De Sanctis [196, 197] examine the application of the generic risk assessment framework for societal optimization (LQI criterion) of installation of smoke alarms in residential dwellings and reduction of the uncertainty of the calculation methodologies by calibration with statistical fire loss data. This case study involves generic fire risk modelling of single-family homes based on sub-models of minor loss (fire contained to room of origin) and major loss (fire spread beyond room of fire origin). The models quantify fire spread relative to fire brigade intervention and are a result of assumptions and simplifications that introduce uncertainty and bias into the results. Fischer and De Sanctis found that the uncertainty and bias could be reduced through calibration with statistical data based on parameters that included distribution for the minor loss model, fire spread, and fire control time [196]. Based on the results of their analyses, Fischer and De Sanctis [196, 197] concluded that implementing a requirement in the Swiss Building Code for mandatory smoke alarms in residential dwellings is not monetarily optimal to society (LQI).

The framework developed by Fischer and De Sanctis was applied to specific aspects of the Swiss Building Code, which, of course, differs from the NBC in terms of its requirements, developmental history, and scope of application. Nevertheless, given the generic design of the framework, these differences do not impact its applicability for facilitating re-evaluation of regulatory requirements in the NBC within a current context and at a societal level. It offers a structured approach to managing uncertainty in the variability of building designs, addressing key interconnections within complex systems, and streamlining future updates combined with the flexibility for incorporation of new data and advancements in knowledge as they are obtained. As such, this type of framework could well form the backbone on which to build new tools appropriate for promoting performance-based design in Canada.

Further to the work by Fischer and De Sanctis [196, 197], it is clear that to effectively integrate risk criteria into building regulations at a societal level, it is essential to develop a structured framework designed to bridge the gap between high-level (social) objectives and building-specific design solutions. The IRCC hierarchy provides a generic framework for this purpose, one which allows regulatory requirements to be aligned with societal goals through identification of risk criteria and definition of acceptable levels of risk. The following section introduces the Inter-Jurisdictional Regulatory Collaboration Committee (IRCC) hierarchy and explores how it might also support the development of a performance-based framework for the fire safety requirements of the NBC.

3.3.4 The IRCC Hierarchy

Over the past two decades, and since the development of the objective-based framework of the current NBC, several countries have transitioned from specification-based to performance-based frameworks for their building codes, or have further refined their existing frameworks. Notably, these countries have

contemplated an updated version of the NKB framework developed by Meacham and the IRCC [231, 232]. This IRCC hierarchy is schematically illustrated in Figure 3-8.

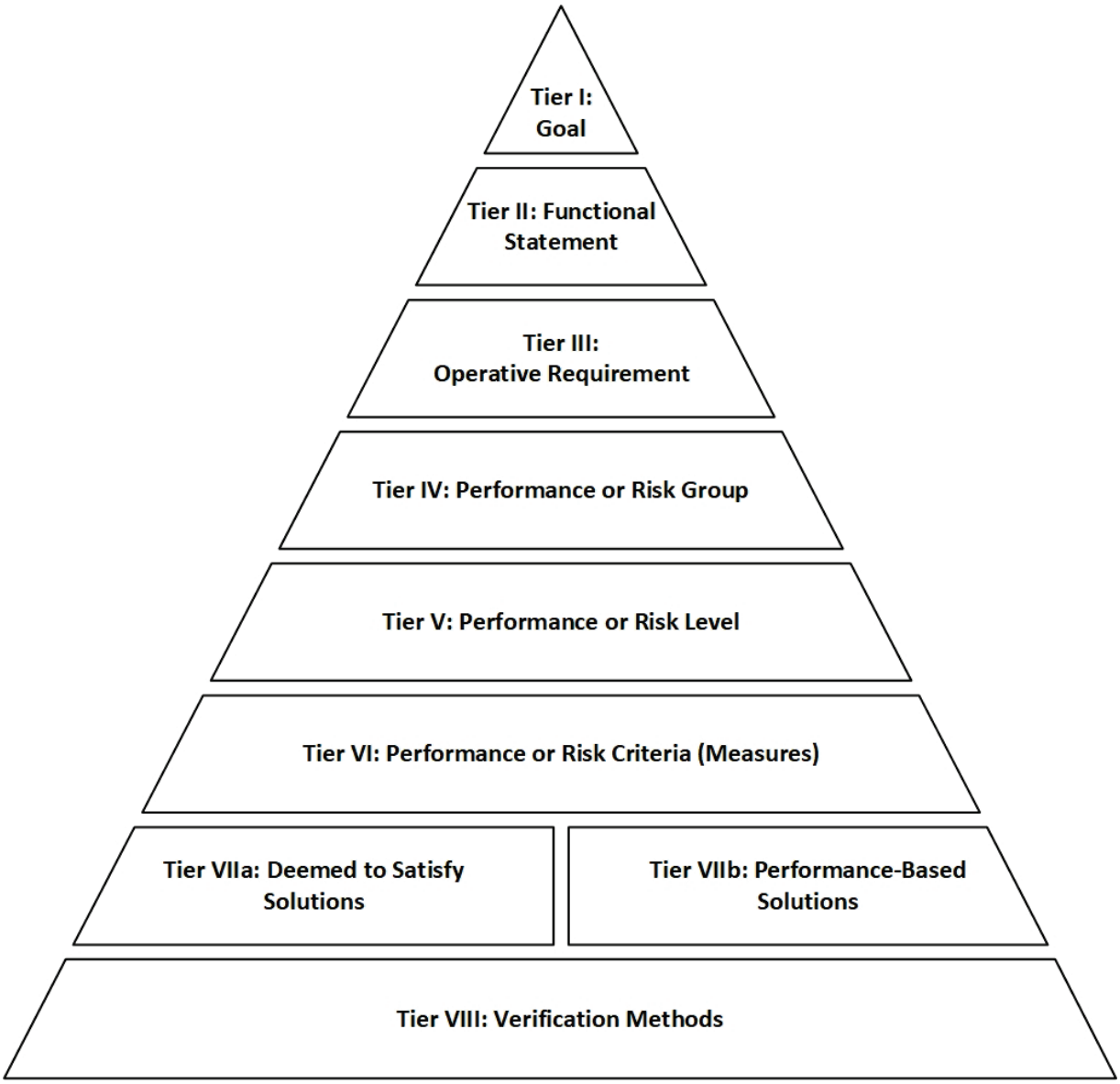


Figure 3-8: A version of the IRCC hierarchy

The IRCC itself was formed in 1996 to develop guidelines for advancing performance-based regulations world-wide. It is composed of representatives from the lead regulatory agencies in 14 countries, including Canada [233]. The hierarchy improves the original NKB framework by introducing additional tiers to describe risk and performance characteristics as a function of certain categories, such as occupancy classification. The additional tiers include performance/risk groups, levels, and criteria, along with a partial reorganization of the lower tiers of the original NKB concept. The eight tiers of the IRCC Framework, detailed in Table 3-1 [232], outline a risk-structured approach for linking societal goals (Tier I) to regulatory solutions (Tier VII) in a top-down, qualitative to prescriptive, manner with inclusion of corresponding methods of verification as well.

Table 3-1: IRCC Framework Tiers

Tier	Name	Description
I	Goal	Outlines top level societal goals (completely qualitative). These are similar to the objectives of the NBC, described in Section 2.2.3.
II	Functional Statement	Describes how goals are met (almost completely qualitatively), and provides key risk descriptors to structure a risk assessment. These are similar to the functional statements of the NBC, described in Section 2.2.3.
III	Operative Requirement	Describes the intended outcome (qualitative performance) of the Goal and Functional Statements. May include quantitative criteria. These are similar to the intent statements of the NBC, described in Section 2.2.3.
IV	Performance or Risk Group	Describes groups with common expected performance outcomes or level of tolerable (acceptable) risk. Examples include groups of buildings or uses with similar characteristics.
V	Performance or Risk Level	Describes different levels of acceptable performance or tolerable (acceptable) risk for specific entities, such as buildings, contents, or persons.
VI	Performance or Risk Criteria (Measures)	Outlines the quantitative (semi-quantitative) criteria by which the performance of design strategies are evaluated with respect to achieving the top-level tiers (Tiers I, II and III).
VIIa	Deemed to Satisfy Solutions	Describe the prescriptive requirements as discussed in Section 2.2.2. These are primarily the legacy-based requirements that pre-dated objective- and performance-based building code frameworks.
VIIb	Performance-Based Solutions	Describe the performance requirements as described in Section 2.2.2. These are the solutions that enable evidence-based (i.e., engineering) best-practice in achieving the top-level goals.
VIII	Verification Methods	Outline [232, p. 14] “suitable document, system, test, method or tool that is needed to verify a design, and its components.” An example of a verification method is a fire performance test standard.

The IRCC hierarchy is structured in a way that could facilitate the transition of the current NBC objective-based framework to a performance-based one since it is designed to link existing societal-level objectives, functional statements, and intent statements to design requirements through gradients of risk-based performance characteristics and criteria. These characteristics and criteria could be established through a review and analysis of existing requirements or the development of new ones, while also connecting the requirements to methods of performance verification. Application of this approach therefore forms one of the key elements of the methods developed during this research and described in detail in the next chapter.

3.4 Summary and Review of Research Focus

The limited acceptance of innovative building designs in Canada stems primarily from the prescriptive nature of the fire and life safety requirements in the NBC coupled with a lack of understanding of the rationale behind these requirements. This was addressed in early editions of the NBC through the equivalency provision, and was specifically intended to be strengthened in 2005 in the transition of the NBC to an objective-based framework. Even with that change, reasoning and rationale for the requirements remain elusive, while the need to facilitate innovative design has become all the more urgent as evolving environmental challenges impact the built environment. The current comparative method of performance verification is insufficient for all but the most basic innovation in designs and, in some cases, may result in designs that fail to meet acceptable safety levels.

Identification and quantification of performance criteria and determination of verification methods consistent with existing requirements is particularly challenging due to generational amnesia precipitated by longstanding reliance on a “test-of-time” approach, both of which have obscured the original rationale. Without this background rationale on which to judge alternative designs, building authorities, already prone to impacts of status-quo bias and the regulatory ratchet effect, are reluctant to accept innovative designs. This is complicated by shifting baselines of acceptable performance through time. Ferguson, one of the original contributors to the development of the NBC, highlighted this challenge in the early 1960s, while also suggesting historical knowledge as a solution [234, p. 2, 235, p. 4]:

> *There is a reason for almost every regulation. Code authorities are reluctant to change or rescind the regulations when the reasons are not known. Once the reasons are known it is easy to modify the regulation and relate it to changes which may have taken place in building and safety practice during the years since the regulation was first passed.*
>
> *…*
>
> *Progress towards better regulations in this country will be speeded when we have an understanding of the history of the regulations which are now enforced.*

To move forward and address these longstanding issues of misinterpretation and ambiguity that continue to limit acceptance of innovative designs, it is necessary to properly identify the rationale underlying current fire and life safety requirements in the NBC, as was intended during the transition in

2005 to an objective-based framework. This was also recently reaffirmed as a key measure to shift the NBC toward a performance-based structure through a series of NRC consultation workshops [151].

The predominantly prescriptive nature of the NBC fire and life safety requirements, coupled with the absence of quantitative performance criteria and verification methods, has moved fire safety design practice to literal interpretation of outdated and somewhat subjective regulatory specifications. This has overshadowed the application of fire science and fire safety engineering principles, which would more effectively align fire safety strategies with the specific fire hazards they are meant to mitigate. Thus, in addition to rationalizing existing fire and life safety solutions through historical analysis, it is essential through the present research to develop strategies by which to integrate fire science and fire safety engineering principles into the NBC to address current challenges and support future advancements. It is anticipated that information identified through the historical analyses may be nontechnical, outdated, or incorrect, and therefore even some of the most basic criteria within the current code may require reconsideration to facilitate the integration of fire science and fire engineering concepts in a more current and risk-based context. Armed with this new information, quantitative performance criteria, verification methods, and risk-based technical reconciliation will be integrated to draw clearer correlations between fire hazards in the built environment and their societal impacts on people and property. By incorporating risk assessment methodologies and using risk as a measure of performance, the approach developed and outlined in this thesis aims to resolve the deficiencies of the traditionally ad-hoc development of fire safety strategies and the dependence on the "test-of-time" validation currently plaguing determination of acceptable performance of innovative designs. Similar context has been provided by Law who noted that [144, pp. 78, 77]:

> *there will always be a place for prescriptive standards… But let us not pretend that if these standards are applied, they will always, in some magic way, give the best solution. As soon as they frustrate design, we should be able to re-establish the rationale behind the rules and thereby develop new approaches.*
>
> *…*
>
> *To move forward,* ***rules need to have an engineering basis and to be goal-related [emphasis added]****: The purpose of the rules needs to be understood by both researchers and regulators.*

As such, this thesis focuses on developing, and subsequently testing via three case studies, a new framework to transition the NBC from an objective-based to a performance-based model, as detailed in the following chapter.

Chapter 4
The New Framework

This Chapter presents the key elements of the new holistic, risk-based framework developed in this research to support the transition of the NBC from objective-based to performance-based for fire and life safety. The framework is designed to address the various challenges inherent in the current structure of the NBC, which have historically limited the development and acceptance of performance-based designs. In particular, the framework has been designed to address challenges related to the effects of time, including the persistence of legacy assumptions and generational amnesia, thereby facilitating broader incorporation of risk-based performance concepts. Central to the framework is a regulatory risk paradigm serving as the foundation for analytical sub-frameworks that identify the basis, when present, underlying legacy specification-based fire safety requirements, reconcile these requirements with more modern fire and life safety engineering principles [196, 197, 224] using risk-based methods, and align the resulting information with a modified IRCC hierarchy. Once developed, the utility and effectiveness of the framework are evaluated through a series of case studies described in subsequent chapters of the thesis.

4.1 Research Objectives and New Regulatory Risk Framework

The primary objective of this thesis, then, is to develop and evaluate the utility of a new framework to support the transition of the NBC from objective- to performance-based for fire and life safety. The new framework is designed to address the challenges of the objective-based structure of the NBC as discussed above. To accomplish this, a new framework is developed that encompasses four main elements as outlined through the objectives below.

1. **Regulatory Risk Paradigm:** Development of a regulatory risk paradigm to characterize the risk associated with the existing acceptable solution requirements. This paradigm will serve as a foundational component of the subsequent sub-frameworks for identification of historical information, technical reconciliation of the historical information, and then population of the levels of the modified IRCC hierarchy with the identified and modified information.
2. **Historical Analysis:** Development of a historical analysis sub-framework to examine the origins of existing fire and life safety acceptable solution requirements. This sub-framework will identify their underlying rationale, including risk characterization, performance criteria, and verification methods. The information established from this assessment is essential [21, 133, 145, 151, 234, 235] to address longstanding issues of misinterpretation and ambiguity, thereby enhancing the acceptance of innovative designs.
3. **Technical Reconciliation:** Development of a technical reconciliation sub-framework through which to associate and more scientifically reconcile historical regulatory development with

modern fire science, fire engineering principles, and best practices [144, 194] in a broader societal-level risk-based context [182, 196]. The result of the technical reconciliation process is key to modifying or supplementing the information established from the historical analysis and providing more up-to-date and quantified risk criteria to demonstrate acceptable performance through fundamental risk-based methods rather than relying on ad-hoc and somewhat artificial comparative methods.

4. **IRCC Hierarchy Alignment:** Development of a sub-framework to populate the tiers of a modified version of the IRCC hierarchy [231, 232] with the information developed from the historical and technical reconciliation analyses. This framework establishes a direct, quantifiable link between high-level goals and parallel prescriptive-based and performance-based regulatory solutions through shared risk metrics and verification methods. It serves as the foundation of a new performance-based framework for the NBC, supplemented by information developed within and aligned to the regulatory risk paradigm. It serves as a dynamic archive to support future changes and advancements.

The overall structure and interconnection of the regulatory risk paradigm developed in this research, including the three key sub-frameworks, are schematically illustrated within a unified framework in Figure 4-1. The numbers in the Figure align with those in the list above. The following sections detail the structure and function of the new regulatory risk paradigm and the new historical, technical reconciliation and hierarchical sub-frameworks.

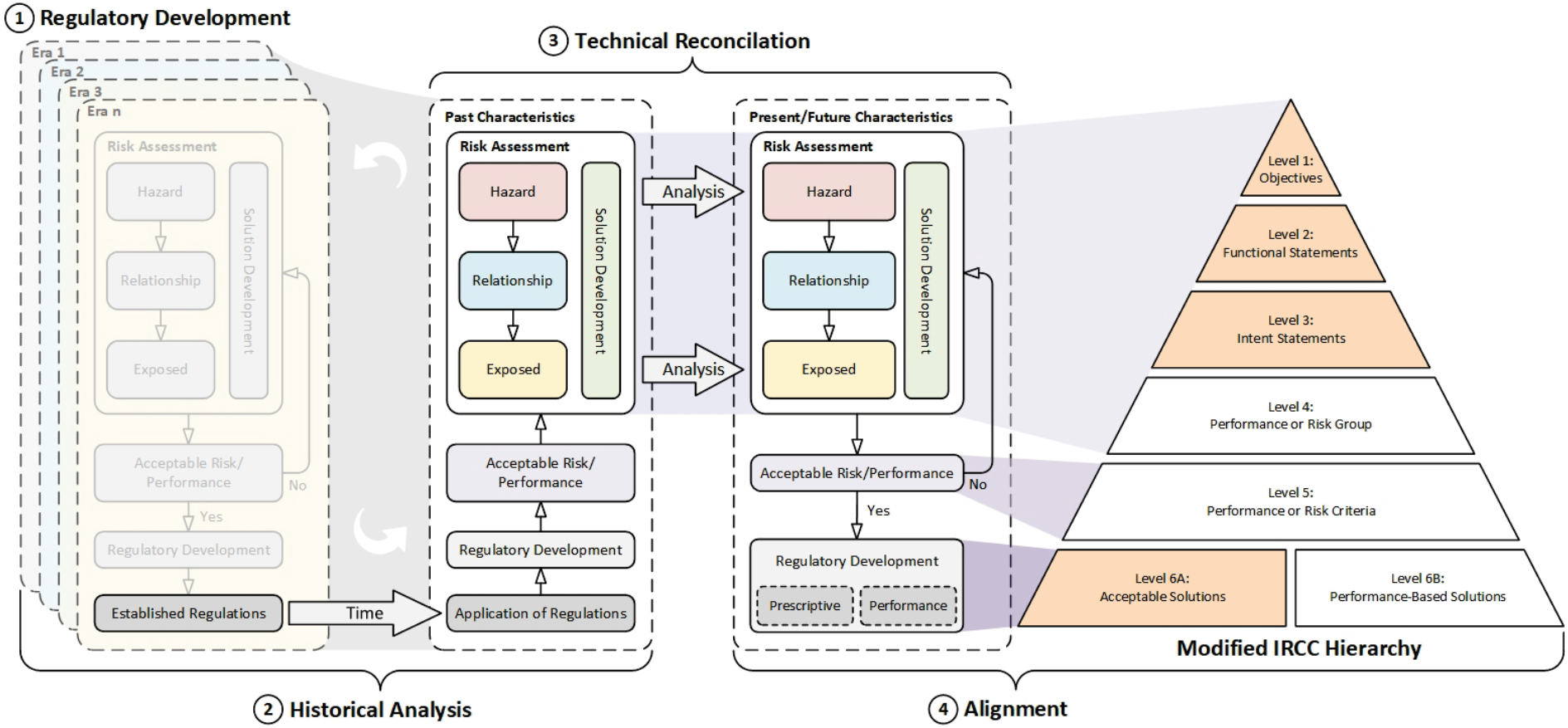


Figure 4-1: New framework

4.2 Regulatory Risk Paradigm

The regulatory risk paradigm chosen is a refined adaptation of the typical risk assessment process, tailored here to the context of regulatory development and its application in building design and construction. This paradigm is illustrated in Figure 4-2. It incorporates the key risk elements outlined earlier to enable a risk-structured evaluation of the existing fire and life safety acceptable solution requirements in the NBC.

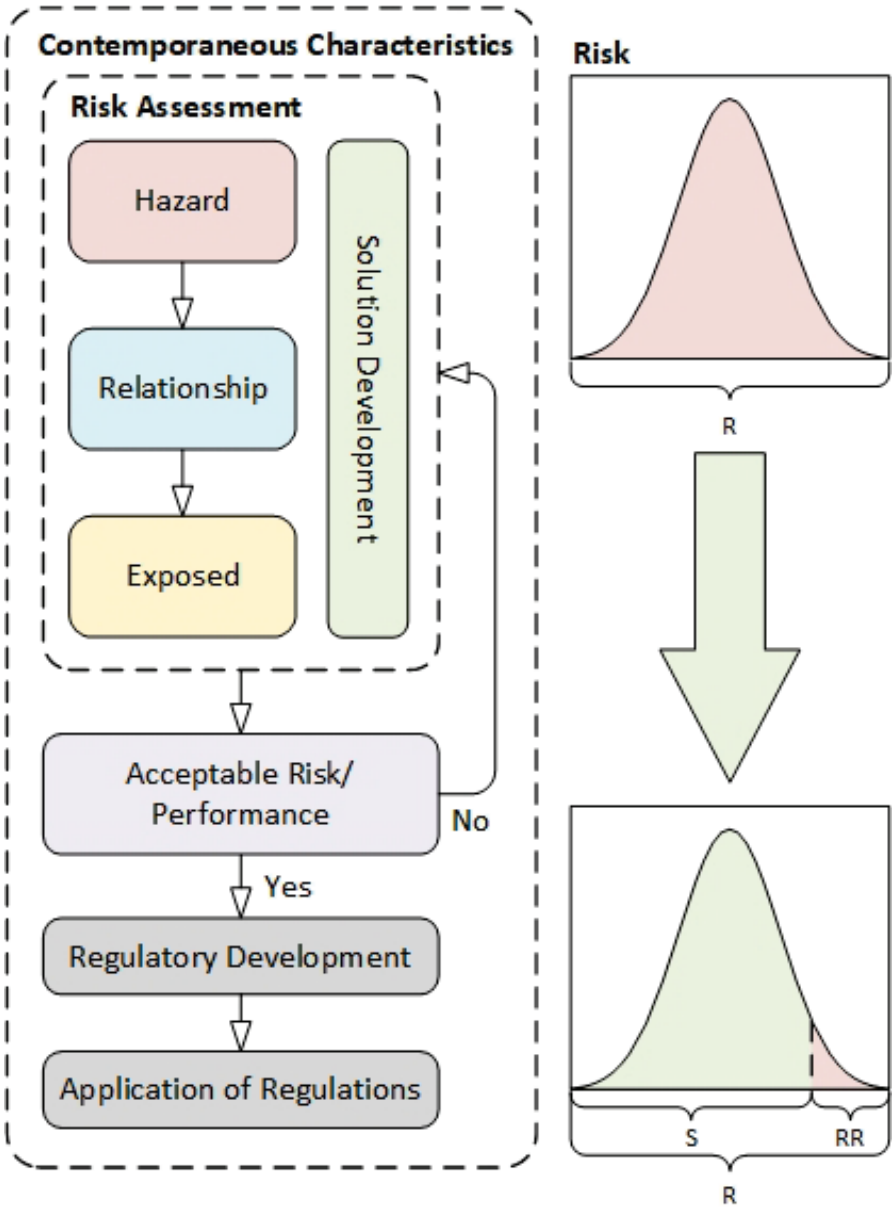


Figure 4-2: Regulatory risk paradigm

This regulatory risk paradigm has been designed to facilitate analysis of the historical evolution of the current fire and life safety acceptable solution requirements in the NBC and to reconcile the requirements into a current and future (predictive) context. As outlined through review of the literature and discussed

previously, the key components of the regulatory risk paradigm are structured to allow characterization of the hazards, the exposed, and the relationships amongst them. Following this, are elements involving development of solutions, assessed against performance criteria that can finally be reconciled and applied as regulatory requirements. The main intent of each of the sections are briefly outlined again to set the context for the following discussions.

1. **Fire Hazard:** Characterization of the nature, likelihood, and potential severity of hazardous fire events as described in Section 3.3.2.1.
2. **Exposed:** Characterization of the people, property, or other factors (i.e., environment) that may be affected by the fire hazard as described in Section 3.3.2.2.
3. **Relationship:** The relationship between the hazard and the exposed, as described in Section 3.3.2.3, which allows for an assessment of the impact.
4. **Solution Development:** The strategy(ies) employed to reduce the impact of the fire hazard on the exposed, as described in Section 3.3.2.4.
5. **Acceptable Risk/Performance:** The judgement of the efficacy of the solution in limiting the impact of the fire hazard on the exposed as described in Section 3.3.2.5.
6. **Regulatory Development:** Distillation of the acceptable solution to be written in concise regulatory language**.**
7. **Application of Regulations:** Interpretation of the language of the acceptable solution requirements to apply to building design and construction.

As illustrated by the red and green plots in the regulatory risk paradigm in Figure 4-2, the intent of the development of fire and life safety solutions (S) is to reduce fire risk (R) to acceptable (tolerable) levels of residual risk (RR). The regulatory risk paradigm proposed here serves as a foundational risk-structured component within the historical analysis, technical reconciliation, and alignment sub-frameworks. As such, it forms the basis on which to overcome the historical issue that risk assessment has relied more on experience and observation than on scientific methods. Further, through its components, it will provide a new, more quantitative risk assessment platform on which to overcome the traditional “test of time” and “absence of adverse outcomes” methods for verification of acceptable risk/performance. Through the process of examining existing regulatory solutions with the new approach, instances can be identified where the distilling of solutions into concise regulatory language and applying that language to building design and construction has led to a diminution of the original solution, leading to higher or lower fire risk exposure than intended. As such, design practitioners, regulatory officials and code development organizations will begin to unravel the interrelated factors that are embedded within the historical development of the acceptable solution requirements and be empowered to undertake renewed, more critical reassessment of those requirements. To further detail their role in the new overarching regulatory framework, each of the sub-frameworks is discussed in more detail below.

4.3 Historical Analysis Sub-Framework

Based on a review of the literature and analysis of key provisions in the NBC, the historical analysis sub-framework was designed as a key element of the larger proposed framework. Specifically, the sub-framework was designed to systematically assess the effects on the current requirements of the fact that: a) the fire and life safety requirements embodied within the acceptable solutions of the current NBC were developed over a period of 80 years up to today, and b) some requirements were adopted from even earlier US- and UK-based model building codes dating back hundreds of years. The historical sub-framework should facilitate identification of those areas where the risk and performance implicit in a given solution have been time-locked and therefore should be re-evaluated to determine whether they appropriately represent the severity and consequences of present-day hazards or meet the thresholds of performance expected by society today. Overall then, this sub-framework is intended as a guide to understand and assist with the interpretation of the NBC fire and life safety requirements in a systematic and consistent fashion that accounts for a range of undesirable events (hazards) and helps to characterize the associated risks that initiated the development of the existing acceptable solutions. Following this, account can be taken for the historical context in current and future application and interpretation of that solution.

The general approach to conducting a historical analysis of fire and life safety requirements in the NBC, in order to identify the pertinent historical information within the context of the regulatory risk paradigm discussed above and illustrated in Figure 4-2, consists of the following steps:

1. Identify the current requirement or set of requirements of interest, which, at the time of writing this thesis, are in Part 3 of the 2020 NBC [21].
2. Identify the corresponding requirement(s) from previous editions of the NBC and where the requirement(s) has(ve) changed or originate. This provides the time period over which the code committee contemplated the change(s)/addition(s).
3. Identify the committee minutes or associated documents that discuss such additions, or modifications to the NBC and the origins of those additions/modifications. Where the origins of a requirement(s) precede the first (1941) edition of the NBC, this requires an understanding of the general development and origins of the requirements leading up to the 1941 NBC, as detailed in Section 2.1. Depending on the requirement(s) that precede the 1941 NBC, the original development may be documented in several different archives such as those of the NFPA [73, 80, 93-95, 168, 236-248], NBFU [45, 54, 56, 58-63], NBS [65-71, 85, 86, 249-251], other insurance organization proceedings [44, 252], contemporaneous handbooks [253-256], technical journals (i.e., “Journal of the Royal Institute of British Architects”), periodicals (i.e., “Insurance Engineering”) and similar documents. Often, the development of requirements is associated with individuals such as Braidwood [27, 31, 32, 165], Woolson [73, 257], Ingberg [84, 86], Porter [87-92, 258], and others or follows events in certain places such as Rome or London. Researching the activities of specific individuals or events often simplifies the trail of regulatory development, especially where the individual is involved with one or more associations [46].

4. If the origins of the requirement(s) are obtainable, their development is examined according to the key elements of the regulatory risk paradigm, and relative to the potential implications of time. This includes determining the hazard that was addressed, the exposed that were to be protected, the fire safety technology available at the time of development, the implied intent of the solution's performance, and whether the actual performance (residual risk) today still aligns with what was intended at the time of development. This is conceptually illustrated in Figure 4-3 with the elements of the risk paradigm on the left hand side and by plots showing the residual risk intended by the original solution (middle) and several possibilities for the resultant residual risk (right hand side) that would currently be obtained through the actual performance in the present context of current day characteristics. As discussed earlier, this research does not attempt to quantitatively define acceptable risk, but provides a framework to facilitate more holistic discussion and decision-making in this regard. The framework provides the opportunity to present results from a historical analysis in various forms, of which the conceptual presentation of normal plots with percentile residual risk is just one method.

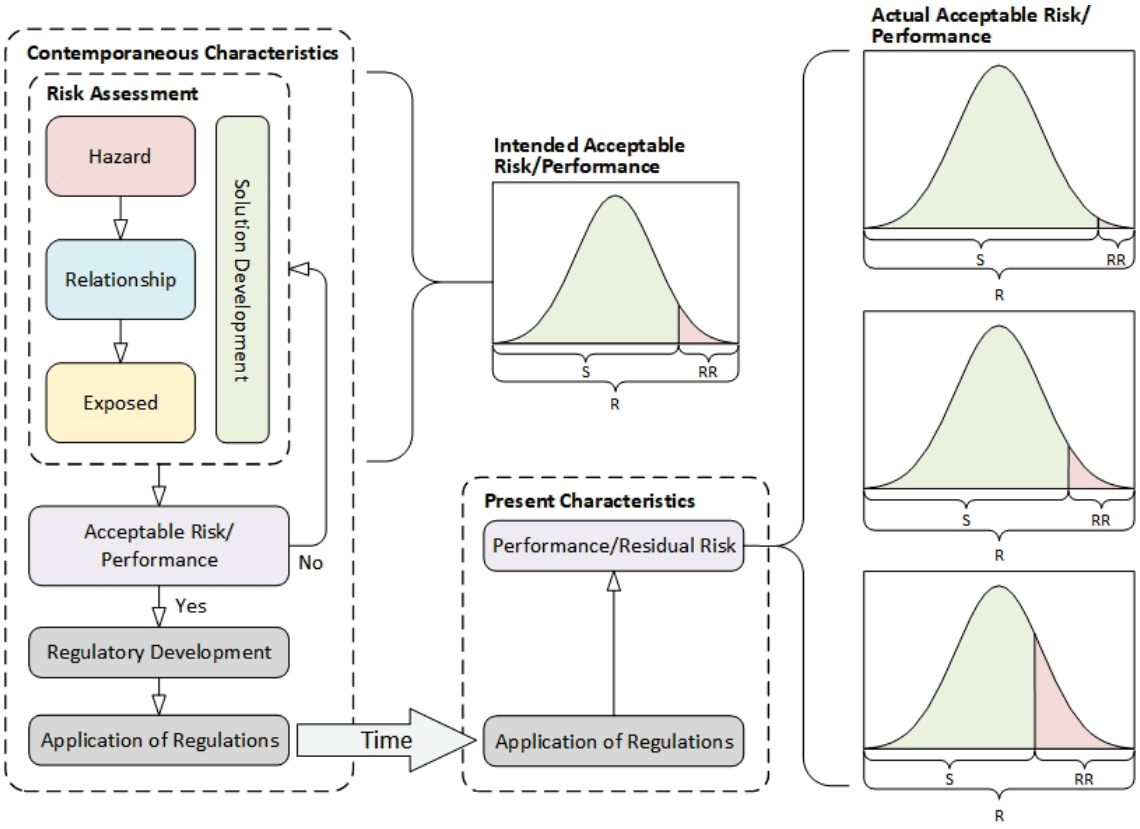


Figure 4-3: The intended versus actual residual risk (performance)

5. Identify committee minutes or related documents that addressed the risk factors associated with the requirements of interest but did not result in changes to those requirements. This includes potential additions or modifications that were considered but never implemented, as well as additions or changes to other associated but separate requirements. An example is the increased mandatory sprinkler requirements in the 1995 NBC, intended to limit the risk of fire growth and

spread, but without implicating a broader reconsideration of other requirements with the same objective, such as those limiting the type of construction.

6. In the case of multi-era regulatory development, as illustrated in the attic fire example, the historical analysis becomes much more complex. In these situations, it requires consideration of the changes to risk characterization that occurred throughout the entire development process. This process is illustrated in Figure 4-4, again with the initial regulatory risk paradigm on the left hand side, with several stages of development simplified as coloured boxes representing modified paradigms at each intermediate step and the final paradigm on the right hand side. The multi-era analysis aims to identify the changes to risk characterization at each stage that have together resulted in the present set of requirements and any shifting to the risk parameters and/or acceptable performance (risk) that may have occurred over that same period of time.

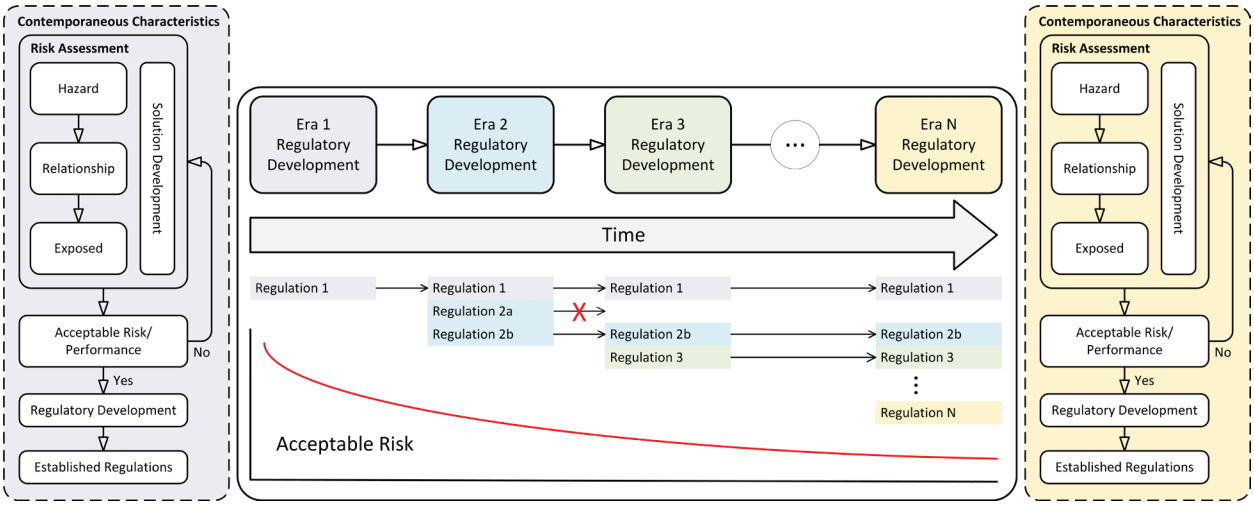


Figure 4-4: Multi-era regulatory development

7. A final consideration in the historical analysis is the transition of units of measure from imperial to metric in the 1970s. In preparation of the 1977 NBC, some imperial values in the 1975 NBC were converted to metric values based on “soft” conversions [259] rather than using the applicable “hard” conversion factors [260]. The “soft” conversions were established to allow simplification through rounding, but in a manner “consistent with the sensitivity of the particular dimension to the standard of safety to be achieved” [259, p. vii]. The result was an inconsistent set of converted values. For example, “hard” conversions with minimal rounding were applied to typical product dimensions, such as glass thickness. In contrast, building areas were converted using a “soft” conversion factor, where 10 ft² was approximated as 1 m², even though the actual conversion is 0.93 m². To limit confusion, historical analyses included in this thesis will identify contemporaneous values and units of measure, and where those values have been converted to metric based on a “soft” conversion, the original imperial value and unit of measure will be included in brackets.

The historical analysis sub-framework is designed to facilitate the identification of the rationale, or lack thereof, underlying the NBC’s existing fire and life safety acceptable solution requirements. Within the

regulatory risk paradigm, this framework supports the quantification of risk by incorporating not only performance criteria but also the characteristics of the hazard, the exposed, and their interrelationship. The resulting information addresses longstanding issues of misinterpretation and ambiguity that have limited the acceptance of innovative designs. It also provides a foundation for the next stage of analysis toward a performance-based framework, as outlined in the following section.

4.4 Technical Reconciliation Sub-Framework

The technical reconciliation sub-framework is designed to build on the findings of the historical analysis and evaluate fire and life safety acceptable solution requirements within a modern technical context. Through this sub-framework, requirements or elements that are outdated or erroneous may be identified from the tracing of their historical basis with subsequent assessment of their relevance against current advancements in knowledge, technical and analytical capabilities, and the use of modern materials and methods. This portion of the analysis, then, provides a roadmap for application of fire science and engineering principles and/or risk based analysis to existing requirements recognizing that many of these were initially developed through observation and experience, and then verified over time rather than originally developed and supported by application of scientific or risk-based principles.

This portion of the analysis allows identification and evidence-based rectification of critical issues such as mischaracterized or evolving risk elements, errors, oversimplifications, and inadequate performance verification. It also promotes the inclusion into the requirements of any advancements in fire science, fire safety engineering, and associated best practices that may have emerged since the original solutions were developed. Finally, the technical reconciliation sub-framework facilitates incorporation of more holistic evaluation of potential impact of multiple solutions and their cumulative risk reduction, particularly when combinations of strategies are involved. By reassessing the applicability of existing requirements in light of the most recent fire science and engineering knowledge, as well as modern design, this process ensures that they do not expose society to unacceptable levels of fire and life safety risk or impose unnecessary costs through ineffective protective features.

The general schematic for the technical reconciliation sub-framework is illustrated in Figure 4-5. It again utilizes the components embodied in the regulatory risk paradigm to guide the technical reconciliation process. In this illustration, the elements of the regulatory risk paradigm on the left represent the information established from the historical analysis. The modified regulatory risk paradigm on the right schematically illustrates how, through reassessment and further analysis, the corresponding technically reconciled information can be re-examined in a current, and even future-looking context, to facilitate the development of parallel prescriptive and performance requirements well-founded on scientific and risk-based principles.

Several issues may necessitate technical reconciliation of the existing regulatory requirements. These may include initial mischaracterization of risk elements; changing characteristics of the hazards, the exposed, or the available fire safety technologies; shifting baselines of acceptable performance; or weak

assumptions and simplifications employed when deriving the original solutions to limit fire risk. Each is discussed in turn below.

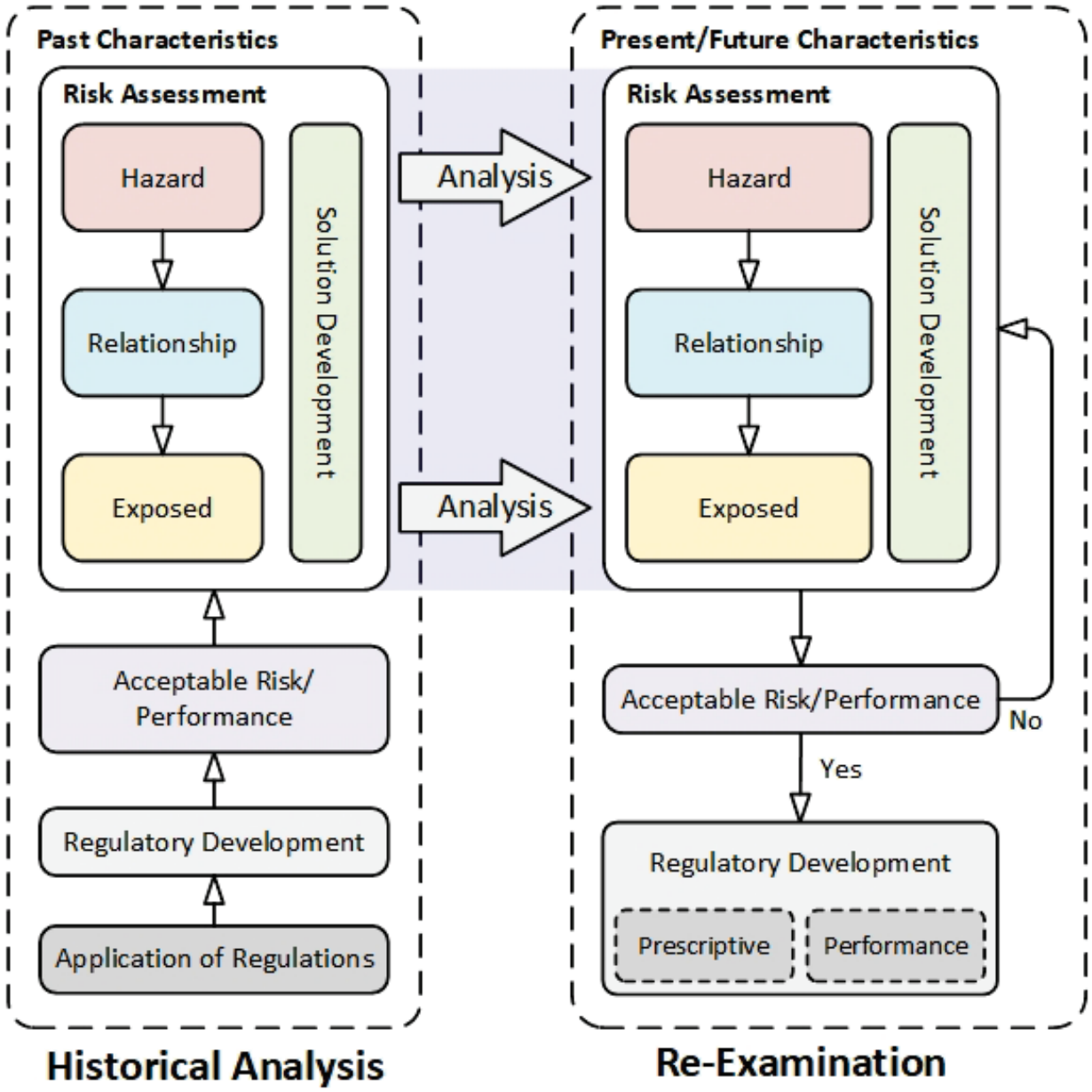


Figure 4-5: Technical reconciliation process

The first issue prompting technical reconciliation of an existing requirement is the identification and need to resolve risk mischaracterization. This often arises from the assessment of single, or potentially only a few, large-scale or high impact undesirable fire events that drew attention to specific building design issues and initiated an assessment and resultant regulatory control. An example of mischaracterization of risk is evident in the attic fire example where the location of fire initiation and spread mechanisms (fire hazard) were mischaracterized. The solution and subsequent requirements warranted reconsideration following continued attic fires; however, as is often the case in these situations, the investigations and

analysis to establish the conditions that led to the incident(s) focused on specific characteristics (i.e., hazards, exposed) of the events, rather than considering the broader range of characteristics or conditions present in all similar building designs that could result in similar incidents in future. This has led to solutions and fire and life safety requirements that, when applied to conditions beyond those considered during their development, result in a level of performance (residual risk) that may be either higher or lower than intended, a situation that should be addressed through technical reconciliation.

Mischaracterization can also arise from a lack of understanding or full use of fire science and fire engineering principles at the time of regulatory development. For example, the requirements for fire compartmentation were developed to address the hazard of fire severity characterized by the quantity of combustible material, which, as understood today, is only one of the variables that impact fire growth and development. Another key variable is ventilation. However, this was not considered in the development of these requirements. As a result, there may be ventilation or other conditions that limit, or alternatively exacerbate, fire growth and spread, but these are not recognized in the existing requirements.

The second issue necessitating technical reconciliation is changing characteristics of hazards, exposed and/or technologies, including, for example, building materials and design configurations [223], shifts in anthropometrics, human behaviour, or other related factors that influence the outcome of the regulatory risk paradigm. The shift in these characteristics often occurs over a period of time due to evolving practices, advancements in technology, and changes in demographics.

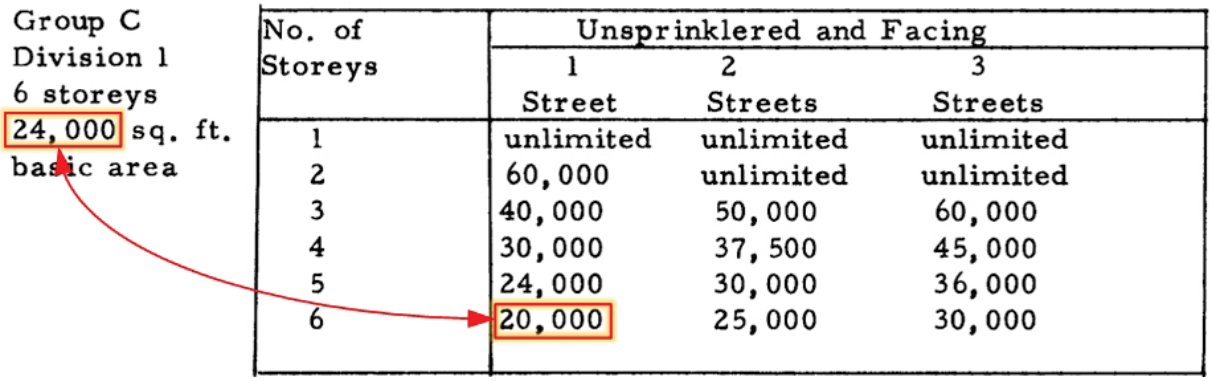
Similar to the example above, but in the context of changing characteristics, is the specification of fuel load to characterize potential fire severity. Fuel load was originally established through survey and statistical analysis in the late 1930s and into the 1940s [108, 251]. Through such analysis, residential occupancies were determined to have a fuel load of 50 kg/m² (1200 MJ/m²) representative of combustible contents and interior finish. For a variety of reasons, surveys and statistical analyses today [261] indicate residential occupancies have a substantially lower fuel load in the range of 450 to 940 MJ/m² (95th percentile), depending on room use.

Another example, this time related to solution development, can be found in the limits on building height for buildings of combustible construction. When these requirements were originally developed in the 1850s [46], building height was restricted to 60 ft due to limits on the size of fire apparatus and equipment used to fight fires from the exterior of a building. This limit still appears in the NBC today, even though firefighting capability has increased significantly since that time. As with the fuel load example above, this is a requirement that has remained in the code because there is no clear analysis framework through which to quantify and account for differences in how a hazard was limited/controlled by the fire service at the original time versus what would need to be assumed as the corresponding hazard control measure today.

The difference between the originally characterized elements of the regulatory risk paradigm versus the characterization of those same elements today will impact the outcome of the assessment of regulatory solutions. It is thus important for the technical reconciliation sub-framework to help remedy any disconnects in order to proceed toward alternative solutions that offer an appropriate level of safety today.

A third issue prompting technical reconciliation, similar to changing characteristics, is shifting baselines of acceptable performance, as illustrated in the example of the increasing shift of the NBC requirements toward mandatory use of sprinklers (Section 3.2.5). All other elements of the regulatory risk paradigm remaining equal, such a shift in performance expectations can impact the acceptance or optimization of past strategies even where characteristics are not mischaracterized or have not changed.

A fourth issue prompting technical reconciliation relates to the simplifications and assumptions employed when deriving complex solutions to limit fire risk, and further, when distilling those solutions into concise specification-based regulatory language. These can result in requirements that do not adequately reflect the intended outcome of the original complex solution. Compounding this issue are errors that may be made in any of the elements of the regulatory risk paradigm. An example of such an error can be found in the development of the building height and area limits as a function of building occupancy and type of construction in the 1970 NBC. The area limit for a six-storey multi-family residential building (with one street facing) was listed as 24,000 square feet in the 1965 NBC but was modified to 20,000 in the 1970 NBC. There is no rationale in the code committee minutes for this change, and an excerpt from the code committee meeting minutes [262] actually shows a discrepancy in the use of these two maximum building area values, as shown in Figure 4-6.



No. of Storeys	Unsprinklered and Facing		
	1 Street	2 Streets	3 Streets
1	unlimited	unlimited	unlimited
2	60,000	unlimited	unlimited
3	40,000	50,000	60,000
4	30,000	37,500	45,000
5	24,000	30,000	36,000
6	20,000	25,000	30,000

Figure 4-6: Residential building maximum building area error – 1970 NBC [117]

The erroneous value remained in the NBC until the 1990 edition. It was changed in the 1995 NBC when the maximum building heights and areas were reconsidered during the adoption of requirements for mandatory sprinklering; however, a multiple of this value, 6,000 m² [Article 3.2.2.49.], remains in the current (2020) NBC for sprinklered buildings. Had the original error not occurred, this value would be 7,200 m². As a result, buildings with areas between 6,000 m² and 7,200 m² today require double the fire-resistance rating for floor assemblies compared to buildings with areas of 6,000 m² or less, adding unnecessary costs to building construction.

One of the complexities in both the development and application of a technical reconciliation sub-framework in assessing existing elements of the NBC is that the four issues outlined above are often compounded or amplified due to multi-era regulatory development. The impact of this is illustrated in the development of the attic concealed space requirements. It is outlined in Figure 4-4 in the context of this new regulatory risk paradigm. At present, due to the primarily prescriptive nature of the NBC, there is little

consideration of such cumulative risk factors [196]. Thus, it is important to be able to identify such situations to deconvolute the multiple compounding changes that have become further and further entrenched through combined generational amnesia, status-quo bias and the regulatory ratchet effect. At present, the compounded set of requirements is accepted as standard practice. Going forward, it is important to recall and reassess the incidents on which these regulatory requirements were based, to reveal the specific risk context of the intended versus the actual performance (residual risk) in subsequent modifications as time passed [263]. The lack of such re-evaluation led Ferguson to consider the present form of regulatory development as malpractice, since "further regulations should have been considered as part of the initial risk" [182, p. 11]. Such challenges can be technically reconciled by utilizing the framework outlined here in combination with fire safety engineering analysis and tools such as the FSCT and generic risk assessment methods to identify and quantify unnecessary redundancies at a broader societal level.

Once the history of requirements is known and necessary elements have been technically reconciled, the new information obtained can be used to populate a modified IRCC hierarchy toward a new performance-based NBC as discussed in the following section.

4.5 Modified IRCC Hierarchy Alignment Sub-Framework

The combination of the regulatory risk paradigm and the IRCC hierarchical framework [231] (IRCC Framework) together form the foundation of an empirical and risk-structured performance-based framework, as shown schematically in Figure 4-7. First, the IRCC Framework is modified to align with the existing tiers of the NBC objective-based framework as well as the key components of the regulatory risk paradigm. The levels of the hierarchy that align with the components of the current objective-based framework of the NBC are highlighted in orange in Figure 4-7. The remaining levels then need to be populated with the information derived from the historical analysis and technical reconciliation process that form the key elements of the new overarching framework. At the same time, the entire hierarchy has to be aligned with major sections of the regulatory risk paradigm to support the creation, maintenance, and updating of parallel prescriptive and performance requirements as the NBC is taken forward. Under the present framework, this is achieved through the historical and technical analysis steps outlined above, and the resulting knowledge and understanding of the shared risk characteristics, criteria, and evaluation methods originally employed in conjunction with previous steps taken in the abridgement of solutions into specification format. As the new framework is applied and evolves over time, it will thus provide a new basis, founded in an appropriate combination of historical experience and technical concepts to structure clear links between the solutions and societal objectives that govern the requirements. The final alignment process with the IRCC hierarchy is discussed below in more detail, according to the levels shown.

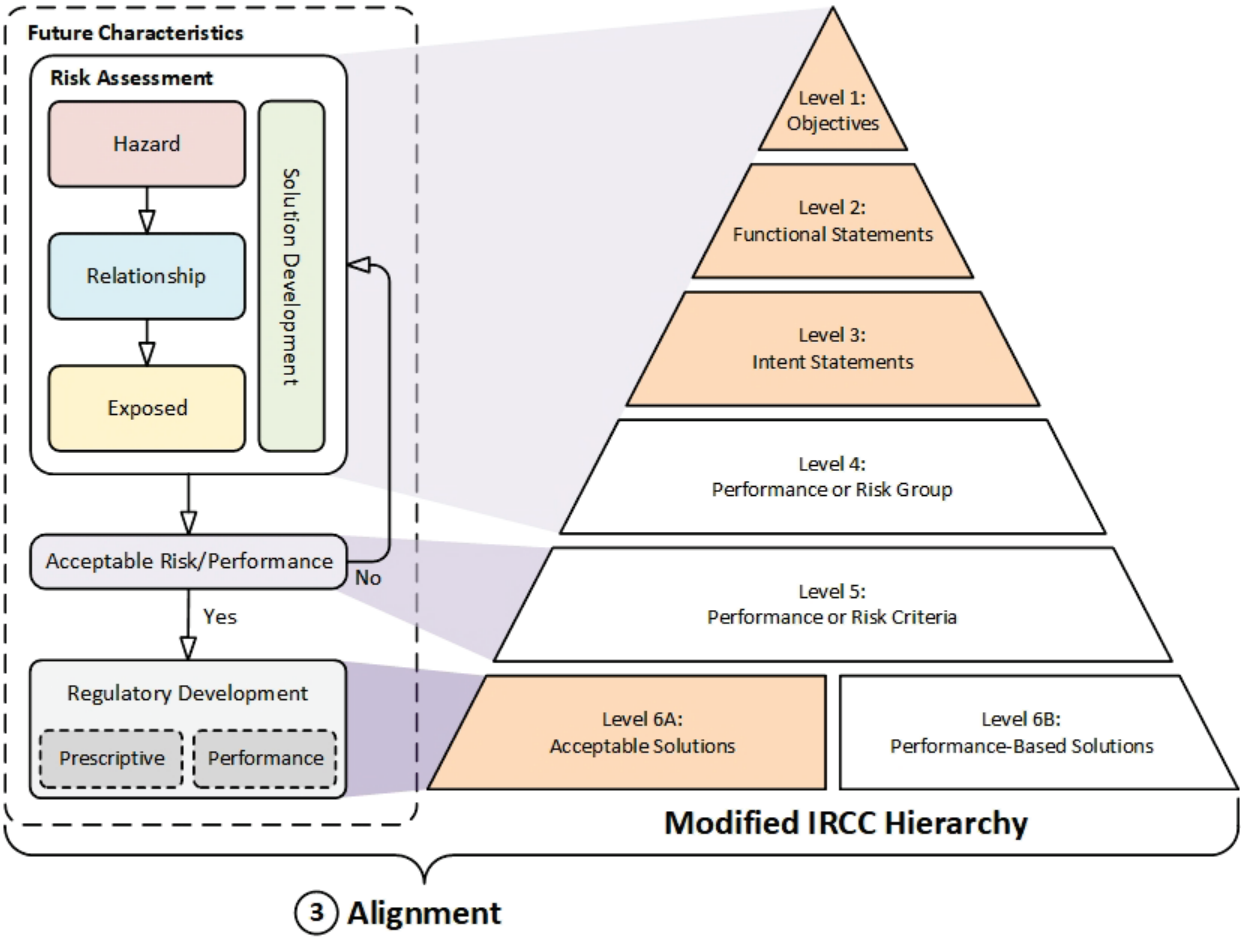


Figure 4-7: Modified IRCC hierarchy alignment

Level 1: Objectives

The objectives level describes the top level societal goals, in a completely qualitative fashion, and expressed in a way that "describe undesirable situations and their consequences, which the Code aims to prevent from occurring in buildings" [21, p. viii]. The mode of expression of the objectives establishes the qualitative risk relationship between hazard and exposed. For example, the wording for NBC Objective OP1, "Fire Protection of the Building," notes that (emphasis added as bold text) [21, Div. A, p. 2-5]:

> *An objective of this Code is to **limit the probability that**, as a result of its design or construction, **the building will be exposed to an unacceptable risk of damage due to fire**.*
> *The risks of damage due to fire addressed in this Code are those caused by—*
>
> *OP1.2 - **fire or explosion impacting areas beyond its point of origin**.*

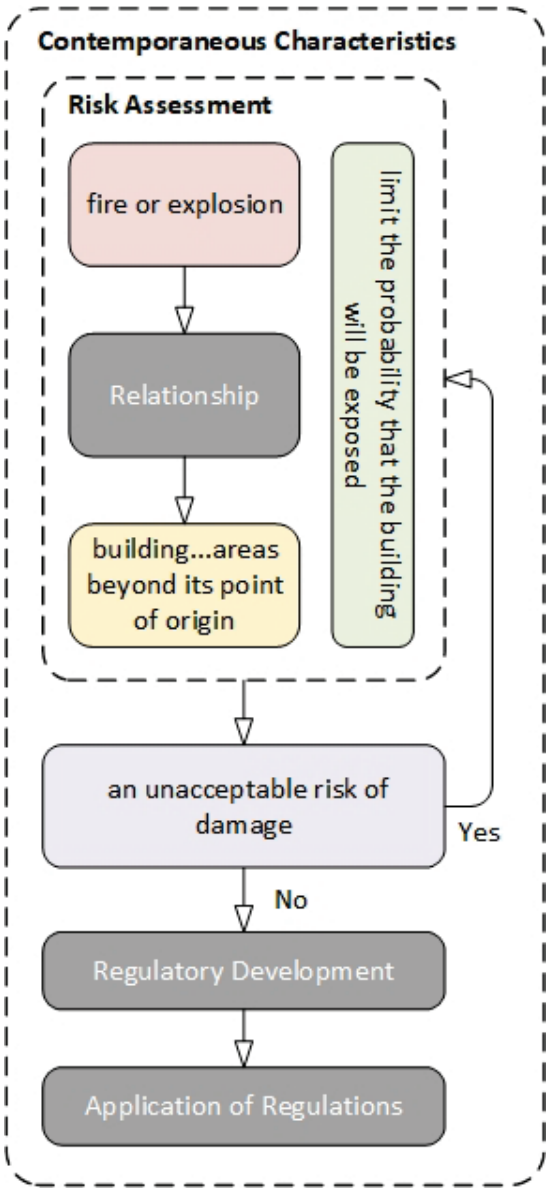


Figure 4-8: Regulatory development paradigm – populated with NBC objective information

The key components of the objective above are positioned as illustrated in the appropriate component boxes of the regulatory risk paradigm (Figure 4-2) in Figure 4-8. As this is done, component(s) of the regulatory risk paradigm not specifically addressed in NBC objectives are greyed out, so it is clear that these are either missing or not deemed important to the particular objective.

It should be noted in relation to this level of the analysis and alignment process that the objectives of the NBC were developed through a comprehensive top-down and bottom-up process of evaluating the legacy-based requirements of the earlier editions of the NBC. Therefore, while a historical analysis and technical reconciliation of the current fire and life safety acceptable solutions may result in recommended changes to the objectives that are currently stated, these changes are not expected to be significant.

Level 2: Functional Statements

The functional statements of Level 2 describe how the objectives are achieved, again almost completely in qualitative terms, using high-level statements that describe the impact of a hazard(s) that is intended to be addressed in achieving the associated objectives. As illustrated in Figure 4-8, the functional statements also supplement the solution. An example is the following functional statement [21, Div. A, p. 2-5]:

> ***F02*** *To limit the severity and effects of fire or explosions.*

The objectives and functional statements are not intended to be applied in isolation, but instead are paired to describe the intent of regulatory solutions in addressing a particular relationship between hazard and exposed in terms of risk. An example of the combination for the solution requiring a fire separation is [21, Div. A, pp. 2-2, 3-1]:

> ***Attribution:*** *[Functional Statement: F03, Objective: OP1.2]*
>
> ***OP1 Fire Protection of the Building***
>
> *An* objective *of this Code is to limit the probability that, as a result of its design or construction, the building will be exposed to an unacceptable risk of damage due to fire. The risks of damage due to fire addressed in this Code are those caused by—*
>
> ***OP1.2*** *– fire or explosion impacting areas beyond its point of origin*
>
> ***F03*** *To retard the effects of fire on areas beyond its point of origin.*

This combination of statements provides the qualitative risk relationship and intended outcome associated with the solution requiring the provision of a fire separation, summarized as follows [21, Div. A, pp. 2-2, 3-1]:

- [F03] *To retard the effects of fire on areas beyond its point of origin* by [OP1] limiting *the probability that … the building will be exposed to an unacceptable risk of damage due to* [OP1.2] *fire or explosion impacting areas beyond its point of origin*.

Similar to the objectives, the functional statements were developed through a comprehensive top-down and bottom-up process by evaluating the legacy specification-based requirements of earlier editions of the NBC. Therefore, while there may again be recommended changes, these are not likely to be significant.

Level 3: Intent Statements

The objectives and functional statements of the NBC are qualitative, and due to their formulaic nature, result in language that is convoluted. To overcome this, the intent statements are written in plain language to describe the intended outcome, in terms of qualitative performance, of the objectives and functional statements. The intent statements, in some instances, also provide further qualification of intended performance or acceptable risk. As an example, the intent statement attributed to the provision of a fire separation between different major occupancies (building uses) is as follows [131, p. 2]:

> *To limit the probability that a fire will spread from one major occupancy to an adjacent major occupancy having a different degree of fire risk, which could lead to damage to the building.*

The current intent statements, while more clearly expressing the risk relationships between a hazard and an exposed, still include limited information. Further, information that is provided is almost entirely qualitative. The initial historical analysis embodied in the application of this new framework, therefore, is expected to uncover additional information through which the existing intent statements can be enhanced toward the desired aim of providing additional levels of performance/risk quantification.

Level 4: Performance or Risk Groups

The current version of the NBC does not explicitly define or include the elements identified in Level 4 of the IRCC Hierarchy. In fact, this is one of the major deficiencies, and one that the present framework is intended to directly address. This level in the hierarchy outlines performance/risk groups across common risk characteristics, such as material combustibility, provision of sprinklers, or type of occupancy. This information sometimes exists within the historical records of the existing acceptable solutions in the NBC and, in fact, is implicit in those requirements. As such, it could also be uncovered during the historical analysis. For example, the NBC regulates the design and construction of buildings as a function of the intended use of the building. These uses (occupancies) are grouped based on common risk characteristics, but the characteristics are not explicitly identified or quantified as part of the NBC making it difficult, if not impossible, to align a new innovative building design with comparable existing solutions. The intent statement discussed above identifies that there may be different levels of risk between the major occupancies separated by a fire separation, but does not elucidate how those might have been defined or grouped at the time [131, p. 2]:

> *from one major occupancy to an adjacent major occupancy* ***having a different degree of fire risk [emphasis added]****.*

A historical analysis of the current regulations should, therefore, identify whether certain requirements were established based on common risk/performance characteristics that can be grouped together. Where the requirements were developed through more traditional and experiential methods, without consideration of risk/performance characteristics, it is possible that no underlying groups or common risk/performance characteristics are discovered through this analysis. In these instances, the appropriate characteristics and groupings may be qualified or quantified through the technical reconciliation process. These new characteristics and groupings would then subsequently be used to inform the development of new requirements.

Level 5: Performance or Risk Criteria

Similar to how the performance or risk groups in Level 4 are not defined, the associated criteria needed to populate Level 5 of the IRCC hierarchy are not explicitly identified in the NBC for existing prescriptive fire and life safety requirements. They also are not identified as part of the intent statements. Contrasting this are the few performance requirements that are included in the fire and life safety acceptable solutions

of the NBC. One example of a performance-based requirement specific to limiting smoke from certain medical treatment compartments where it is impractical to move patients in an emergency was included in Section 2.2.2 [21]. This performance specification requires that a solution be provided such that where a fire occurs outside of the medical treatment compartment, the compartment will "not contain more than 1% by volume of contaminated air from the fire area" [21, Div. B, p. 3-133] [Subclause 3.3.3.6.(1)(b)]. This is the performance criteria. In this example, the Level 4 risk group is medical treatment compartments and the Level 5 performance criterion is infiltration of less than 1% by volume of contaminated air from the fire source.

Performance-based acceptable solutions in the NBC by necessity include performance criteria, which avoid the complexities involved with more general risk characterization by focusing on specific performance targets (outcome) for tangible resources such as personnel (i.e., fire service), equipment, and materials. The downside to this method of performance specification, however, is that it limits the breadth of possible solutions to those that incorporate and can meet the performance required of the specified resources. Therefore, while this method avoids statements around performance, it is also not ideal since the performance of the resources considered at the time of development of the performance specification may be forgotten (generational amnesia) or may change significantly over time (fire apparatus design, for example). As such, a historical analysis of the performance-based acceptable solutions in the current requirements should aim to identify performance/risk criteria upon which those requirements were originally based, and then update those criteria where required, as part of the technical reconciliation process in alignment with level 5 risk criteria, in particular, risk criteria that incorporate uncertainty, as discussed in Section 3.3.3.

Level 6: Acceptable and Performance-Based Solutions

Level 6 of the IRCC hierarchy consists of two parallel pathways for final regulatory development and acceptance of innovative design [119]. Level 6A continues to promote design through the direct use of "Acceptable Solutions," which are the elements already contained in Part 3 of the NBC. Parallel to this is Level 6B, which promotes the use of "Performance-Based Solutions." Evolution of this portion of the hierarchy will require a more direct link to be drawn between requirements and the fundamental physical phenomena upon which the requirements are based. This requires specialized knowledge of the application of the fundamental physical phenomena, in this case fire science and fire engineering, to building design and construction. This presents a conundrum in the current Canadian context, since the practice of fire safety design is predominantly governed by use of Level 6A of the hierarchy, which involves the direct application of existing fire safety regulations rather than employing fire safety engineering concepts in the design. Therefore, it must be recognized that a complete and immediate shift to use of Level 6B of the hierarchy would cause a significant disruption to the current practice and would not be serviceable, given the limited number of fire engineers in Canada who have experience in the more holistic practice of fire engineering.

The solution is therefore to garner a "dual path" compliance approach via both elements of Level 6 of the hierarchy. On the one hand, compliance through Level 6B will allow greater flexibility in design but will

require a more holistic and consistent incorporation of fire science and fire safety engineering concepts into the requirements, as well as the design and approval process that govern fire safety design. Appropriate principles can be identified during both the historical analysis and technical reconciliation stages in application of the present regulatory risk framework, with premises regularly reviewed and modified according to emerging knowledge of fire science and current best practice. Compliance with Level 6A, on the other hand, will come with more limited design flexibility but will continue to provide a path for direct solutions to achieve compliance without requiring advanced knowledge of those solutions or resources to demonstrate compliance beyond fairly straightforward and measurable or observable building characteristics.

The dual path framework provided under Level 6 of the hierarchy will allow innovation through a performance-based compliance path where knowledge and resources are available, or greater simplicity of design through prescriptive-based compliance. Under the present regulatory risk framework, these parallel paths of compliance would be linked through documented technical rationale that would be made available to the NBC users, as discussed in the next section.

Level 7: Technical Basis and Methods of Validation

The transition to a dual path of prescriptive/performance requirements is not expected to be immediate and will evolve through additional analysis of the current solutions within the NBC, as well as with advances in knowledge, capabilities, materials, and methods. Use of the present framework to identify, maintain, and provide consistent availability of the knowledge at the basis of the requirements, however, forms a good starting point with which to avoid the challenges associated with time that have plagued the current set of acceptable solution requirements upon which the objective-based framework of the NBC is currently based. This approach is supported by Ferguson, who notes that [11, p. 53]:

> *A practical philosophy of building regulations should embrace tradition, law, and science. A knowledge of the characteristics of each can help in dealing with individual requirements. We can avoid freezing a building tradition in written law, avoid the futile search for reason in arbitrary law, and avoid legal persuasion with nature's laws, which are not ours to meddle with.*

Therefore, a means of “basis documentation” is essential as part of the combined regulatory risk paradigm and modified IRCC hierarchical sub-framework structured to identify all key characteristics, variables, analysis methods, and decisions that formed the basis of the development of the acceptable solution requirements (prescriptive and performance). Knowledge and consistent documentation of this information will allow for more frequent updating and facilitate on-going greater alignment between requirements and advancements in capabilities, materials, methods, and best practices in fire science and fire engineering.

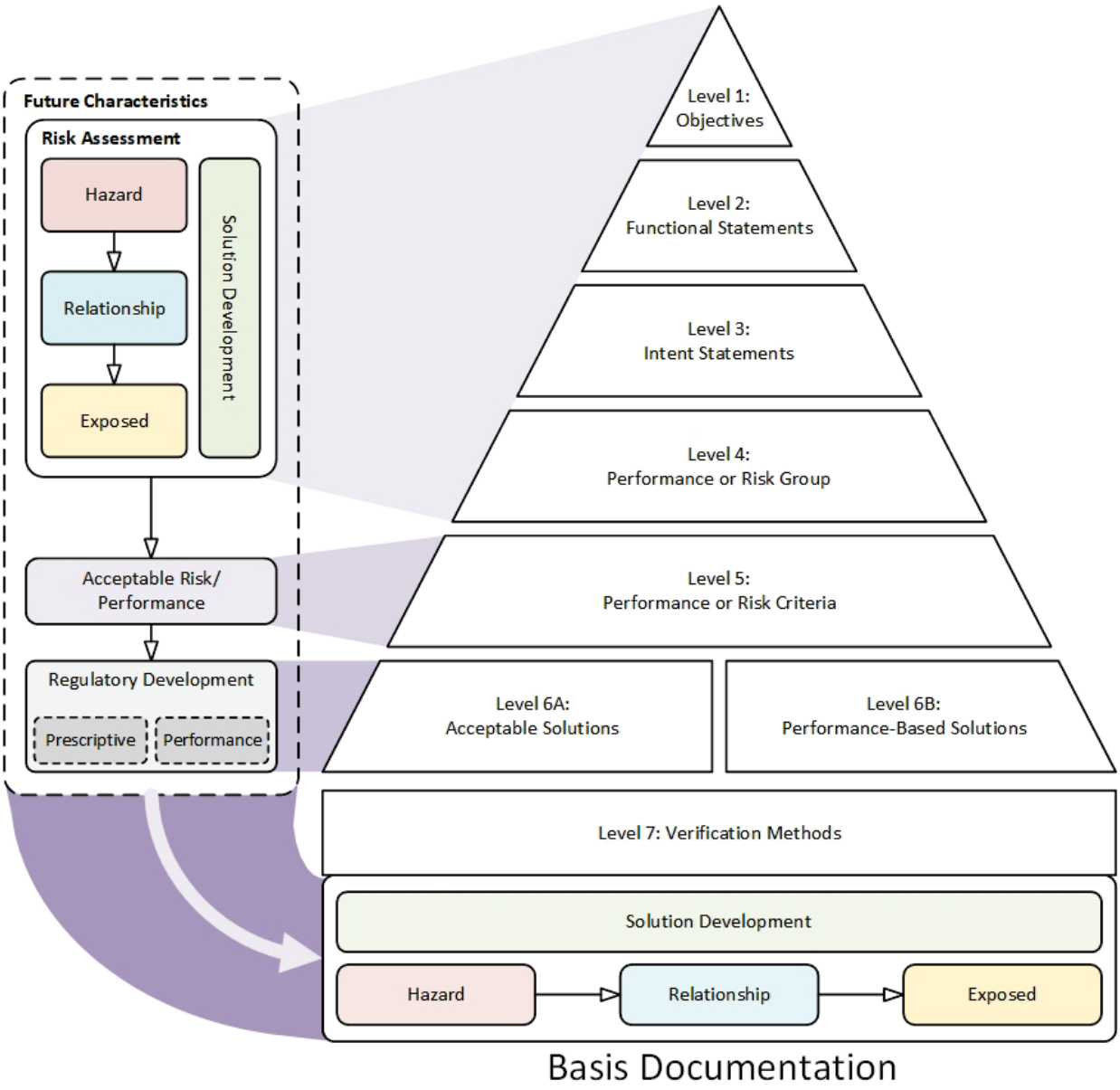


Figure 4-9: Diagram illustrating technical basis and methods of validation

The historical analysis of the current requirements is expected to identify the detailed solutions upon which the requirements were based and allows assessment of whether those solutions remain valid or need to be updated as part of the technical reconciliation process. Once the detailed solutions are known or have been updated, the underlying methods of validation can be identified. Since these methods of validation formed part of the original detailed solutions at the basis of the requirements, it may be reasonable to utilize these same methods of validation for designs governed by new performance-based requirements, or alternative and equally acceptable methods of analysis may be specified. Similar to technical elements of the requirements, the methods of validation can be updated as new methods of analysis are established. In this way, requirements will continue to align with current fire science and fire engineering best practices.

A repository of "basis documentation," structured within the combined regulatory development paradigm and modified IRCC hierarchy framework proposed in this research is recommended as a key element of the NBC regulatory development system to be made available to code development committees and members of the public concerned with building design and construction. This is conceptually illustrated as the final stage of the proposed framework, as shown in Figure 4-9.

4.6 Demonstration of the Framework - Case Studies

The following three chapters provide three case studies that demonstrate the efficacy of the proposed regulatory risk framework in facilitating the transition of the NBC from the current objective-based to a future performance-based approach. The case studies are structured to address specific risk characterization elements of the framework in Chapter 5, and then application of the entire framework in Chapter 6 and Chapter 7, including the FSCT approach and societal risk assessment methods detailed in Section 3.3. Each case study will include recommendations for change as discovered through use of the proposed framework to facilitate the transition of the NBC from objective-based to performance-based.

Chapter 5
Case Study – Risk Characterization

The case study in this chapter addresses the analysis of two key related risk characteristics associated with building occupants (the exposed). These include the number of building occupants (occupant load) and the width required for occupant egress, which are used together in the NBC to establish appropriate requirements for building evacuation. Individual risk characteristics have been selected over broader regulatory solutions as an introduction to the effectiveness of the proposed framework. Subsequent case studies will delve into the analysis of broader aspects of the code.

The analysis of each risk characteristic includes the regulatory requirement, its objective, functional statements, and intent statements; a detailed historical analysis of the development of the specification; technical reconsideration of the historical basis of the specification; and alignment of the information from these analyses with the modified IRCC hierarchy.

5.1 Office Occupant Load Factors

The number of occupants in a building is specified in the NBC on a floor area (occupant load factor) and building use (occupancy) basis. A larger occupant load increases the risk of exposure to fire hazards, necessitating effective measures to mitigate this risk. At present, risk reduction is achieved through the timely movement of occupants to a safe place, which relies on early notification, facilitation of movement, and the provision of protected areas. Accurate determination of occupant numbers is essential for effective notification, appropriately sizing egress facilities, and designing protected areas.

The following sections detail the acceptable solution requirement for establishing occupant numbers, provide a historical analysis of its development, including a technical reconciliation of the requirement in light of the historical context and current knowledge, and present recommendations for changes and updates.

5.1.1 Requirement, Objective, Functional Statements and Intent Statements

The occupant load factor for calculating the number of persons in office floor areas is specified as 9.3 m^2 per person, as outlined in Sentence 3.1.17.1.(1) and Table 3.1.17.1. of the 2020 NBC [21]. For example, using this factor, an office with a total area of 1,000 m^2 would have an occupant load of 108 people. The objective, functional statements, and intent statements associated with this requirement are as follows:

Objective - OS3.7 [21, Div. A, p. 2-2]: “To limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable

risk of injury due to hazards. The risks of injury due to hazards addressed in this Code are those caused by persons being delayed in or impeded from moving to a safe place during an emergency."

Functional Statement - F10 [21, Div. A, p. 3-2]: "To facilitate the timely movement of persons to a safe place in an emergency."

The intent of this requirement is to [131, p. 95]:

- *limit the probability of overcrowding, which could lead to delayed egress during emergency evacuation, which could lead to harm to persons.*
- *determine the minimum design occupant load in order to calculate egress and exit capacity.*

The NBC does not identify the basis of the office occupant load factor beyond the information detailed above. The lack of quantitative rationale underlying the office occupant load factor is addressed through the historical analysis detailed in the following section.

5.1.2 Historical Analysis

The historical development of the office occupant load factor spans approximately 170 years. This history is detailed below.

5.1.2.1 Ventilation

Due to large losses in British army field hospital barracks during the Crimean War (1853 to 1856), a Commission was formed to examine the situation and provide recommendations to enhance the sanitary conditions in barracks and hospitals [264]. The investigation revealed that "ill health and excessive mortality prevailed among the troops in proportion to the defects in the air supply of their barracks" [264, p. 38].

In the late 1850s, Florence Nightingale observed that "[w]herever cubic space is deficient, ventilation is bad. Cubic space and ventilation will therefore go hand in hand" [265, p. 13]. In 1859, she further noted that, for hospital design, a cubic air change capacity of 600 cubic feet per hour for a healthy adult was inadequate and recommended a minimum of 1,000 to 1,500 cubic feet per hour [266]. This recommendation was based on passive ventilation.

Building on Nightingale's observation, the 1860s and 1870s saw a detailed analysis of factors such as room dimensions, usage patterns, duration of occupancy, external and internal temperatures, and the number of occupants to determine appropriate ventilation rates [264]. The results of these analyses were ultimately simplified into minimum cubic space requirements per person for regulatory purposes.

In the 1870s, Max von Pettenkofer examined the factors related to ventilation in greater detail and developed a procedure for calculating required ventilation based on exhaled carbonic acid [264, 267]. Pettenkofer found that a person occupying an office space of 1,000 cubic feet produces approximately 12 parts per 10,000 of carbon dioxide in an hour, when air change occurs only through leakage. This

concentration is considered the minimum level required to support tenable conditions. Bolton analyzed these results and produced the plot shown in Figure 5-1 [267, 268]. The red shaded area represents untenable conditions, the green shaded area represents tenable conditions, and these areas are separated by a line representing a concentration of carbon dioxide as a function of floor area. The yellow lines show the optimum occupant floor area for business occupancies.

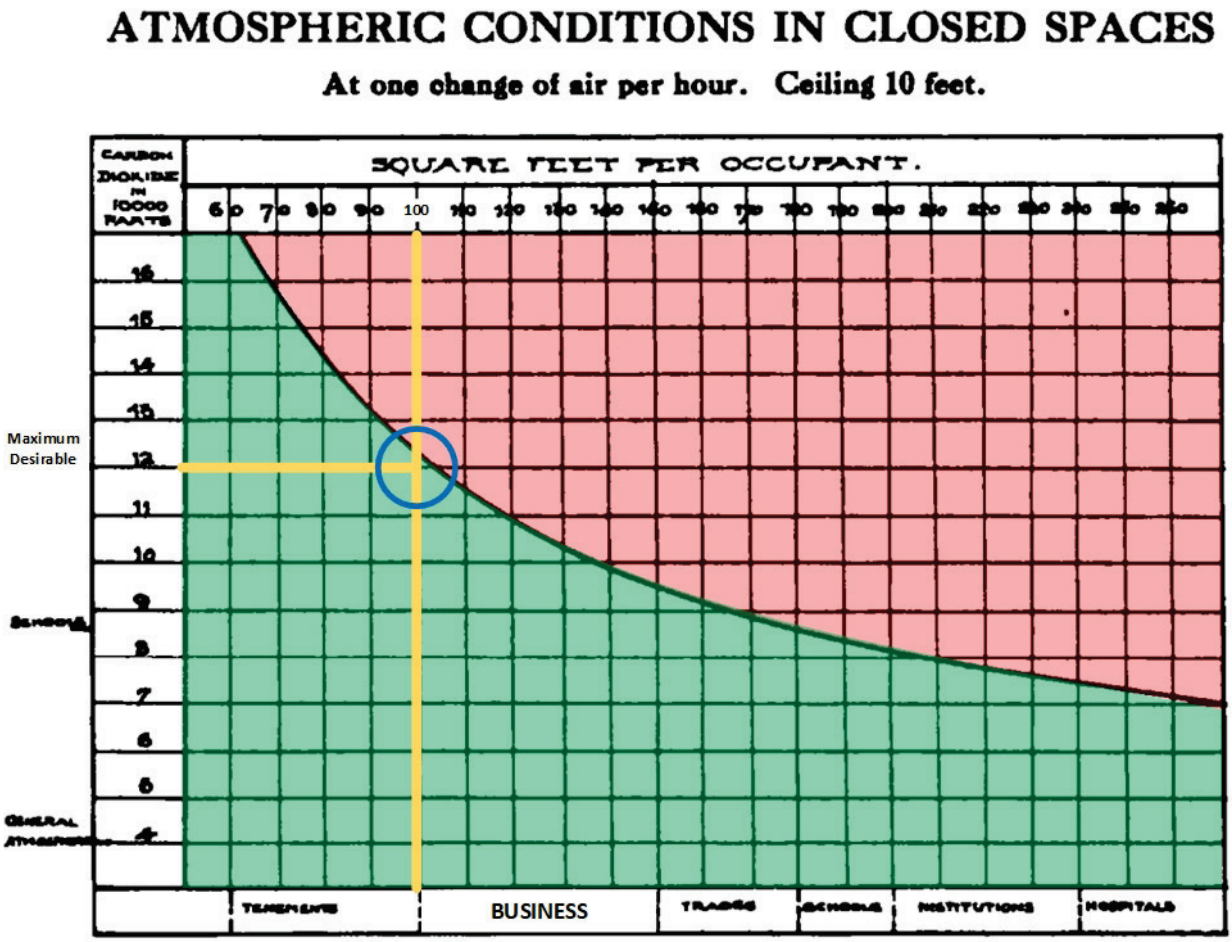


Figure 5-1: A plot of atmospheric conditions as a function of occupancy and square feet per occupant [267, 268]

5.1.2.2 Elevator Service

Timely and reliable elevator service is important to facilitate access to the upper storeys of buildings that are more than a few storeys in building height. Designing an efficient elevator system requires an understanding of the building's occupant load to determine the appropriate number and size of elevator cars. This was recognized by Reginald Pelham Bolton in the early 1900s and discussed in his 1908 book, “Elevator Service” [268]. At the time, elevators were not intended for evacuation.

In his work, Bolton outlined a method for determining the population of office buildings based on cubical air capacity and floor area (ventilation basis). He validated the method using statistical surveys of office buildings (statistical basis). These are detailed below.

Ventilation Basis

As discussed above, a specific cubic capacity per person was required to maintain a tenable environment in buildings that were predominantly passively ventilated. These cubical capacities became the standard for ventilation design and served as the basis for requirements in the late 1800s. As a result, building populations were indirectly limited through the cubical limits associated with ventilation requirements. Bolton recognized this limitation as a practical approach to determining building population for the purpose of establishing elevator service. Bolton noted the following [268, p. 49]:

> *The answer may be found in the proportion of the cubical contents of the occupied portion of the building, which is occupied by these passengers. For practical purposes it may be assumed that the modern building of twelve-foot floors will have a clear height from floor to ceiling of about ten feet, so that the question nets down to the cubical contents divided by ten, or, in other words, to the area of floor space related to the passengers.*

Bolton noted [268] that office rooms were ventilated through leakage at a rate not exceeding one change of air contents per hour and that heating systems for office buildings were designed on that basis. He referenced Pettenkofer's method for calculating appropriate air quality, in which the limit of desirability equated to 1,040 cubic feet of air per occupant [267, 268]. This corresponded to 104 square feet per person for a 10-foot ceiling, representing a typical occupant density for offices where tenable ventilation was used as the basis.

Statistical Basis

To validate the ventilation requirements as a means of determining office occupant density, Bolton provided statistics on actual occupant loads on a floor area basis for various types of office buildings in the City of New York [268]. The results covered those business occupancies considered the busiest at the time (i.e., stockbrokers, lawyers, city departments, banks, real estate agencies), with floor areas ranging from 100 to 150 square feet per occupant. The density calculated using Pettenkofer's ventilation method corresponded with the highest density office type from Bolton's statistical survey. Based on this result, Bolton used an occupant load density of 100 ft^2/person in the design of elevator systems for office buildings.

5.1.2.3 Factory Investigation Committee

Several years following the publication of his book, Bolton's methodology was referenced as part of an investigation into Factory conditions following the Triangle Shirtwaist Fire in 1911. The Factory Investigation Commission interviewed Bolton about his experience with building safety in the Borough of Manhattan. Bolton noted the following [269, p. 1556]:

> *I have made a considerable study of the occupancy of the interior of buildings of all kinds under city conditions, which appear in my book above referred to. It will be observed therefrom, that the densest occupancy of business buildings in the heart of this Borough is one person to one hundred square feet of net occupied area, an amount which spread over a number of floors, constitutes a severe task for elevator operation.*

It is important to note that in the early 1900s, office occupancies were grouped with factories and workrooms. This grouping was based on the common use of these occupancies as places of employment. However, the characteristics of these occupancies were significantly different.

5.1.2.4 Life Safety Code

As discussed in Section 2.1.3.5, the formation of the NFPA Life Safety Committee followed the Triangle Shirtwaist Factory fire by less than 2 years. The Life Safety Committee initially focused their efforts on limiting the population of a building as a function of exit stair capacity and occupant flow rate. However, this was problematic as it relied on building designers/constructors to establish their building's exit stair capacity (within certain limits) at the time of construction and then police that capacity over the lifetime of their building. This method also required detailed tables and graphs of egress capacity as a function of various building characteristics.

An alternative and simpler method was developed in 1919 [239] to establish occupant load factors as a function of use (occupancy), representing actual populations at the time and based on statistical analyses. The first occupancy for which occupant factors were established in 1919 was for schools. The second was for office occupancies in 1922 [240], when the Life Safety Committee "tentatively" established an occupant load factor of 100 ft² per person based on existing knowledge as well as more current studies of the number of occupants in office buildings in Philadelphia and New York [240].

The same year the Life Safety Committee tentatively established the office occupant load factor as 100 ft² per person, a member of that Committee (C. Heller) published an article in the NFPA Quarterly on "Some Fundamentals of Safeguarding Life from Fire," noting the following [270, p. 180]:

> *Office Buildings. The number of occupants per office varies with the class of business conducted in the building. For instance, buildings which house large corporations using large open spaces for their clerical forces have a greater density of population than those in which there is a mixed tenancy of many small private offices. As a general rule in these buildings in the larger cities there will be from 140 to 200 square feet per person of gross area of upper floors,—that is, the area within the building lines and not the rentable space. One person per 150 square feet of space is recommended as a safe figure.*

The NFPA Life Safety Committee continued studies of occupant populations for other occupancies until at least 1927 [241]. The first occupant load factor table appeared in the 1934 Building Exits Code [168], and noted an occupant load factor of 100 ft² per person for office occupancies, conservatively based on the lower value from range of studies conducted up to that time.

5.1.2.5 NBS Design and Construction of Building Exits

As discussed in Section 2.1.3.5, the NBS Building Code Committee undertook a study of exit requirements in cooperation with the NFPA Life Safety Committee. The "Design and Construction of Building Exits," published by the NBS in 1935 (1935 DCBE), incorporated many of the same requirements as the Building Exits Code of that time. Section 7-5-1., "Determination of Population" of the 1935 DCBE listed the

occupant load factor for an "Office, factory, and workroom" as 100 ft² per person. The notes to this occupant load factor identified the following as sources [70, p. 57]:

- *Some years ago Rudolph P. Miller. as superintendent of buildings of Manhattan. prepared a tabulation showing the density of population in workshops in the city of New York. The tabulation resulted from population counts in connection with 'exit orders' in 500 workshops and factories. The occupants of each story of the buildings Investigated were determined as accurately as possible and the area occupied per person computed from the gross area of the story. As might be expected the tabulation revealed a wide variation in areas per person ranging from 19 to 560 square feet. This variation is accounted for by the different kinds of industries represented In the tabulation. The average for the entire group of buildings in the table was 107 square feet per person, which corresponds very closely with the average figure of 100 square feet per person adopted by the committee for this occupancy.*
- *A census of the Equitable Building in New York City, taken in 1924 was made available to the committee through the courtesy of C. T. Coley, operating manager of that building. Here, again. there was a considerable variation, ranging from 43 square feet to 260 square feet per person, but the average was 107.*

The sources of data referenced above could not be determined, and it is possible that the data collected by R.P. Miller was also utilized in the NFPA Life Safety Committee's establishment of their office occupant load factor. The result is not unexpected, given the occupant limits associated with adequate ventilation design at the time.

5.1.2.6 National Building Code of Canada

As discussed in Section 2.1.4, the requirements in the 1941 NBC were substantially based on the US model building codes up to that time. Table 1 (Section 4.6), "Maximum Area of Floor Space per Person to be Assumed in Determining the Number of Persons to be Accommodated by Exits," of the 1941 NBC specified an occupant load of 100 ft² per person for "Offices, Factories, and Workrooms, Stages and 'Back-stage' Areas." The description of these occupancies was consistent with those of the 1935 DCBE.

Table 3.5, "Maximum Area of Floor per Person to be Assumed in Determining the Occupant Load of any Area," of the 1953 NBC specified 100 ft² per person for "offices." This remained unchanged until the 1980 NBC, where the occupant load was expressed in metric units as 9.3 m² per person. This office occupant load factor has remained unchanged up to the current 2020 NBC. However, this factor was questioned during the development of the 1985 NBC based on studies by Pauls [271], which identified an approximate occupant load factor in Canadian offices as a much larger 26 m² (278 ft²) per person. This difference was likely due to changes in office use since the original 9.3 m² per person was established.

The office occupant load factor of 9.3 m² (100 ft²) per person appeared in the life safety code (NFPA 101) up until the 2015 edition (see Section 3.2.2 for an example of an attempt at an earlier change to this value).

This factor was then changed in the 2018 edition of NFPA 101 to be 150 ft²/person or 14 m²/person; however, it was not changed in the NBC.

5.1.2.7 Summary of Basis

The previous sections detailed the historical development of the 2020 NBC office occupant load factor, spanning approximately 170 years. The results of this analysis established that the office occupant load factor (100 ft² per person) was based on minimal passive ventilation limits in office buildings in the late 1800s and early 1900s. Statistical analyses of populations of office buildings in the early 1900s confirmed this factor, which is not unexpected given the underlying ventilation limit and associated requirements. However, with advances in ventilation design since then and changes to office spaces, this value may no longer be technically or statistically representative.

5.1.3 Technical Reconciliation

As discussed above, the office occupant load factor of 9.3 m² per person in the 2020 NBC is based on passive ventilation limits in office buildings in the late 1800s and early 1900s, confirmed by statistical analyses of these occupancies in the early 1900s. Ventilation system design and associated requirements have changed significantly in the last 100 years, along with office uses. Therefore, the office occupant load factor of 100 ft²/person is a risk characteristic that has changed since its original development (i.e., changing characteristic) and may no longer be technically relevant.

As discussed in Sections 3.2.2 and 3.2.3, a change was proposed to the office occupant load factor in the 2012 edition of NFPA 101 to be revised from 9.3 m² to 14 m² per person. However, this proposed change was rejected due to a lack of historical and statistical data (generational amnesia and status quo bias).

A similar change was proposed to the 1990 NBC, based on anecdotal population densities of 18.6 m² to 23.6 m² per person, reported by interior designers [272]. The Committee at that time suggested that the value was based on “reasonably severe conditions” and that “there will be occasions when there are visitors when the number of persons in an office will substantially increase” [272, Agenda FSO, 11.7.7., p. 13]. Still, the Committee agreed to study the proposed change and re-examined it 10 years later [273] in light of the results of the research report [167], which would later be considered in the proposed change to the 2012 Life Safety Code (Section 3.2.2). However, similar to the Life Safety Committee, the NBC Committee rejected the proposed change for the following reasons [273]:

- Given the minimum number of required exits (2) and minimum exit width (1100 mm), it was determined that an increase in the office occupant load factor would only benefit floor areas greater than 2,750 m², and many office spaces at the time were assumed to have a lesser floor area.
- The office occupant load factor in the Life Safety Code at the time (the 2000 edition) was 9.3 m², and a change to the NBC would then differ from the Life Safety Code.

The reasons for rejecting the change are not technically based and are more consistent with rationalizing the status quo. It is important to note that contrary to the first reason for rejection, other requirements of the NBC are based on occupant load and have a much lower threshold than identified above. These include:

- a total occupant load of more than 300 requires a fire alarm system [Clauses 3.2.4.1.(4)(d) and (e) of the 2020 NBC],
- an occupant load of more than 60 people requires at least two routes of egress from a roof, single room or suite [Sentence 3.3.1.3.(4) and Clause 3.3.1.5.(1)(b) of the 2020 NBC],
- an occupant load of more than 60 people requires a door swing in the direction of travel to an exit [Sentence 3.3.1.11.(2) of the 2020 NBC],
- a room or suite of assembly occupancy containing an occupant load of more than 100 is required to be equipped with panic hardware [Sentence 3.3.2.7.(1) of the 2020 NBC],
- in addition to travel distance and area requirements, a single exit is permitted from a floor area where the total occupant load served by the exit is not more than 60 [Sentence 3.4.2.1.(2) of the 2020 NBC],
- relaxations for mezzanine egress where the occupant load of the mezzanine is not more than 60 [Clause 3.4.2.2.(2)(b) of the 2020 NBC],
- exit signs in a building having an occupant load of more than 150 [Clause 3.4.5.1.(1)(b) of the 2020 NBC], and
- the number of sanitary facilities as a function of the floor area occupant load [Sentence 3.7.2.2.(10) of the 2020 NBC].

A second attempt to change the office occupant load factor was proposed [274] to the 2018 edition of the Life Safety Code [275] and was based on an additional study [276] (the Muha Report). The Muha Report examined the history of the office occupant load factor and statistical analysis of more current office occupant loads. Similar to an earlier study of office occupant loads [167] (the Milke Report discussed in Section 3.2.2), the Muha Report identified the origins of the office occupant load factor to the 1922 NFPA Proceedings [240]. The Muha Report also reviewed previous office occupant load studies conducted between 1935 and 2012 in the US, as well as distributed questionnaires to architects, real estate personnel, and building owners. The questionnaire requested data on area allowances per person in office spaces. The Muha Report did not delve further into the historical basis of the office occupant load factor beyond what had already been identified in the Milke Report (i.e., the 1922 NFPA Proceedings). From this, in 2018 the Muha Report identified an average office occupant load factor of 204 ft^2 per person [276], and recommended replacing the original office occupant load factor with two new ones:

- 150 ft^2 per person for general offices, and
- 100 ft^2 per person for high density spaces such as call centres.

The rationale for the proposed change was as follows [277, p. 7]:

> *studies … have concluded that the 100 ft²/occupant (gross) occupant load factor for business occupancies is very conservative which has led to requiring Group B occupancies and office buildings in general to have additional egress capacity and a greater number of exits to accommodate an "overestimated" building population. The increase from 100 ft²/occupant (gross) to 150 ft²/occupant (gross) for business occupancies is still a conservative figure; yet reasonable, based on recent changes in office building design as well as changes in the North American workplace and work style trends; such as work station configurations, flexible work schedules, telecommuting, work at home, etc.*

Based on the results of the Milke and Muha studies, the change to the office occupant load from 100 ft²/person to 150 ft²/person was accepted and incorporated into the 2018 edition of the Life Safety Code [275].

In addition to the rationale above, the International Codes Council (ICC) of the United States had already made a similar change to their office occupant load factor from 100 to 150 ft² per person in the 2018 edition of the International Building Code (2018 IBC) [278]. The IBC is the predominant building code used throughout the United States. The rationale for the change to the IBC was the same as for the 2018 edition of the Life Safety Code [277].

Without the original basis of the development of the office occupant load factor, as provided above, the eventual changes to the NFPA Life Safety Code and the IBC were significantly reliant upon statistical data of actual office occupant loads. A combination of the actual technical basis of the original 100 ft²/person value (passive ventilation) and the more current statistical data is expected to have provided sufficient rationale for the earlier proposed changes to both the 1990 NBC and the 2012 NFPA Life Safety Code.

5.1.4 Conclusion and Recommendations

This case study has demonstrated the use of the new framework developed in this research to identify the historical basis of the office occupant load factor in the 2020 NBC and to technically reconcile that basis in a current context. The analysis has demonstrated that the original passive ventilation basis of the office occupant load factor is no longer representative of either current ventilation practices (i.e., active ventilation) or the actual occupant loads of office occupancies since at least the 1920s [167, 270, 271, 276]. Earlier efforts to change the office occupant load factor in Canada [273] and the US [170] were impeded for reasons more consistent with generational amnesia (Section 3.2.2) and status quo bias than technical rationale.

While the office occupant load factor did change in two of the US model codes [275, 279] in 2018, it remains unchanged in the 2020 NBC. This case study demonstrates the use of the new framework to analyze a risk characteristic in the NBC and provides a technical rationale in support of a change, specifically to the office occupant load factor in the NBC. Additionally, the information uncovered can be retained as a reference to inform future regulatory changes or performance-based solutions, particularly

in scenarios where specific characteristics differ from the generalized (averaged) load factor of 14 m² (150 ft²) per person identified in the recent studies [167, 276].

The office occupant load factor is not a regulatory solution to directly address the risk of fire but rather a key characteristic through which to represent the "exposed" population in office occupancies, which is critical for evaluating the impact of fire hazards. In this context, the office occupant load factor serves as one of the risk characteristics associated with a defined group (office occupancies), corresponding with Level 4 of the modified IRCC Hierarchy: "Performance or Risk Group." Such characteristics contribute to the formulation of regulatory solutions. Thus, to continue the example, further analysis of the use of occupant load factors is detailed in the next section as part of the development of a regulatory solution for required exit width.

5.2 Exit Width

The 2020 NBC requires that the width of exit stairs and corridors be based on the number of occupants using the exit, which is determined by the risk characteristic of occupant load within a given floor area, storey, or building, as outlined in the previous section. The purpose of the minimum required exit width is to facilitate the timely movement of occupants to a safe place during an emergency.

The following sections detail the acceptable solution requirement for determining the minimum exit width, including its historical basis, a technical reconciliation of the requirements based on historical analysis and current knowledge, and corresponding recommendations.

5.2.1 Requirement, Objective, Functional Statements and Intent Statements

The NBC mandates, with limited exceptions, a minimum width of 1,100 mm for exit corridors, ramps, and stairs, as outlined in Sentence 3.4.3.2.(8) and Table 3.4.3.2.-A of the 2020 NBC. This base width is required to be increased by 9.2 mm per occupant for any number of occupants exceeding the base threshold, as specified in Clause 3.4.3.2.(1)(c) of the 2020 NBC. The key objectives and functional statements associated with these requirements are as follows:

Objective - OS3.7 [21, Div. A, p. 2-2]: to limit the probability that, as a result for the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this Code are those caused by persons being delayed in or impeded from moving to a safe place during an emergency.

Functional Statement - F10 [21, Div. A, p. 3-2]: To facilitate the timely movement of persons to a safe place in an emergency.

The intent of these requirements is to [131, p. 533]:

limit the probability that exits will be of insufficient width to permit efficient egress in an emergency situation, which could lead to delays in the evacuation or movement of persons to a safe place, which could lead to harm to persons.

Similar to occupant load factors, the NBC does not identify the basis of the exit width requirements beyond the information detailed above. The lack of quantitative rationale underlying the exit width requirements is addressed by the historical analysis detailed in the following section.

5.2.2 Historical Analysis

The development of exit width requirements has evolved over approximately 230 years and partly parallels the history of the development of occupant load factors. In particular, the cumulative width of a building's exits is a function of the number of building occupants expected to use those exits during an emergency. As the first step in applying the new framework to this analysis, the following sections provide a detailed account of the historical evolution of exit corridor and stair width requirements within the NBC.

5.2.2.1 Factory Inspection, Fire Drills and the Factory Investigation Committee

In the United States, exterior factory fire escapes built up to the 1880s were typically 16 to 18 inches wide, a dimension considered insufficient at the time [280]. To address this limitation, Rufus Wade, Chief Inspector of Factories in Boston, introduced an improved design requiring exterior fire escapes to be at least 22 inches wide, with balconies not less than 44 inches wide [280]. However, no rationale was documented for selecting these specific dimensions.

Following the Triangle Shirtwaist Factory Fire in 1911, H.F.J. Porter, an industrial engineer with experience conducting fire drills across the United States since 1904 [243], was appointed as the Factory Investigation Commission's "advisory expert on the fire problem" [87, p. 15]. In this role, Porter conducted several hundred inspections of manufacturing facilities and prepared a report for the Commission titled "The Fire Hazard" [87], drawing on observations from his inspections and prior experience. In his report, Porter claimed that the number of occupants on any single floor should be limited by the capacity of the exit stairs. He further emphasized [87, p. 158]:

A stairway 12 feet high between floor and ceiling, 3 feet wide, will accommodate 12 people per floor. If the width is increased to 44 inches the capacity is doubled, viz: 24 people per floor. If there are more people per floor than these numbers they will collide on the landings and congestion will occur so that the downward movement practically ceases.

Porter illustrated the effects of congestion for stair widths narrower than 44 inches, as shown in Figure 5-3. About a year later, he developed a "formula for emptying a floor by one stairway" [281, p. 2]. The formula, along with an example, is presented in Figure 5-2.

FORMULA FOR EMPTYING A FLOOR BY ONE STAIRWAY

Number of couples (number of people divided by 2)	c
Time of formation in line after signal, seconds	10
Time one couple takes to march to top of stairs, seconds	10
Time each couple takes to pass through door at top of stairs, seconds	1
Number of stair flights (one less than number of floors)	f
Time of one couple to descend one flight of stairs, seconds	10
Time of one couple to go from foot of stairs to street, seconds	10

$$\text{Total time} = T = 30 + c1 + f10$$

Example Time of emptying 100 people from tenth floor

$T = 30 + 50 + 90 = 170$ seconds $= 2$ minutes, 50 seconds

Figure 5-2: Porter's formula for emptying one stairway [281]

Porter emphasized that the time required to evacuate a building should not exceed three minutes, as remaining longer in a burning building is neither desirable nor safe [281]. This assumption, however, presumed the simultaneous evacuation of the entire building. Using Porter's formula and assumptions, evacuating a typical factory building within three minutes proved impractical without a significant number of exit stairs. To address this challenge, Porter recommended that all buildings be bisected by a "firewall" that would allow almost immediate horizontal exiting to the non-fire affected side on each floor [87, 281]. While Porter's firewall solution was not universally adopted [258], some of his recommendations were implemented by New York State Labor Laws and the NFPA, as discussed in the following section.

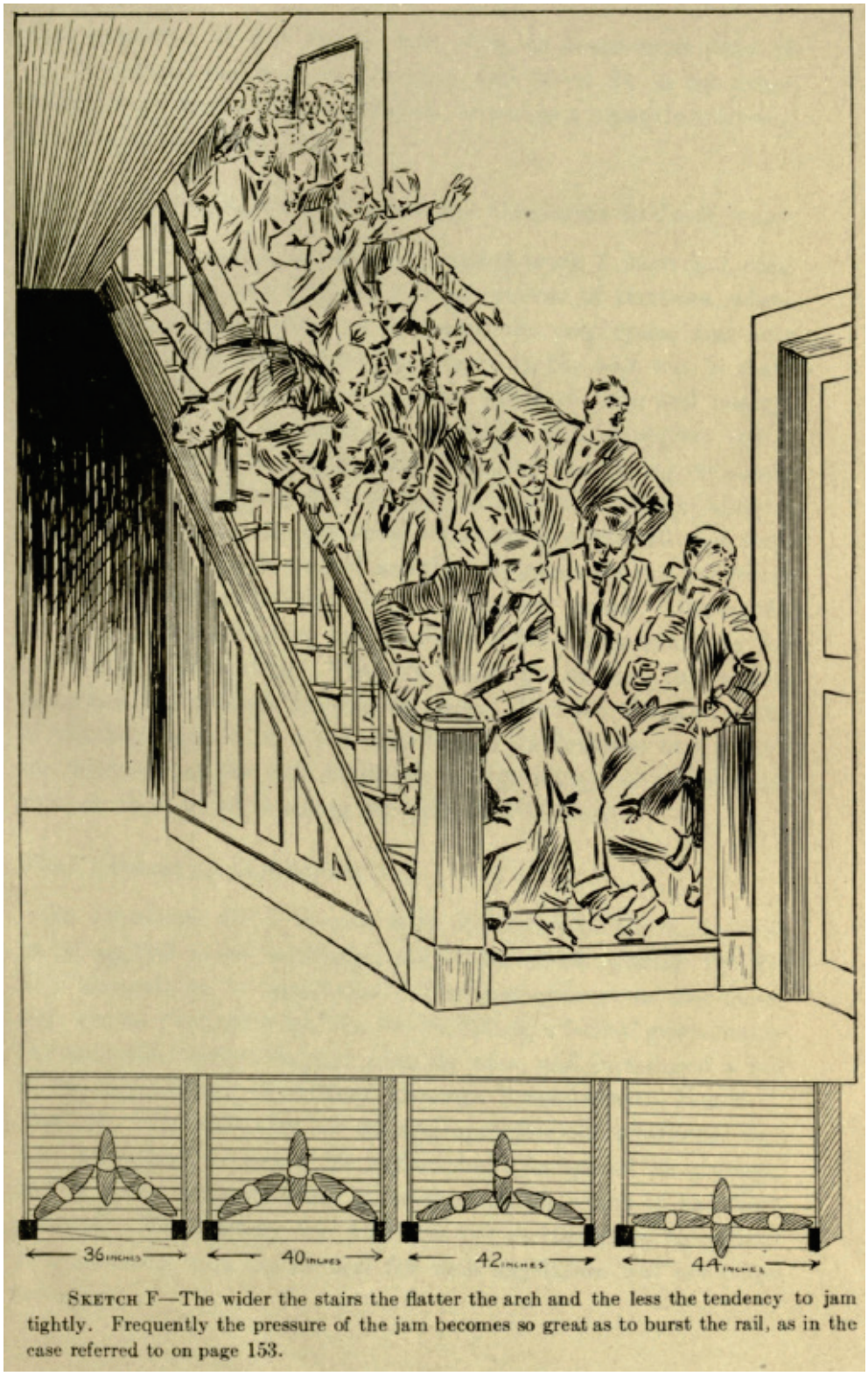
5.2.2.2 Life Safety Code

Exit width was addressed in the NFPA Report of the Committee on Fireproof Construction in May 1913 [242]. This report discussed new requirements for stairways and "smokeproof" towers, requiring a minimum unobstructed width of 44 inches [242]. The following year, as discussed in Section 2.1.3.5, the NFPA Committee on Safety to Life was created and, in its first report, reviewed other requirements, including the Report of the NFPA Committee on Fire-resistive Construction (1914) and the Laws of the New York State Department of Labor (1913). Their review discussed a recommendation from the Report of the NFPA Committee on Fire-resistive Construction, which noted the following with respect to exit width [237, p. 3]:

> *The occupants of every floor above the first shall be provided with exits computed on the basis of at least 22 inches of width for every fourteen persons for stair exits*

In review of this recommendation, the Chairman of the Safety to Life Committee (H. W. Forester) noted that "[t]he average man being estimated to be 22 inches wide" [93, p. 71]. The same width was identified in the Laws of the New York State Department of Labor (1913), which noted the following [282, p. 252]:

> *no more than fourteen persons shall be employed or permitted or suffered to work on any one floor for every full twenty-two inches in width of stairway*



SKETCH F—The wider the stairs the flatter the arch and the less the tendency to jam tightly. Frequently the pressure of the jam becomes so great as to burst the rail, as in the case referred to on page 153.

Figure 5-3: Porter's illustration of stair congestion [87]

The limit of fourteen persons was based on the number that could be contained within a stair tower, assuming one person on every other stair and several persons on a landing for a typical storey height of 10 feet [93]. The Report of the Safety to Life Committee further noted that [93, p. 72]:

> *Stairs at least 44 inches wide are specified for new buildings, this width being reported sufficient to prevent three persons from forming an arch and blocking traffic.*

The 22-inch unit width, 44-inch minimum stair width, and the associated reference to a three person stair congestion align with H. F. J. Porter's report to the Factory Investigation Commission, as illustrated in Figure 5-3. Building on these findings and consistent with Porter's recommendations, the Safety to Life Committee focused on limiting maximum floor populations as a function of available stair capacity.

Between 1915 and 1918, the Safety to Life Committee developed a method to establish maximum floor populations as a function of building emptying (evacuation) time, building characteristics and occupant flow rates [244]. The evacuation time was calculated using the following criteria:

1. The time for people to get from the floor area (work space) to an exit. This time was assumed by the Committee to be 30 seconds [244]. No basis was documented for this assumption.
2. The time to traverse the exit to the building exterior. This time was based on a flow rate of 45 persons per minute per unit of stair width (22 inches) [244]. This flow rate was established by the Committee based on information available to them and was considered conservative for buildings up to seven storeys. This specific information was not identified in the Committee Report. Using this flow rate, the total time for all building occupants to traverse the stairs was calculated using Equation 5-1 below [244]:

$$stair\ flow\ time = persons \cdot \frac{60\ seconds/minute}{45\ persons/minute} \qquad \text{Equation 5-1}$$

The time required to reach an exit was combined with the stair flow time to determine the total building evacuation time, with the assumption that occupants on the first floor would use separate exits. Using this method, if the stair had sufficient capacity to accommodate the building's occupants, no queuing was considered to occur at the stair. However, when the number of occupants exceeded the stair's capacity, which was assumed for buildings taller than seven storeys, queuing was expected at the entry from the floor to the stair. This was the rationale for limiting the application of this procedure to buildings not more than 7 storeys in height. Stair capacity is illustrated in Figure 5-4, and is based on the following criteria [244, pp. 227, 228]:

- "One person per unit of stair width allowed for-each two treads in the flight, running from the floor on which persons are located to the floor, immediately below. The 'every other step' rule is essential if persons are to move down stairs."
- "One person in addition to be allowed for each 5 square feet of floor space on landings and in passageways in or between flights of stairs. This will allow from 2.5 to 3 feet between persons in line."

The emptying time was then set by the Committee as a function of the building's "inflammability," using this parameter to calculate the number of stairs needed to achieve the specified evacuation time. The inflammability of a building was assessed based on its occupancy classification and the hazard rating associated with that classification, as outlined in the "Classification of Occupancy Hazards" by the National Board of Fire Underwriters, which was part of the insurance rating schedules in use at the time [252]. Accordingly, the evacuation times defined by the Committee were as follows:

- 3 minutes for a high inflammability building
- 4 minutes for a medium inflammability building, and
- 5 minutes for a low inflammability building.

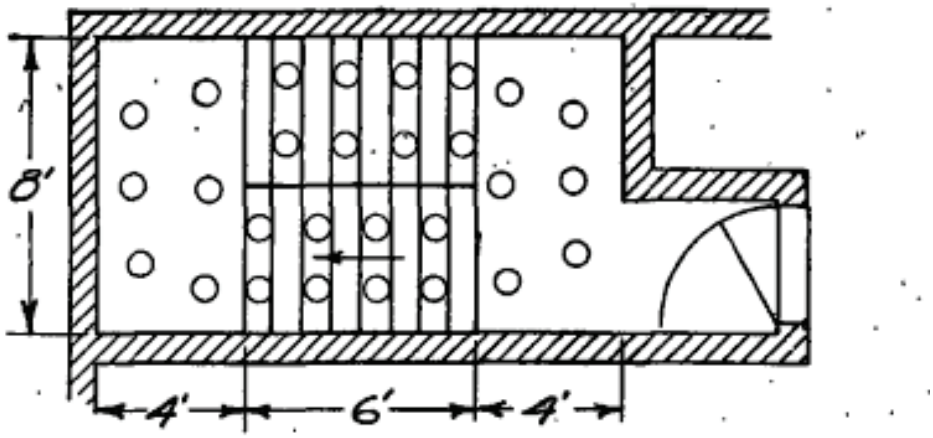


Fig. 1.

Shows type of stairs with intermediate landings and the plan indicates how many persons could be accommodated upon the basis of one every other step and one every 5 square feet of landing area. A stair 4 feet wide accommodating two rows of people and with landings of the dimensions shown, could contain per flight 28 persons or 14 per unit of stair width.

Figure 5-4: Safety to Life Committee illustration of stair capacity [244]

The "building emptying time" method was used to develop a table correlating floor populations and evacuation times with factors such as building height, construction type, sprinkler systems, and the combustibility of contents [244]. This table was applicable only to buildings up to 7 storeys, ensuring that evacuation times did not exceed those specified earlier for each occupancy classification. Due to the height limitations and complexity of the tables, the 1924 Report of the Life Safety Committee [245] introduced a simplified formula as an alternative. However, the formula was still considered overly complex, prompting the 1933 Report of the Life Safety Committee to replace it with a table of persons per floor and unit of stair width, as a function of occupancy [246]. These values, shown in Table 5-1, combined with the occupant load factors in the 1934 Building Exits Code [168] (discussed in Section 5.1), allowed for a simplified determination of the required exit width. For example, a low hazard floor area (office) with an occupant load of 120 people would require two units of stair width, or 44 inches. This simplification also reconsidered the assumption of full building egress and shifted the determination of total exit width to the assumption of only a single floor area (storey) egress [246].

Table 5-1: Building Exits Code - Persons per floor per unit of exit width

Occupancy	Number of Persons Per Floor Per 22 Inch Unit of Exit Width (Enclosed Stair)
High hazard	30
Moderate or low hazard	60
Institutional and residential	30
Public assembly	100

The simplification of stairway width requirements based on occupant load was intended not only to streamline calculations, as previously discussed, but also to align with the National Bureau of Standards (NBS) in the development of their exit requirements [246]. The NBS exit width requirements, outlined in "Design and Construction of Building Exits," are discussed in the following section.

5.2.2.3 NBS Design and Construction of Building Exits

The 1935 NBS DCBE required a minimum unobstructed exit stair width of 2 units of 22 inches (44 inches) [Section 7-6-1-1., "Minimum Width"]. A footnote accompanying this requirement provides the following clarification [70, p. 59]:

> *In the opinion of many who have studied the matter, 22 inches can be taken as the width of a file of people in motion. Its origin is said to be in experience gained in the Army. A stairway width of 44 inches will permit 2 files of people to move freely down the stairs at the same time. In occupancies where fire drills are common, the 44-inch width permits the orderly movement of 2 files where individuals walk side-by-side.*

In alignment with this clarification, the 22-inch unit width originates from a 1792 publication on army troop formations, as illustrated below [283, p. 41]:

> The platoon FALLS IN, in three ranks at cloſe order, with ſhouldered firelocks; the files lightly touching, but without crouding; each man will then occupy a ſpace of about 22 inches.

The required exit width was determined, similar to the method outlined in the 1934 Building Exits Code, based on the population of each floor and the specified number of persons per unit of stair width according to occupancy type, as shown in Table 5-2. These values align with those specified in the 1934 Building Exits Code [168].

Table 5-2: NBS Exits Code - Persons per floor per unit of exit width

Occupancy	Number of Persons Per Floor Per 22 Inch Unit of Exit Width (Enclosed Stair)
Institutional and Residential	30
Other	60
Assembly	100

5.2.2.4 National Building Code of Canada

The 1941 NBC required that the minimum width of stairways and ramps be not less than 44 inches [105] [Sub-items 4.6.5.4 (c) and (d)], while corridors were required to have a minimum width not less than 36 inches [105] [Sub-item 4.6.5.4 (f)]. These base widths were required to be increased by 22-inch units of exit width based on the number of occupants exceeding the base threshold, in accordance with Table 5-3 [105] [Sub-item 4.6.5.4 (b)].

Table 5-3: 1941 NBC - Persons per floor per unit of exit width

Occupancy	Number of Persons Per Floor Per 22 Inch Unit of Exit Width (Enclosed Stair)
High hazard industrial, Institutional and Residential	30
Medium or low hazard commercial or industrial, and other	60
Assembly	100

The number of persons per floor per unit of exit width was simplified in the 1953 NBC as follows [108]:

- 30 for floor areas intended for the treatment or care of infirm persons or in which people sleep.
- 60 for other floor areas.

The minimum exit stair width of 44 inches, the unit stair width of 22 inches, and the 1953 NBC number of persons per floor per unit of exit width remained unchanged from the 1960 NBC [110] to the 1977 NBC [185]. The 1980 NBC introduced metric equivalents for these dimensions, specifying a minimum exit stair width of 1,100 mm and a unit stair width of 550 mm [184]. The number of persons per floor per unit of exit width remained consistent until the 1985 NBC [154].

In 1988, the Ontario Ministry of Housing proposed a change to reconsider the 550 mm unit basis approach for determining exit width, based on the results of egress studies [284]. The proposed change

suggested replacing the “stepped” unit based relationship with a linear relationship between the number of occupants and the required width. For cases where the exit width exceeded the minimum 1,100 mm, a fractional increase in width based on the occupant load was recommended instead of the incremental approach. Specifically, rather than a stepped increase of 550 mm for each additional 60 occupants or less, the proposal allowed for fractional width increases as a function of each additional occupant, as detailed in Equation 5-2 below.

$$exit\ width\ per\ person = \frac{550\ mm}{60\ people} = 9.17\ mm\ per\ person \qquad \text{Equation 5-2}$$

The result was rounded to 9.2 mm per person, and the difference between this new approach and the original unit-based method is illustrated in Figure 5-5. The fractional increase in width of 9.2 mm per person was included in the 1990 NBC [186].

The minimum exit stair width of 1,100 mm (120 people) and the incremental increase of 9.2 mm per person beyond the 120-person base have remained consistent through to the current 2020 edition of the NBC [21].

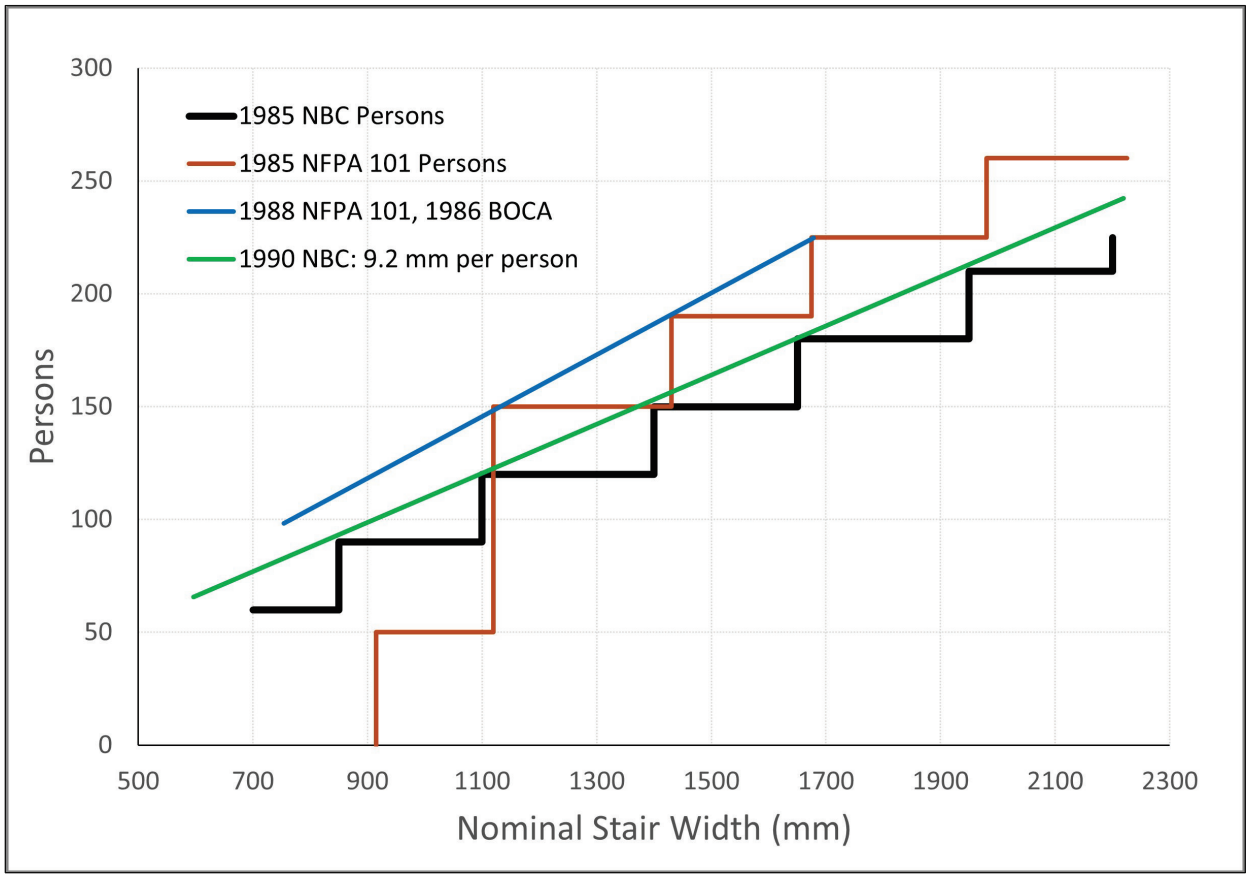


Figure 5-5: Relationship between occupant numbers and exit width

5.2.2.5 Summary of Basis

The previous sections reviewed the historical development of the 2020 NBC's minimum exit width, tracing its evolution over approximately 230 years. This analysis has identified that the current minimum exit width requirement (1,100 mm, or 9.2 mm per person) originated from the approximate width of two files of soldiers, based on anthropometric data from the late 1700s to the early 1800s. However, considering the varied nature of modern building occupants and changing demographic profiles, these values may no longer accurately represent current characteristics (anthropometric data).

5.2.3 Technical Reconciliation

As discussed above, the unit exit width (22-inches or 550 mm) is based on the width of the "average man," with origins "said to be in experience gained in the army" [70, p. 59, 282]. This width was further informed by 1800s factory exit design and the experience of factory fire drills, and therefore also represents the characteristics of factory occupants from that era. However, even in the 1910s, it was already noted that this width and the associated occupant movement were considered to only represent a subset of building occupants, as illustrated in the following comment [244, p. 270]:

> *the number of people that can occupy each floor of a building in proportion to the number that can pass out of the main entrance of the building in a given period of time … varies in accordance with whether the average age of the employees in the building is 55 or 15. We took this Committee on Safety to Life to fire drills in New York, where more than 60 people per minute passed out of the main entrance, according to their observation and then we took, them to another building where there was a lady of advanced years and considerable girth, who occupied more than 18 inches and went downstairs putting two feet on each step before she put one foot on the next step, and they got out at the-rate of only 22 a minute. Now, unless you can standardize the people that occupy your building (laughter) you cannot make that the measuring stick. But the committee has not even made that the measuring stick; they have made the average. What is the average? An average is the mean that you find by a consideration of a certain number of conditions on one side that are super-average and a certain number on the other that are sub-average. When the committee, says that 45 per minute is the average number that can pass out of a building, it means there are some cases where 45 cannot pass out.*

This observation acknowledged the variability in occupants' abilities but highlighted the challenges of regulating for such diversity. As a result, the Committee chose to use the average for purposes of simplicity in regulatory development. Since then, the 22-inch unit width has served as the standard for determining minimum exit stair widths across all occupancies, extending beyond even the original context of factories.

While the characteristics of occupants in other types of occupancies likely differed from those in factories, these differences were not analyzed before the 22-inch unit width was adopted as a representative standard for these groups. As a result, the 22-inch unit width may have represented only a

subset of the population of exit stair users, which may have been adequate at that time. However, more recent studies have indicated that this width does not accurately represent the needs of current populations of exit users [285-289].

Fruin illustrates this disparity through a diagram of the dimensions of a human body ellipse, with a modified version shown in Figure 5-6, and found that [288, p. 20]:

> *The plan view of the average adult male human body occupies an area of about 1.5 square feet. An 18 by 24 inch body ellipse, equivalent to an area of 2.3 square feet, has been used to determine the practical standing capacity of New York City subway cars. A U.S. Army human factors design manual also recommends the use of these dimensions. The larger design ellipse allows for the fact that many pedestrians are carrying personal articles, natural psychological preferences to avoid bodily contact with others, and body sway. Body sway may be observed during both human locomotion and while standing.*

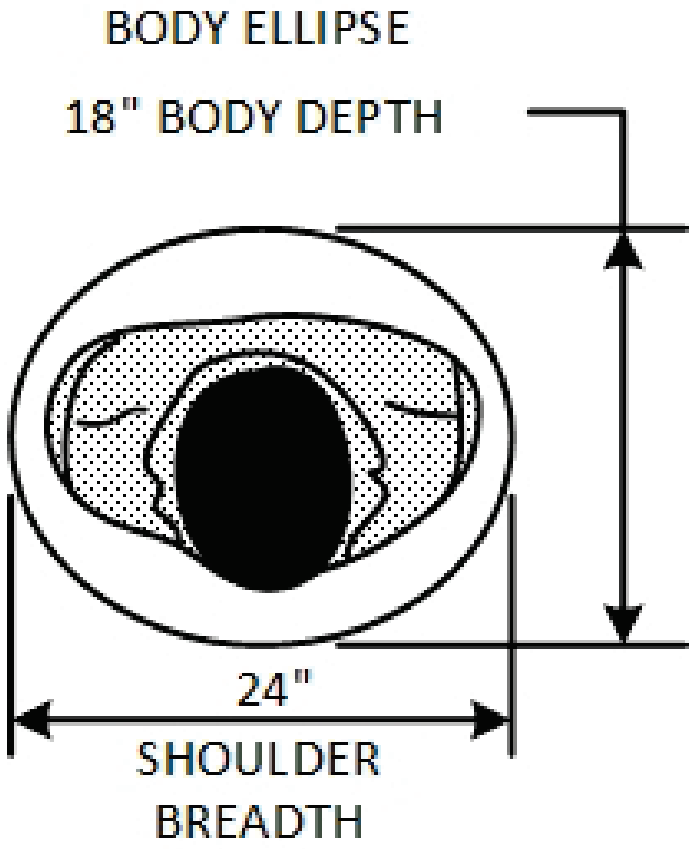


Figure 5-6: An illustration of Fruin's body ellipse measurements

Pauls observed that when body sway is considered, "two-abreast, unidirectional movement was very rare with the traditional 1,120 mm [sic] nominal width" [290, p. 10, 291]. Consequently, he recommended a minimum stair width of 1,400 mm (55 inches) to better accommodate body sway and to allow for counterflow from responding fire service personnel who might be using the exit stairs to access the fire

floor or assist with egress. Additionally, changes in demographics, including increases in body size, weight, and reduced physical fitness for traversing stairs in high buildings, suggest that the original 22-inch unit width may no longer adequately represent the broader population of exit stair users [291].

In recognition of these factors, a change was introduced in the 2006 edition of the Life Safety Code (NFPA 101), requiring a minimum stair width of 1,420 mm (56 inches) for stairs serving occupant loads of 2,000 or more [292] from floor areas or individual storeys. Given the shared historical foundations between the Life Safety Code and the NBC, a similar update to the egress requirements in the NBC would be justified.

In summary, similar to office occupant load factors, the 22-inch unit exit width, originally based on an outdated dataset of average male shoulder width, has evolved over time and therefore been incorporated into various life safety guidelines. In contrast, the current NBC requirements are no longer reflective of the characteristics of the current population or the increased heights of modern buildings, which are expected to be addressed through specifically increasing the minimum stair width to 1,420 mm.

5.2.4 Conclusion and Recommendations

This case study has illustrated the application of the new framework developed in this research to identify the historical basis of the unit exit width factor in the 2020 NBC, and then to technically reconcile that historical basis in a current context. The analysis shows that the 22-inch unit exit width, established over 100 years ago, no longer reflects the anthropometric characteristics of the current population [285-289]. Yet, the 22-inch (550 mm) unit width persists in the 2020 NBC. It underpins both the currently specified minimum exit stair width of 1,100 mm and the calculation of stair width as a function of occupant load based on the factor of 9.2 mm of exit stair width per person. The findings of this case study support revising the minimum exit stair width and the associated exit width factor in the NBC. They serve as a better defined technical basis for developing performance-based solutions, particularly for scenarios where even if recent recommendations of 1,420 mm and 11.8 mm per person are adopted based on findings in recent studies [286, 287, 289-291], there will be design situations when these cannot be met and performance-based design will be required.

In context of performance-based design, exit width is a regulatory solution intended to mitigate the risk of exposure to fire and smoke. Similar to the office occupant load factor, it is based on a characteristic of “exposed” persons, specifically the occupant width required for movement. It may vary depending on the type of occupancy. As such, it aligns with Level 4 of the modified IRCC Hierarchy, “Performance or Risk Group,” and informs the flow rate of occupants in exit stairs. The flow rate determines the evacuation time for a given floor area, storey, or building when compared to set time criteria or a more technical “time of tenability” analysis (ASET/RSET). These evacuation time criteria, though not explored in detail in this case study, align with Level 5 of the modified IRCC Hierarchy, “Performance or Risk Criteria,” and support the development or modification of prescriptive/performance-based solutions. Therefore, this case study serves to illustrate that the new information, identified through Objectives 2 and 3 of the new framework and within the context of the IRCC Hierarchy, can be used to:

- present, maintain, modify, or address future changes to the existing prescriptive exit stair solutions, and
- develop and maintain parallel performance-based solutions.

This initial case study focused primarily on risk characteristics. The next chapter will introduce a more complex case study addressing the risk of fire spread, which encompasses broader aspects and elements of the new framework including risk characteristics, criteria, and solutions, and thus serves to illustrate how the framework might be applied in the assessment of even more complex provisions in building codes such as the NBC.

Chapter 6
Case Study - Building Size Limits and Types of Construction

The 2020 NBC restricts building size based on the type of construction, specifically placing limitations on the size of combustible buildings. These restrictions take into account factors such as occupancy, fire service intervention, and the degree of compartmentation. The requirements governing building size and construction type have developed over many generations, often in response to significant historical conflagrations and major building fires.

The following sections outline the acceptable solution requirements for building construction type and size, examine the historical basis of these requirements, and provide a technical reconciliation of these requirements in the context of historical analysis and current knowledge. They also detail suggestions for aligning this information within the modified IRCC hierarchy, toward clear and structured technical rationale in support of parallel prescriptive and performance requirements and a performance-based framework for the NBC.

6.1 Overview of Requirements

Subsection 3.2.2. of the 2020 NBC specifies the type of construction and fire-resistance rating of boundaries (i.e., floor assemblies) and structural elements based on factors such as occupancy, sprinklering, streets facing, and building size (height and area) through regulatory Articles.

The purpose of Subsection 3.2.2. is to “prevent fire spread and collapse caused by the effects of fire” [21, Div. B, p. 3-47]. This Subsection also contains several clarifications and exceptions to the principal construction requirements outlined in Articles 3.2.2.20. to 3.2.2.92. (72 construction Articles). The following sections provide an example construction Article, including the attributed objectives, functional statements, and intent statements.

6.1.1 Example Specification

The following is an example construction Article requirement (Article 3.2.2.59.) [21, Div. B, pp. 3-65, 3-66]:

3.2.2.59. Group D, up to 6 Storeys, Sprinklered, Noncombustible Construction

1) A building classified as Group D is permitted to conform to Sentence (2) provided

a) except as permitted by Sentences 3.2.2.7.(1) and 3.2.2.18.(2), the building is sprinklered throughout,

b) it is not more than 6 storeys in building height, and

c) it has a building area

i) that is not limited if the building is not more than 2 storeys in building height,

ii) not more than 14400 m² if 3 storeys in building height,

iii) not more than 10800 m² if 4 storeys in building height,

iv) not more than 8640 m² if 5 storeys in building height, or

v) not more than 7200 m² if 6 storeys in building height.

2) Except as permitted by Article 3.2.2.16., the building referred to in Sentence (1) shall be of noncombustible construction, and

a) floor assemblies shall be fire separations with a fire-resistance rating not less than 1 h,

b) mezzanines shall have a fire-resistance rating not less than 1 h, and

c) loadbearing walls, columns and arches shall have a fire-resistance rating not less than that required for the supported assembly.

Although titled "Building Size and Construction Relative to Occupancy," these requirements have evolved with the intent to limit ultimate fire size, and thus the collapse of larger and taller buildings in case of fire.

6.1.2 Objectives, Functional Statements and Intent Statements

There are many objectives, functional statements, and intent statements attributed to the construction Article requirements. These are summarized below for clarity and conciseness.

Hazard

The fire hazards addressed by the construction Article requirements are identified as [21, Div. A, p. 2-2]:

- (**OS/OP1.2**) **fire** or **explosion** impacting areas beyond its point of origin.
- (**OS/OP1.3**) **collapse** of physical elements due to a fire or explosion.

Exposed

The exposed addressed by the construction Article requirements are identified as [21, Div. A, pp. 2-2, 2-5]:

- (**OS1**) A **person** in or adjacent to the building will be exposed to an unacceptable risk of injury due to fire.
- (**OP1**) The **building** will be exposed to an unacceptable risk of damage due to fire.

Solutions

The solutions addressed by the construction Article requirements are intended to limit the impact of the hazard of fire on the exposed people and property. This may be done through the provision of sprinklers,

noncombustible construction, and/or fire separations and structural elements with specified fire-resistance ratings. These solutions are intended to functionally achieve the following outcomes [21, Div. A, pp. 3-1, 3-2]:

- (**F02**) To limit the severity and effects of fire or explosions.
- (**F03**) To retard the effects of fire on areas beyond its point of origin.
- (**F04**) To retard failure or collapse due to the effects of fire.

The intent of the construction Article requirements is detailed below as a function of each of the key fire safety strategies (solutions):

- **Sprinklering [131, p. 229]:** The intent of requiring sprinklers is to limit the probability that:
    - loadbearing walls, columns and arches exposed to fire will prematurely fail or collapse.
    - fire will grow and spread from one storey of a building to another.
    - fire will spread within the storey during the time required to achieve occupant safety and for emergency responders to perform their duties.
- **Noncombustible Construction [131, p. 229]:** The intent of requiring noncombustible construction is to limit the probability that
    - combustible construction materials within a storey of a building will be involved in a fire, which could lead to the growth of fire, which could lead to the spread of fire within the storey.
- **Fire-Resistance Rated Fire Separation [131, p. 229]:** The intent of requiring a fire-resistance rated fire separation is to limit the probability that:
    - loadbearing walls, columns and arches exposed to fire will prematurely fail or collapse.
    - fire will grow and spread from one storey of a building to another.

In addition to the solutions detailed above, strategies to facilitate firefighting intervention have also been identified as part of the intent of the construction article requirements. In particular, to limit fire growth and spread and structural collapse to allow “emergency responders to perform their duties” [131, p. 229].

As detailed above, the objectives, functional statements, and intent statements attributed to the building size and construction requirements are qualitative, which significantly limits design flexibility. Reasons for the lack of quantitative rationale underlying these requirements are investigated and rationale for those requirements identified by the historical analysis are detailed in the following section.

6.2 Historical Analysis

Combustible materials, both in contents and construction, have historically been a factor that contributes to the growth and spread of fire within and between buildings. This has been acknowledged over millennia, leading to the gradual implementation of regulatory measures intended to address combustible materials and ultimate fire size. Correspondingly, fire severity outcomes have evolved over time, shifting from large-scale city-wide conflagrations [14, 15, 20, 40] to primarily single building fires and, in many

cases, localized fires within buildings [293]. The current provisions deal largely with interior building fires. This is in contrast to recent wildfires (i.e., those in Los Angeles) that have resulted in neighbourhood-scale conflagrations. This fire spread hazard was not contemplated in the past development of the NBC and, therefore, does not form part of the historical record analyzed in the present research. However, given the magnitude of the impact, it could certainly be given consideration in future regulatory development, using decision making based on the recommendations from the present research.

The following sections provide a brief overview of the history of building size limits and type of construction requirements, in the context of the present case study with a more comprehensive account available in the report by Calder [46].

6.2.1 Summary of Early History

The early history of building size limits and type of construction requirements is summarized below:

- **Circa 1000 to 2000 years ago (Section 2.1.1):** Early solutions to the hazard of city-wide conflagrations involved constructing exterior walls of noncombustible material and spatially separating buildings.
- **Circa 350 to 1000 years ago (Section 2.1.2.1):** With too limited space to allow good separation, the hazard of conflagration was addressed by the City of London through the development of substantial noncombustible walls (firewall) between buildings. Firewalls remain a regulatory solution today.
- **Circa 170 years ago (Section 2.1.2.3):** With increasing building size due to increased proliferation of trade and dry goods warehouses, some large building fires grew to sizes that were beyond the capability of a responding fire service to control. Building size limits were therefore regulated to keep fires to sizes within the capability of the responding fire service to control.
- **Circa 120 to 150 years ago (Section 2.1.3.1):** Following significant insurance losses from city conflagrations in the US, the insurance industry developed an insurance rating system that scaled insurance rates to fire risk as a function of building characteristics. The insurance rating system credited fireproof (noncombustible) construction as a factor in reducing the growth and spread of fire. Alternatively, non-fireproof construction was considered to increase the potential for fire growth and spread. From a fire safety perspective, use of one or the other of these types of construction were correlated with an allowable building size considered to relate to relative risk.
- **Circa 100 to 120 years ago (Section 2.1.3.3):** Model building codes were developed in the US to foster uniformity in construction across the country. The development of these model building codes was primarily driven by the insurance industry, with regulation of building size and construction type based on insurance rating schedules already developed.

- **Circa 70 to 100 years ago (Section 2.1.3.4):** Fire experiments were conducted to determine the required fire-resistance rating of construction elements (fire compartmentation) needed to contain the complete combustion of increasing densities of fuel load (burn-out concept). New correlations for fire-resistance as a function of combustible fuel load were developed.

These combined strategies formed the basis of the development of the building size limits and associated building construction type requirements in the first (1941) NBC. The further evolution of these requirements is examined in the following sections, as a function of the subsequent significant regulatory development eras.

6.2.2 Circa 70 Years Ago: The 1953 NBC and Fire Science

The building construction requirements of the 1941 NBC were predominantly adopted from the existing US model building codes. Thus, they closely followed the approach from 70 to 120 years ago as discussed above. The 1953 NBC was a complete overhaul of the 1941 NBC, both in its structure and in terms of moving from a primarily experiential based system to inclusion of additional scientific principles to reinforce the approach to fire safety of building construction [108]. For this, the following principles were considered [294]:

1. fire severity due to contents of buildings (occupancy fuel load),
2. fire severity due to structure construction (structure combustibility),
3. containment and resilience against fire (fire separations and fire-resistance), and
4. protection against fire (fire separations and fire-resistance).

The incorporation of these principles is discussed in more detail in the following sections.

6.2.2.1 Fire Severity (Items 1 and 2)

Contents constitute the predominant combustible material within buildings, and their impermanent nature has long posed challenges for regulatory control. Therefore, regulatory focus has been to identify and characterize combustible content as a function of occupancy (i.e., as a fire hazard), and provide solutions to address contents for specific occupancy classifications rather than attempting to implement provisions to more explicitly control combustible contents. Fire severity (Item 1) that can potentially arise due to the generalized contents of a particular occupancy has been addressed using the burn-out concept developed by Ingberg [84]. Into the 1950s, this was continued by surveying various occupancies to establish representative combustible fuel loads [86]. These fuel loads were subsequently recognized as representative within a Canadian context and were correlated with the occupancies defined in the 1953 NBC to assign a combustible fuel density to each occupancy, as illustrated in Table 6-1.

The major occupancy classifications listed in Table 6-1 still align with those in the 2020 NBC [21], except for Group G, which was incorporated as part of Group F major occupancies in the 1960 NBC [110]. These fuel loads were subsequently applied as input to Ingberg's correlation between fire-resistance and fuel

load [84] to then attribute fire-resistance rating requirements to each major occupancy as listed in Table 6-1.

Table 6-1: Fire Loads for Major Occupancies of Buildings – 1953 NBC [108]

Major Occupancy	**Fire Load (lb/ft²)**	**Fire-Resistance Rating (h)**
Group A Assembly, Group B Institutional, Group C Residential, Group D Business, Group G Commercial and Industrial Division 3	10	1
Group E Mercantile and Group G Commercial and Industrial Division 2	20	2
Group F Hazardous and Group G Commercial and Industrial Division 1	30	3

Structure fire severity (Item 2) was characterized by the combustibility of structural elements. This was addressed by limiting the use of combustible material or by protecting those elements that were considered to be combustible, to prevent their contribution to fire growth and spread, and limit the potential for their collapse. However, at the time, methods available for protecting combustible structural elements were limited and provided only short durations of protection from fire exposure and ignition. Consequently, the use of combustible structural elements was significantly restricted in this era of the NBC, as will be explored further below.

6.2.2.2 Containment and Resilience (Item 3)

Ingberg's correlation of fuel load to fire-resistance was utilized in the development of the fire separation requirements of the 1953 NBC, as detailed in the following explanatory note [108, p. 31]:

> *[Fire load] is used in the Code to determine the amount of fire protection which is necessary. It is obvious that the greater the severity of fire the greater must be the protection if the fire is to be contained. It has been found in actual burn out tests that a fire load of ten pounds per square foot can be contained by fire-resistive construction of roughly one hour. A fire load of twenty pounds can be contained by construction of two hours and so on. The values of resistance required for certain fire loads in the Code are based on these findings.*

This formed the basis of fire containment requirements (Item 3 - containment and resilience) in the NBC. The intent was to limit a fire from spreading from one compartment to another, allowing burn-out of the combustible contents in the compartment of origin. Given the limited technologies and ability to protect combustible structural elements from contributing to fire growth and spread at the time, this further dictated that structural elements were required to be of noncombustible material. This was discussed in an explanatory note in the 1953 NBC as follows [108, p. 30]:

> *Because the potential fire severity of occupancies vary, and* ***because of the limitations of fire resistance in some types of construction [emphasis added]****, four grades of separation of varying fire-resistance have been set up. The grade of separation required for complete containment of fire in anyone storey is dependent on the degree of the fire hazard of the occupancy. It is not always practical to require complete containment under burn-out conditions. In many circumstances the fire is contained for a limited time consistent with the capabilities of the type of construction. In these cases the heights and areas are limited to dimensions that facilitate fire fighting by outside forces.*

It was thought that a building incorporating combustible structural elements would not contain a fire to burn-out, which could ultimately result in the complete involvement of the building in fire. This would then limit firefighting to the building exterior. To address this, requirements were incorporated into the NBC to limit the height and area of such buildings so they were sized to be within the capability of a responding fire service to control from the exterior. This capability was further based on the need to provide direct access to the building exterior (i.e., on streets facing the building) for equipment and suppression purposes.

Conversely, a building of noncombustible construction and with structural elements and assemblies having the appropriate level of fire-resistance, was considered to be capable of containing a fire to burn-out. The containment would restrict the fire to a localized area of the building, such as a compartment or storey, and with the addition of protective measures, would allow firefighting efforts to occur within the building. As a result, the height and area of such buildings were allowed to be significantly greater than those of combustible buildings. In some cases, building size could even be “unlimited” where additional measures were provided to facilitate egress and firefighting. A safety factor of an additional 1-hour of fire-resistance was required for the floor assemblies and structural elements of buildings greater than 6 storeys. This arbitrary factor was introduced to account for the perceived increased fire risk associated with the height of such buildings and to address the “intolerable havoc” [295, p. 21] that could result from building collapse.

6.2.2.3 Protection (Item 4)

In addition to containment and resilience, certain uses within floor areas were considered to be a higher risk than the remaining floor area and therefore, required separation from lower risk floor areas. This separation was intended to “limit the probability that a fire will spread from one major occupancy to an adjacent major occupancy having a different degree of fire risk” [131, p. 2]. This same principle was applied to exits.

An assessment of the time required for life safety protection (i.e., egress time) for each major occupancy was undertaken at the same time as fire severity was evaluated. This assessment determined that the required egress time was generally lower, approximately 45 minutes, than the estimated time required for burn-out of the fire. The exception to this was for Treatment and Detention (Group B) occupancies, where occupants might be unconscious or have limited mobility due to security. Therefore, despite the fire load

survey results for these facilities, the required degree of protection for Group B occupancies was set at 2-hours of fire-resistance.

Consideration of the protection of adjacent uses with differing risks resulted in the definition of a set of fire-resistance ratings based on major occupancy as detailed in Table 6-2. These ratings could then be applied to separations between major occupancies, as was discussed in Section 3.3.1 as an example of the use of risk terminology in the NBC. In some instances, the fire-resistance rating of an assembly (such as the floor assembly between storeys) is determined by both the containment and resilience requirements (Section 6.2.2.2) and the requirements covered in this section. In such cases, the higher of the two fire-resistance requirements takes precedence.

Table 6-2: Correlation of fire-resistance rating protection to hazard

Occupancy	**Fire Load (lb/ft²)**	**Egress**	**Governing Factor**
A: Assembly	10 (1-hour)	Low (45-min)	Fire Load
B1,2: Detention, Treatment	10 (1-hour)	High (2-hour)	Egress
B3: Care	10 (1-hour)	Low (45-min)	Fire Load
C: Residential	10 (1-hour)	Low (45-min)	Fire Load
D: Business	10 (1-hour)	Low (45-min)	Fire Load
E: Mercantile	20 (2-hour)	Low (45-min)	Fire Load
F3: Low Hazard Industrial	10 (1-hour)	Low (45-min)	Fire Load
F2: Medium Hazard Industrial	20 (2-hour)	Low (45-min)	Fire Load
F1: High Hazard Industrial	30 (3-hour)	Low (45-min)	Fire Load

The 2020 NBC contains a table of major occupancy fire separations [Table 3.1.3.1. of the 2020 NBC] that are still consistent with the values in Table 6-2.

6.2.3 Circa 60 Years Ago: “The Problem of Noncombustible”

It can be seen that up to the 1953 version of the NBC, there was significant emphasis on the combustibility or noncombustibility of the building structure in setting height and area limits. However, up to the 1960 NBC [110], the definition of “noncombustible” was broad, allowing for some combustible materials. This definition was revised in the 1965 NBC [111] to more closely align with its dictionary counterpart. This resulted in a shift towards stricter criteria for combustibility than had been used in earlier editions of the NBC. Under the revised definition, noncombustible buildings were required to be constructed almost entirely of noncombustible materials, with only minor exceptions for components such as paint, the paper facing of gypsum board, glues, mastics, sheathing paper, and other similar minor elements.

Problems with the proposed 1965 NBC definition of noncombustible were identified by Ferguson in a Technical Note published in December 1964 [114]. He highlighted that historically, noncombustibility had been the primary approach to fire protection over centuries (e.g., the use of stone instead of wood). At the same time, he noted that more recent research had identified the existence of additional methods for fire protection of buildings over that obtained through characterization of a material as combustible versus noncombustible. These included [114]:

- Stability and prevention of collapse achieved through fire-resistance.
- Fire spread managed through compartmentation.
- Life safety hazards mitigated by limiting interior finish flame spread and ensuring adequate exits.

Ferguson observed that the three measures are employed in both combustible and noncombustible buildings. Historically, they served as supplements to noncombustibility, which was traditionally regarded as the primary fire safety measure. Instead of continuing this, he suggested that identifying the appropriate hazards associated with building size and establishing an acceptable level of risk would better aid in developing the necessary combination of protection methods to meet fire safety requirements. While acknowledging that noncombustibility continues to be a solution for addressing fire risks related to building size, he noted that it may no longer remain the primary solution [114, p. 3]:

> *there is no preamble to the present regulations outlining the hazards they are intended to mitigate or the conditions they are intended to satisfy. What are these conditions? They may be known, but it is not general knowledge. Lacking a satisfactory diagnosis of the problem, responsible authorities place their trust in noncombustibility. Where one can truly eliminate all combustibles there can be no fire.*
>
> *This solution cannot be justified much longer. Attention should be directed to the hazards that size, and particularly height, introduce. Agreement on what the hazards are and the degree of risk acceptable will pave the way for alternate solutions "deemed to satisfy" these conditions. Noncombustibility will always be one, but not necessarily the only, solution.*

While Ferguson's recommendations did not lead to changes in the building size limits in the NBC, they drew attention to the limitations of specifying material characteristics, particularly in the context of evolving fire safety strategies informed by advancements in fire science, as will be discussed further in the next section.

6.2.4 Circa 50 Years Ago: Additional Fire Compartmentation

Ten years following examination of the limits associated with the definition of "noncombustible," Ferguson further reviewed one of his earlier recommendations for managing fire spread, which was through compartmentation [114]. While this concept was developed and utilized in limiting storey-to-storey fire spread to allow greater building height, Ferguson's examination focused on the increasing fire

compartmentation over time that had been incorporated into the NBC. In this context, fire compartmentation was initially a solution to the hazard of building size, but evolved over time to also be a solution to protect one space from another with a differing level of hazard, to an even greater extent than discussed above for separation of major occupancies. However, even with increasing fire compartmentation, the full building remains the primary unit of regulatory control in the NBC.

Building in the NBC is defined as "any structure used or intended for supporting or sheltering any use or occupancy" [21, Div. A, p. 1-5]. Although broad, this definition established a practical regulatory unit of control, particularly since most buildings historically were located on a single property under the control of a single owner. Early regulatory considerations centred around balancing the practicality of restricting activities within an individual's own building, such as a private house, while emphasizing the importance of limiting risks to neighbours and neighbouring properties [11].

In recent times, the traditional application of using the building as the primary unit of regulatory control has become increasingly problematic due to the emergence of integrated uses and a broader range of designs diverging from what were previously "conventional" building forms. Property boundaries may now be arranged horizontally with floor-to-floor separation of occupancies, as seen in "strata" units, instead of vertically via lot lines. Further, ownership no longer necessarily implies control over an entire building. Consequently, the use of the "building" concept for control through regulations has become increasingly impractical. Ferguson highlighted this shift in control dynamics in an early draft of the Guide to Part 3 of the 1975 NBC, stating [296, p. F-29]:

> *Historically the "building" has been chosen as the space to which control measures have been applied.*
>
> *…*
>
> *The trend is toward the choice of smaller spaces for regulation purposes. The earliest type of regulation applied to zones (fire limits). This was followed by distinguishing between buildings and today, more and more, distinguishing between different rooms.*
>
> *It follows that as the space basis for regulation is reduced a better fit between control and hazard is achieved. Studies suggest that as this happens the trend is more from prohibition to regulation, which is more in keeping with the purpose of the Code.*

Ferguson, therefore, proposed moving away from the "building" as the primary unit of regulatory control and instead suggests using smaller spaces within a building as a more appropriate unit of regulation. This recommendation aligns with a historical trend in building code development that has progressively emphasized the need for, and implementation of, fire compartmentation within structures. The focus on compartmentation has enabled more precise fire containment over subsequent editions of the NBC and, by extension, more effective fire control.

Technical support for the use of fire containment within smaller spaces was provided in research conducted by the National Research Council (then known as IRC) in relation to amendments made to the 1990 NBC, amongst many other sources, to allow buildings of combustible construction to be up to four

storeys in height [297]. The research noted that "[c]urrently there appears to be little evidence of fires spreading beyond the suite of fire origin" [297, p. 17]. Furthermore, the Standing Committee on Fire Protection at the time reinforced this finding noting that [297, p. 18]:

> *it is evident that the compartment to compartment fire separations are performing as intended and that the problem associated with fires in residential occupancies is that of life loss in the room of fire origin.*

This result implies that if fire can be adequately contained within a single fire compartment, regardless of construction type, then limiting overall building size becomes unnecessary. Over the past 50 years, development of the NBC has increasingly focused on addressing fire hazards within buildings through enhanced fire compartmentation of smaller spaces. These smaller spaces include suites, dwelling units, service/storage rooms, and public corridors. This was not always directly regulated along with building size and types of construction materials; however, since the fire separation of smaller spaces was introduced for other purposes. At the same time, since increased fire compartmentation has contributed to significantly reducing the likelihood of fire growth and spread beyond the storey of fire origin, the question becomes: Has this been appropriately connected to changes in “building” as the regulatory unit of control and associated building size limits of various buildings? The following section explores a similar challenge associated with increased sprinkler protection.

6.2.5 Circa 30 Years Ago: Mandatory Sprinklering

Fire and life safety requirements in the NBC to limit fire spread have continually evolved over time. Despite this, the building size limits have remained relatively unchanged. Another example of disconnect in fire spread requirements can be found through examining the incorporation of mandatory sprinkler protection over time in the NBC, as was briefly discussed in Section 3.2.5. Sprinklers have been long recognized as an important measure to control, and thus limit the spread of fire, to the extent that the use of sprinklers even led to reduced insurance rates [41-44] and increases in permitted building area [57]. In the early 1990s, an effort to require the mandatory sprinklering of all Part 3 buildings was undertaken by an NRC Joint Task Group on Sprinklers (JTGS) based on [298]:

- rapidly escalating costs for many municipal authorities (fire services) which led to questions about finding a more efficient means of controlling fires,
- a series of fires in high buildings and hotels which led to multiple deaths and substantial property loss, and
- results of a public inquiry into fire safety in highrise buildings in Ontario.

The JTGS laid out the intent and reliability of sprinklers, as well as connecting the use of sprinklers to size and occupancy considerations, and compartmentation of buildings as detailed below [299]:

- Intent of Sprinklers:
    - Sprinklers should control the spread of fire from the compartment of fire origin to the remainder of a building.

- Sprinkler Reliability:
    - National Fire Protection Association statistics from 1897 to 1969 - sprinkler performance was considered to be satisfactory in 96.15% of the 81,425 fires considered.
    - Australian statistics from 1886 to 1968 - sprinkler operations were judged to be satisfactory in 99.75% of the 5,734 fires analyzed. In the period from 1968 to 1973, satisfactory performance was achieved in 99.36% of the fires.
    - Sprinkler performance was satisfactory in 98.4% of 1,394 fires in high buildings in the City of New York (excluding office buildings) over a ten-year period. A satisfactory performance rate of 95.8% was achieved in 4,061 fires in Sprinklered low buildings.
- Size and occupancy requirements for fire safety [Subsection 3.2.2. of the NBC]:
    - Structural elements in a fully sprinklered building are rarely subjected to a fire intensity that would challenge their ability to control the spread of fire.
- Compartmentation:
    - Sprinklers have a high degree of reliability and are superior in providing both life and property protection compared to compartmentation when a sprinkler system is properly designed, installed and maintained.
    - In rare situations where there is a sprinkler system failure, compartmentation would provide inherent passive fire protection. However, the statistics reviewed by the JTGS indicated that the failure of a sprinkler system is far less likely than the failure of a compartment boundary.

The recommendations of the JTGS, following four years of review, led to the mandatory sprinklering of all institutional buildings (Group B), a broader range of high-hazard (Group F, Division 1) and medium-hazard (Group F, Division 2) industrial buildings, and all buildings exceeding 6 storeys in building height. Additionally, in buildings equipped with a sprinkler system, certain relaxations of other building code requirements were introduced based on the reliability of these systems reflected in the JTGS's review of their statistical performance. However, despite strong statistical evidence supporting their reliability, which has not been examined in the present research, no relaxations were made to building size limits. One related relaxation, however, allowed a reduction of the fire-resistance rating for floor assemblies in mercantile (Group E) and medium-hazard industrial buildings (Group F, Division 2) from 3 hours to 2 hours.

Even with the increased fire compartmentation and mandatory sprinklering provisions discussed above, the building size limits in the NBC have remained relatively unchanged, with only minor variations, since the 1953 NBC. However, this has begun to change, as discussed in the next section.

6.2.6 Circa 15 Years Previous: Midrise and EMTC

Efforts to expand the use of wood in building construction have increased significantly over the past 15 years, leading to substantial changes to the building size limits of the NBC. Changes to the 2015 NBC have permitted building height for wood framed residential and office buildings to increase from 4 storeys up to 6 storeys, based in part on strategies that have been developed to address key risk factors of fire spread

identified in similar buildings in which fires have occurred [210]. Additional changes to the 2020 NBC have introduced encapsulated mass timber construction (EMTC) and permit residential and office buildings of EMTC to be up to 12 storeys in building height. These changes have been supported by comprehensive testing, advancements in material performance, and research into mass timber burning characteristics, although there are also still recognized gaps in available information [46, 300-306]. Even with these gaps, some provinces have recently permitted larger EMTC buildings for all occupancies [307] in their building codes.

One key factor associated with these changes, permitting larger and taller buildings of combustible (timber) construction, is a reconsideration of the burn-out concept. Historically, the application of this concept was restricted to noncombustible construction due to inherent material limitations, as discussed earlier. However, recent tests of compartments of combustible (mass timber) elements with degrees of encapsulation protection have demonstrated eventual fire decay or cessation of burning with limited contribution of the mass timber to the growth and spread of fire [305, 308-313].

This result has prompted the reconsideration and moderation of the burn-out performance expectations. Previously, the boundary elements and fire-resistance of a compartment were designed to contain complete burn-out without consideration of fire department intervention. On top of this, they were often required to have an additional safety margin. The acceptable performance has now shifted to recognize significant fire decay, but not full cessation, with the assumption of eventual fire department intervention and suppression. While this adjustment is currently limited to mass timber construction, should an appropriate technical reconciliation support the notion, there is potential to extend this performance criterion to encapsulated lighter timber elements without increasing fire risk.

6.2.7 Summary of Historical Basis

The historical analysis of the building size limits and type of construction requirements are complex and thus are often best summarized in tabular format in order to highlight the key elements upon which different decisions were based. This is done for the present case study in Table 6-3 to Table 6-7. Entries in the tables are also aligned in the context of the elements of the proposed regulatory risk paradigm.

Table 6-3: Circa 1000 to 2000 years ago

Hazard:	City-wide conflagration in Rome
Exposed:	Property
Relationship:	Observations and experience
Regulatory Solution:	• Noncombustible construction • Spatial separation of buildings
Acceptable Performance:	Limit conflagrations from occurring

Table 6-4: Circa 350 to 1000 years ago

Hazard:	City-wide conflagrations in London
Exposed:	Property
Relationship:	Observations and experience
Regulatory Solution:	• Noncombustible construction • Physical separation of buildings
Acceptable Performance:	Limit conflagrations from occurring

Table 6-5: Circa 170 years ago

Hazard:	Fire spread beyond the building of origin
Exposed:	Property
Relationship:	Fire size beyond the capability of the responding service to control based on expert experience
Regulatory Solution:	• Noncombustible construction • Physical separation of buildings • Limit building size to be within the capability of a responding fire service to control
Acceptable Performance:	Fire contained to the building of origin

Table 6-6: Circa 120 to 150 years ago

Hazard:	Fire spread to involve entire large buildings and beyond the building of origin
Exposed:	Property
Relationship:	Fire hazard related to building construction as a function of building use, developed through fire loss experience
Regulatory Solution:	• Noncombustible construction • Physical separation of buildings • Limit building size to be within the capability of a responding fire service to control
Acceptable Performance:	Fire contained to building of origin

Table 6-7: Circa 70 to 120 years ago

Hazard:	• Combustible content fuel quantity as a function of building use • Combustible construction: fire spread beyond the building of origin • Noncombustible construction: fire spread beyond the storey of origin
Exposed:	• Property • People
Relationship:	Testing results correlating fire severity with fuel quantity
Regulatory Solution:	• Noncombustible construction • Physical separation of buildings • Limit building size to be within the capability of a responding fire service to control • Fire containment
Acceptable Performance:	• Noncombustible construction: fire contained to storey of origin • Combustible construction: fire contained to building of origin

The history of the building size and type of construction regulatory development, up to 70 years ago, supports the following simplified bases of fire safety performance:

- A building of combustible construction is assumed to become fully involved in fire, restricting firefighting efforts to the building's exterior. As a result, the size is limited to within the capability of the responding fire service to control and prevent further fire spread to adjacent buildings.
- A building of noncombustible construction, with an appropriate level of fire-resistance, is designed to contain fire to burn-out within a localized area, such as a compartment or storey. This containment allows for interior firefighting operations, enabling such buildings to have significantly greater height and area compared to combustible buildings. This can extend to even unlimited heights and areas in some cases.

With the exception of midrise and EMTC buildings over the last 15 years, the bases of performance associated with the building size and type of construction requirements in the NBC have remained largely unchanged. This is reflected in the current objectives, functional statements, and intent statements attributed to these requirements, though in a more qualitative manner.

Regulatory solutions defining limits on building height and area as related to limiting fire growth and spread have evolved over time. This has happened in concert with changing building characteristics, decisions based on contemporaneous knowledge, improved capabilities and methods, and in the climate of a shifting baseline of acceptable performance. As noted earlier, noncombustible construction is no longer the only solution. Additional fire risk mitigation strategies, such as additional fire compartmentation and mandatory sprinklering, have been introduced to further limit fire growth and spread. In defining

acceptable solutions, however, these historical changes have not necessarily been fully documented and assessed on the basis of changing technical knowledge, nor have the building size limits and type of construction requirements been iteratively reconsidered along with each regulatory solution advancement to limit fire growth and spread. In this context, the historical reconciliation sub-framework provides a methodology by which to do this, while also providing a sound basis upon which to develop technical evaluations of the existing provisions through the technical reconciliation sub-framework as discussed in this case study below.

6.3 Technical Reconciliation

This section examines the depth of technical rationale that underlies decisions made during the various stages of historical development of building size limits and construction type requirements. Recommendations for technical reconciliation of these requirements are provided based on analysis of whether the identified rationale does or does not align with current knowledge, capabilities, materials, analytical methods, or levels of acceptable performance.

Given the extended timeframe over which these requirements have evolved and the complex nature of fire growth and spread within buildings, the present reconciliation is provided as an example of how to use the framework, and thus focuses on several key illustrative aspects of the building size limits and types of construction that have been impacted by the passage of time. It is not intended to represent a comprehensive review or reconsideration of all aspects of what could form a full technical basis for these requirements and limits. Some of the requirements were analyzed and discussed in earlier sections of this thesis. Of these, the shifting baseline of performance that occurred with the introduction of sprinklers should be mentioned again here, as should the example of the error in specification of area limit that was discussed in Section 4.4. These will not be revisited in this section, but would form portions of a future holistic analysis of this part of the NBC.

6.3.1 Fire Severity and Fire Containment

Investigations following the Baltimore conflagration in 1904 highlighted the limitation of noncombustible (fireproof) construction as a key solution to limit fire growth and spread [80]. This lead to the adoption and regulation of fire compartmentation through fire-resistant boundaries and structural elements. Fire-resistance of those elements was established through testing in a furnace, based on a fire exposure intended to represent a “severe” compartment fire. The definition of a severe fire exposure evolved from the burning of ad-hoc masses of combustibles in the 1770s [26, 27] to a defined time-temperature curve in the early 1900s [81]. However, understanding of compartment fire development at the time the curve was developed was primarily based on experience, the results of ad-hoc testing of floor assemblies [48], and post-fire observations of how different materials had performed during real fire events. Given advancements in understanding and theory of fire growth in compartments (Section 3.3.2.1), the time-temperature curve does not accurately represent actual fire behaviour in a compartment or the severity

of fire exposure as it is known today. This discrepancy was initially recognized in the late 1920s through fire load testing and by comparing the standard time-temperature curve (red) with an averaged fire curve based on actual test data (purple), as illustrated in Figure 6-1 [84].

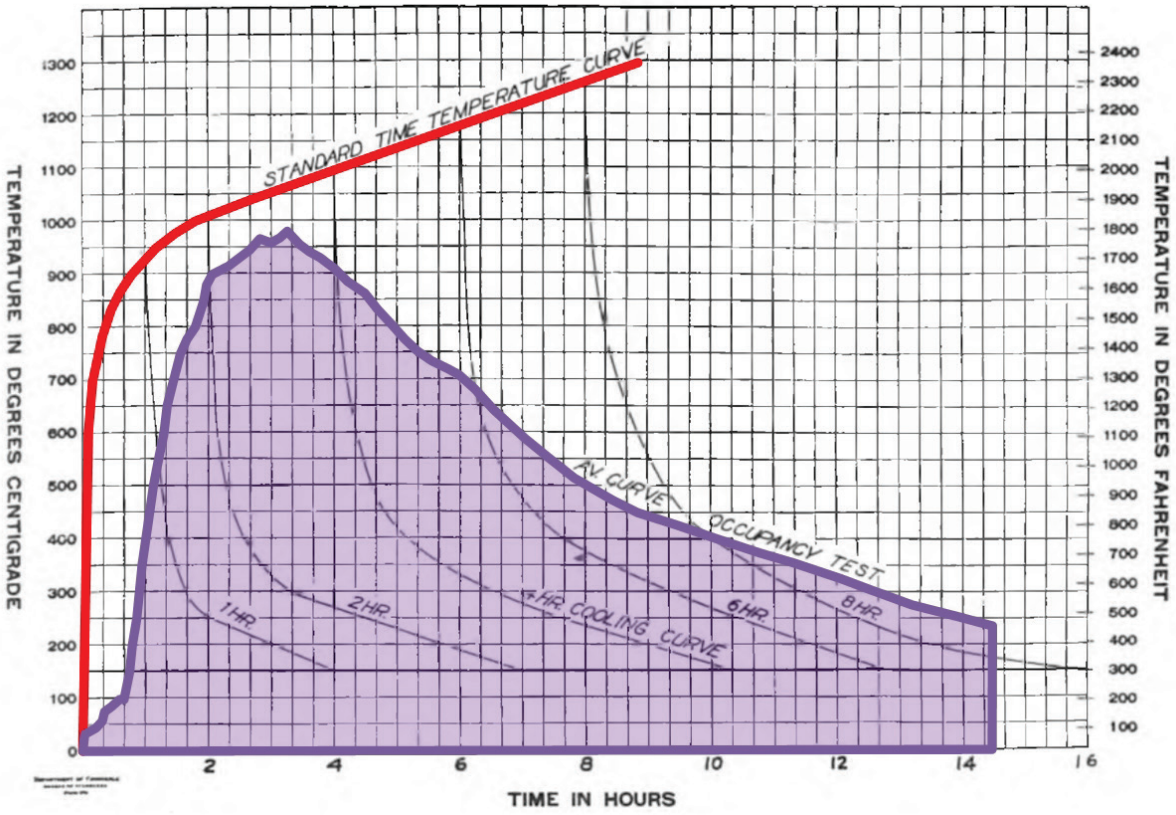


Figure 6-1: Ingberg's fire severity curve [84]

The clear discrepancy between the standard time-temperature curve and the time-temperature history of real fires was then addressed by equating the areas under their respective curves to better represent fire severity [84]. A relationship was developed to link fire loads to the standard time-temperature curve through burn-out tests. This relationship involved area equivalence of compartment burn-out test time-temperature results to corresponding fire-resistance times. For design fire loads within a compartment of less than or equal to 146 kg/m², a time-equivalence correlation based solely on fire load was developed, as shown in Equation 6-1 [314]. Figure 6-2 illustrates this concept, where the standard time-temperature curve is shown in red, the actual burn-out test fire time-temperature history is shown in purple, and the limits of the equivalent areas for 1-hour, 2-hour, and 4-hour fire-resistance are shown in blue, green, and yellow, respectively.

$$\tau_e = 0.0205 \cdot L \qquad \text{Equation 6-1}$$

Where:

τ_e = Equivalent fire duration (h)
L = Fire load ≤ 146 (kg/m²)

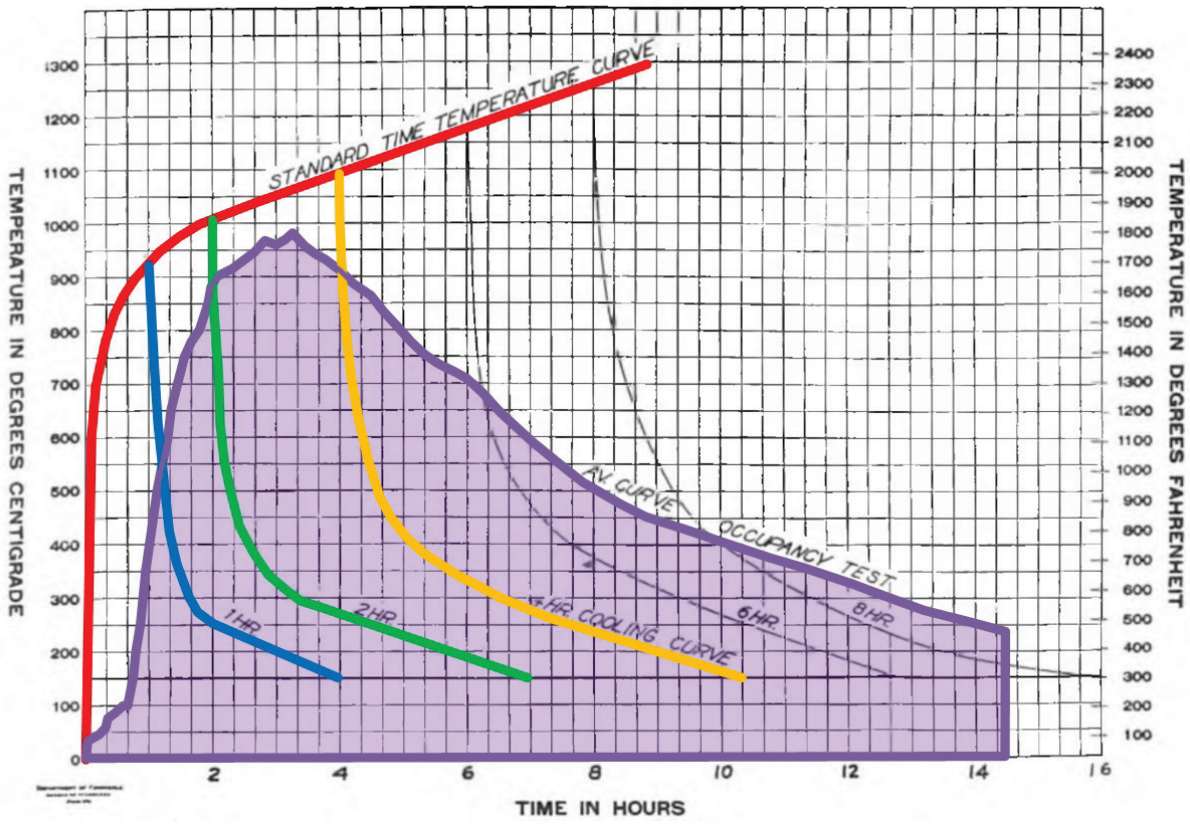


Figure 6-2: Ingberg's correlation between fire load and the standard time-temperature curve [84]

With further advancements in understanding of compartment fire behaviour, the limitations of the simplified time-temperature exposure model and this correlation have become increasingly evident. More accurate time-equivalence methods have since been developed [314-318], accounting for additional important factors that influence compartment fire dynamics such as ventilation and boundary heat transfer (thermal inertia) during post-flashover burning, as shown below:

Law (1971) [315]:

$$\tau_e = K' \frac{L}{\sqrt{A_w A_T}} \qquad \text{Equation 6-2}$$

Where:

K' = A constant close to unity
A_w = Area of ventilation openings (m²)
A_T = Internal surface area of walls and ceiling (m²)

Pettersson (1976) [316, 317]:

$$\tau_e = 0.31C \frac{L}{\sqrt{A_w A_T \sqrt{H}}} \qquad \text{Equation 6-3}$$

$$C = \begin{cases} 0.09, & \sqrt{k\rho c_p} \leq 720 \\ 0.07, & 720 < \sqrt{k\rho c_p} < 2520 \\ 0.05, & \sqrt{k\rho c_p} \geq 2520 \end{cases}$$ Equation 6-4

Where:

C = A factor that depends on thermal inertia (h·m$^{3/4}$/kg)
H = Height of ventilation openings (m)
$\sqrt{k\rho c_p}$ = Thermal inertia (J/m²·s$^{1/2}$·K)

Eurocode (1992) [318]:

$$\tau_e = k_h w Q_f$$ Equation 6-5

$$w = \left(\frac{6.0}{H_c}\right)^{0.3}\left[0.62 + \frac{90(0.4-\alpha_v)^4}{1+b_v\alpha_h}\right] > 0.5$$ Equation 6-6

$$\alpha_v = \frac{A_v}{A_f}, \quad 0.05 \leq \alpha_v \leq 0.25$$ Equation 6-7

$$\alpha_h = \frac{A_h}{A_f}, \quad \alpha_h \leq 0.20$$ Equation 6-8

$$b_v = 12.5(1 + 10\alpha_v - \alpha_v^2)$$ Equation 6-9

Where:

k_h = A constant (min·m²/MJ)
Q_f = Fuel load (MJ/m²)
H_c = Compartment height (m)
A_v = Area of vertical openings (m²)
A_f = Floor area of the compartment (m²)
A_h = Area of horizontal openings (m²)

Despite the development of such advanced correlations for the duration, they have not explicitly been incorporated into the present version of the NBC and the original time-temperature relationships have remained. The current edition of the Canadian test standard for the determination of the fire-resistance of building elements does acknowledge the technical limitations of the standard time-temperature exposure curve. At the same time, it emphasizes its modern, non-technical utility [83, p. 2]:

> *The fire exposure and hose stream tests are not intended to be representative of all fire conditions. It is likely that conditions will vary with changes in the amount, nature and distribution of fire, loading, ventilation, size and configuration of assembly installed. This*

fire endurance test Standard provides a relative measure of fire performance of comparable assemblies under specified fire exposure conditions.

A key factor in fire duration and severity is fire load. In the 1953 NBC, consistent with Ingberg's method, fire loads were expressed as a simple weight of combustibles per unit floor area (Table 6-1), sourced from a survey conducted in 1942 [251]. Since that time, however, due to changes in construction materials and contents (i.e., furniture), total fire load for residential occupancies has changed. This change is illustrated in Table 6-8, including results from three studies conducted between 1942 and 2008 [251, 319, 320]. The NBS studies [251, 319] were conducted in the United States, while the NRC study [320] was conducted in Canada. The results show an increase in total fire load from 1942 to 1980, followed by a decrease in 2008 to 85% of the 1942 value.

Table 6-8: Change in fire load in residential occupancies over time

Combustible Content	**NBS[1], 1942 [251]**	**NBS[1], 1980 [319]**	**NRC, 2008 [320]**
Moveable (MJ/m²)	309 (38%)	618 (55%)	548 (80%)
Floor (MJ/m²)	236 (30%)	536 (45%)	135 (20%)
Non-Floor Finish (MJ/m²)	254 (32%)		< 1% of cases[2]
Total (MJ/m²)	800	1154	683

1 Originally expressed in units of lb/ft², converted to MJ/m² for purposes of comparison.
2 Combustible room linings were only observed in basement living rooms and less than 1% of cases.

For regulatory simplification in the 1953 NBC, the 1942 survey value of 8.8 lb/ft² (800 MJ/m²) was rounded to 10 lb/ft² (909 MJ/m²) using a conversion based on a nominal heat of combustion of 8,000 Btu/lb (18.6 MJ/kg) [108] for cellulosic materials (i.e., wood and paper). The value of heat of combustion was later updated to 10,000 Btu/lb (23.3 MJ/kg) in the 1970 NBC [117], likely to reflect a mixture of cellulosic and higher energy-density materials, such as plastics, in residential occupancies, as these can have a heat of combustion as high as 46 MJ/kg (19,776 Btu/lb) [204]. As a result, converting a fuel load of 10 lb/ft² using this updated heat of combustion corresponds to an energy density of 1,200 kW/m². Examination of Table 6-8 indicates that this translates into an energy density for residential occupancies in the NBC of nearly double that determined via the NRC survey in 2008 [320]. Even the 95th percentile fire load energy density of 745 MJ/m² [320] is only 62% of the value assumed in the development of the fire-resistance requirements of the current version of the NBC. For purposes of comparison, the New Zealand Building Code specifies a much lower fire load density of 400 MJ/m² [206], and the Eurocode specifies a higher fire load density of 780 MJ/m² [321] respectively for residential occupancies. Similar discrepancies are likely to exist for other occupancies, though they are not examined in this thesis.

The discrepancy between the 1,200 MJ/m² assumed for residential occupancies in the NBC and the more recent 2008 NRC survey value of 548 MJ/m² suggests modern fire loads exhibit a lesser fire severity than the value used to establish the fire-resistance ratings required for burn-out that remain applicable today.

It should be noted at this point, however, that the traditional concept of fire severity, even within those methods above, has its limits in representing actual fire hazard. The time equivalence method only

accounts for the total heat evolved from a fire but not differences in fire intensity characterized by the timing, magnitude, and rate of fire growth. For example, only using fire severity in defining a design fire would consider a short-duration fire with a rapid growth rate and high maximum temperature (i.e., quick onset of flashover) to be equally severe as a longer-duration fire with a slow growth rate and lower maximum temperature, given the same area under their respective time-temperature curves. Therefore, the fire severity methods do not account for important elements of real fire behaviour such as the impact of the fire on surrounding materials or the onset of flashover.

As discussed earlier, flashover is a dangerous and rapid transition in fire behaviour from localized burning to full compartment involvement. Once a compartment experiences flashover and becomes fully involved in fire (post-flashover), the negative impact on the fire compartment boundaries and structural elements intensifies considerably. Therefore, the materials of the compartment boundaries and the time to onset of flashover, and thus fire intensity, is an important consideration in the development of requirements intended to limit fire growth and spread.

As outlined in Section 3.3.2.1, the occurrence of flashover depends on multiple factors, including the quantity and configuration of the combustible materials, ventilation conditions, the size and shape of the compartment, and boundary (i.e., walls, ceiling and floor) thermal properties. Among these factors, the fire-resistance values in the NBC, through Ingberg's method, account only for the quantity of combustible materials. More advanced time equivalence methods shown above account for the quantity of combustible materials as well as ventilation conditions, size and shape of the compartment, and boundary (i.e., walls, ceiling and floor) thermal properties. However, these methods still do not account for the configuration of combustible contents within a compartment that may also influence the onset of flashover, even though combustible materials have been classified as a function of their configuration (i.e., wall linings, contents and flooring) since the 1942 survey.

To illustrate this, Table 6-8 not only includes total fire load density found in each survey over time, but also the proportion of fire load density as a function of configuration (i.e., moveable, flooring, wall, and ceiling finish). It has been suggested that times to the onset of flashover have decreased over time due to an increase in energy density of combustible contents [322]. However, this claim is focused on the energy density of moveable contents, which, as reflected in the 2008 Canadian study [320], is nearly double that reported in the earlier U.S. study from 1942 [251].

To further support the claim, the correlation between higher energy density and an increased propensity for flashover has been demonstrated through comparative fire testing of rooms with legacy furnishings (primarily composed of natural materials) versus modern furnishings (primarily composed of synthetic materials), both having comparable mass-based fire load densities (content only) [322]. The furniture in the modern test rooms was composed of materials with higher energy density than the furniture in the legacy rooms. Measured times to the onset of flashover, indicated by ignition at floor and external flaming from the top of the room opening, are summarized in Table 6-9 [322].

Table 6-9: Room fire test results

Room Test	Furniture Type	Fuel Load	Time to Flashover (min:sec)
1	Modern	Not weighed	3:30
2	Legacy	Not weighed	29:30
3	Modern	3.9 lb/ft² (19.0 kg/m²)	4:45
4	Legacy	4.7 lb/ft² (22.9 kg/m²)	34:15
5	Modern	2.3 lb/ft² (11.2 kg/m²)	3:20
6	Legacy	2.3 lb/ft² (11.2 kg/m²)	No flashover

Much shorter times to the onset of flashover were observed for the rooms with modern furniture than the legacy rooms. These relate to less time for occupant escape and greater impact on firefighter safety since the fire grows very quickly with potential for rapid fire spread and compartment collapse [322]. However, the tests did not account for changes in combustible room lining materials, which can have a significant influence on the onset of flashover. As illustrated in Table 6-8, alongside the increase in the energy density of the movable contents over time, there has been a significant decrease in the proportion of combustible fire load associated with wall and ceiling finishes, which can result in a decreased time to flashover.

Research conducted by the British Research Establishment (BRE) in the 1950s demonstrated the significant impact of lining materials on flashover times. Their findings showed that flashover could occur as quickly as 3 minutes in a room lined with insulating fiberboard, compared to 8 minutes in a room lined with plasterboard [323]. Additional tests by the Fire Research Board in the UK in 1953 [324] investigated fire growth in furnished rooms, including scaled models with combustible fibre wallboard. The recorded times to the onset of flashover in these tests are shown in Table 6-10. Where noncombustible lining materials are involved, the times associated with the onset of flashover, as expected, align with those seen in Table 6-9, since that was the construction of the compartment used in the tests. The time to onset of flashover, however, is significantly reduced where the walls and ceiling are lined with combustible material, even when legacy moveable contents are included.

Table 6-10: Fire Research Board room fire test results

Type of Structure	Time to onset of flashover	
	Full Scale (min)	Models (min)
Traditional incombustible walls and ceiling	14 - 20	15 - 19
Fibre insulating board walls and ceiling	5	5

Type of Structure	Time to onset of flashover	
	Full Scale (min)	Models (min)
Plasterboard walls and ceiling	23	14 - 18

The impact of combustible lining materials on fire growth and spread was recognized in the development of the 1960 NBC. The following observations were noted [323, App. A, p. 1]:

> *The dangers arising from the use of combustible wall and ceiling linings in buildings have increased with the development and increasing use of new materials such as fibreboard, plastics, and acoustical connection materials. There have been a number of examples of serious fires attributable to interior finishes having high flame spread properties. The combustible contents are an additional factor in certain types of occupancy.*
>
> *…*
>
> *The period between ignition of a fire and flashover is a measure of the time available for escape. Flashover can occur in as little as 3 minutes.*

Further studies conducted by the NRC in the 1970s reported flashover times ranging from 3 to 20 minutes [325, 326]. Differences in times were again related to the configuration of the combustible contents. Other research has also investigated the relative impacts of movable (content) fuel loads and combustible linings on the onset of flashover. Harmathy suggests that combustible materials with a large surface area to weight ratio ignite more readily than "bulky objects" [325]. Benjamin further explores the balance between combustible contents and lining materials in contributing to the onset of flashover and observes [327, p. 302]:

> *One can choose a fire load of such magnitude that its contribution will mask the effect of the linings. With this scenario, one can show from a large-scale test that the wall linings are insignificant, and, therefore, one should not be concerned about them. However, one can also choose another scenario in which the fire load is very light, and the only way for the fire to spread from one item to another is via the wall linings. With this scenario, the linings become most important. We have considered this latter case to be a more typical scenario. Under this scenario, the wall lining becomes a critical factor in fire spread and hazard, since flashover will not usually occur in a sparsely furnished room if the wall lining does not contribute.*

To the present, the studies suggesting that “modern” building contents exhibit greater fire severity than “legacy” contents [322] have not accounted for the impact on the fire severity of modern versus legacy room lining materials. This is particularly notable, given the substantial impact of room lining materials on early fire development (fire intensity) and thus the onset of flashover. To properly assess the combined effects of moveable contents and compartment lining materials, account should be taken in a modernized

assessment of “fire severity” for the fact that the proportion of combustible room lining materials has decreased over time, while the proportion of combustible contents has increased, even when the total quantity of combustibles has declined. The fire severity may therefore have actually decreased since the early development of fire-resistance concepts or, at worst, remained unchanged.

This section, through the proposed technical reconciliation sub-framework, has highlighted significant changes over time in the characterization of fire loads underlying fire-resistance ratings, fire compartmentation, and the burn-out concept. As a result, the existing fire-resistance requirements of the NBC are no longer technically relevant and should be reconsidered based on more current understanding and theories describing fire severity in terms of factors, such as configuration of fire load and ventilation, that influence early and later fire development, as well as the onset of flashover. The fire-resistance test, itself, does remain applicable today when applied as a comparative test of performance. This is supported by the long-term actual, in-situ performance of the tested elements in a wide range of fire events. At the same time, as building materials, fire safety technologies, and overall characteristics of the built environment evolve and change, the applicability of even a widely used test, such as the fire-resistance test, must be continually re-evaluated.

6.3.2 Structural Fire Protection and Fire Service Intervention

The concepts of fire compartmentation and burn-out have allowed the construction of larger and taller buildings, increasing the probability that fire would be limited to the fire compartment of origin (i.e., a single storey). At the time of the development of these concepts, few, if any, assemblies of combustible construction were available that would allow burn-out without also participating in a fire. As a result, these concepts have relied on the provision of noncombustible construction materials and significant limits on the use of combustible construction materials. These limitations have been applied primarily to building height and, to a lesser extent, building area, to be within the capability of a responding fire service to control if a building becomes completely involved in fire. This dichotomous “type of construction” approach to regulating the fire hazard of building size has created on-going challenges (Section 6.2.3), which necessitates technical reconciliation in a current context as detailed in the proposed new framework.

In the early 1960s, efforts were made to shift from the binary material specification approach toward a more performance-based approach that emphasized the fire-resistance of boundary and structural elements over their combustibility [46]. Work was underway to make revisions to the 1965 NBC to facilitate this more performance-based framework for building construction, but these efforts were curtailed by austerity measures implemented by the NRC in 1962 [46].

Since that time, the classification of “noncombustible” has increasingly presented challenges over time, requiring modifications and relaxations for practical purposes. Initially, only minor combustible building components and materials were permitted, but as time has passed and materials have changed, additional combustible materials and components have been allowed. This has resulted in so many exceptions in the 2020 NBC that certain buildings that are required to be of noncombustible construction, through

exceptions, are now permitted to be constructed almost entirely of combustible materials [Articles 3.2.2.77., 3.2.2.17. and Subsection 3.1.5.]. This practical shift, along with material advancements, have facilitated recognition through performance that fire compartmentation and fire-resistance can significantly limit fire growth and spread without specification of noncombustible materials.

The introduction of EMTC in the 2015 NBC, for example, has permitted buildings constructed primarily of mass timber to be larger than traditionally allowed, based on the encapsulation of the timber with a protective layer that significantly delays its involvement in a fire (Section 6.2.6). This approach, at a minimum, allows time for fire service intervention and, at best, allows for complete burn-out of combustible contents within an encapsulated mass timber compartment. This development, along with other material advancements, is expected to evolve further, enabling larger and taller buildings to be designed based on fire performance rather than through the traditional reliance on type of construction.

No matter the construction type, the concept of containment to burn-out increases the probability that a fire would be limited to the fire compartment of origin and also allows greater time for fire service intervention (if required). The interconnection between these, therefore, needs to be evaluated through a technical lens as well. In this context, fire department intervention has been central to fire risk reduction underlying the development of building size and construction requirements for at least 170 years (Section 2.1.2.3). In addition to considerations of fire containment and fuel load, the size of buildings of combustible construction has been limited based on assumptions about not only the extent of fire spread but also how that relates to the corresponding capabilities of a responding fire service. Based on the historical analysis, these assumptions underlying fire service response can be summarized as follows:

- **Combustible Construction:** It has been assumed that in a building of combustible construction, fire growth and spread could not be adequately limited to stop full building involvement in fire. Therefore, an exterior fire service attack would be required and building size was limited to be within the control of a responding fire service and their technology of the time.
- **Noncombustible Construction:** It has been assumed that noncombustible construction, in conjunction with appropriate fire-resistance of floor assemblies (aligning with the major occupancy), would contain the fire to the storey of origin and allow for a controlled burn-out and, if required, an interior fire service attack.

As noted in Section 2.1.2.3, the first municipal fire chief for the City of London (the London Fire-engine Establishment) noted in the 1850s that [33, p. 12]:

> *With a well organized and properly equipped fire brigade it is found that sixty feet is the greatest height at which a building can be quickly protected, and that the cube of 60, or 216,000 cubic feet, is the largest cubical capacity which can be protected with reasonable hope of success after a fire has once come to a head.*

This observation was affirmed through experience over the following 70 years [58, 257] and has been widely referenced as a benchmark since then [33, 46, 247, 294, 328-330]. The 2020 NBC continues to reference this height limit in relation to:

- Combustible building height limits [Subsection 3.2.2.].
- High building requirements [Article 3.2.6.1.].
- Combustible insulation [Articles 3.1.5.7., 3.1.5.14. and 3.1.5.15.].

Whether purposely or through loss of continued connection to its origins (Section 3.2.2), building size for combustible construction has consistently been limited based on the fire service capability that was established and stated in the 1850s. Contrary to the traditional fire service adage "200 years of tradition unimpeded by progress" [331, p. 17, 332, p. 2], it is evident from observation that fire service capabilities have significantly advanced since that time (Figure 6-3). However, building size as related to type of construction has not been reconsidered in a more current context with respect to the advancement of these capabilities. While the above adage may have originally been crafted as a witty response to criticisms of lack of progress by the fire service itself, in reference to the NBC, it holds more truth than mere wordplay, as it reflects the tendency toward status quo bias and adherence to traditional practice, as discussed in Section 3.2.3.



(a) **(b)**

Figure 6-3: (a) Fire in Los Angeles in 2007 ("Downtown Fire!" by archie4oz is licensed under CC BY 2.0), (b) Equitable building fire in New York City in 1912 [333]

The increased prevalence of mandatory sprinkler systems, discussed in Section 6.2.5, has further modified the present landscape in terms of combustible versus noncombustible construction. It is expected that few sprinklered buildings will become fully involved in fire to the extent of requiring an exterior attack by the fire service. This could support the greater use of combustible construction in larger and taller buildings.

Further, the NBC's building size limits and construction requirements should be re-evaluated in light of modern fire service capabilities. Despite the integration of multiple redundant strategies to limit fire growth and spread, and the significant reduction in the risk of full building involvement since the original fire service capability benchmarks, the underlying assumption of those early limitations remains unchanged. The ultimate fire size that a fire service can control would need to be integrated into the re-evaluation of fire severity and a determination made as to whether the associated fire hazard should be

translated into a building size limit (i.e., “building” as the regulatory unit of control) or a fire compartment limit for purposes of regulation. Holistic considerations should also account for the impacts of advancements in sprinkler performance and enhanced fire compartmentation on the overall severity of fires and the fire service’s ability to respond to them.

6.3.3 Assessment of Changing Risk with Time

Building size limits and types of construction requirements, as well as the technical basis on which these regulations were developed, have evolved over multiple generations, spanning thousands of years, shaped by key “eras” of solution (strategy) development, including:

1) Types of construction and building separation (Section 2.1.1),
2) Building size limits and fire service intervention (Section 2.1.2.3),
3) Fire compartmentation (Section 2.1.3.4 and 6.2.2),
4) Sprinklers (Section 6.2.5).

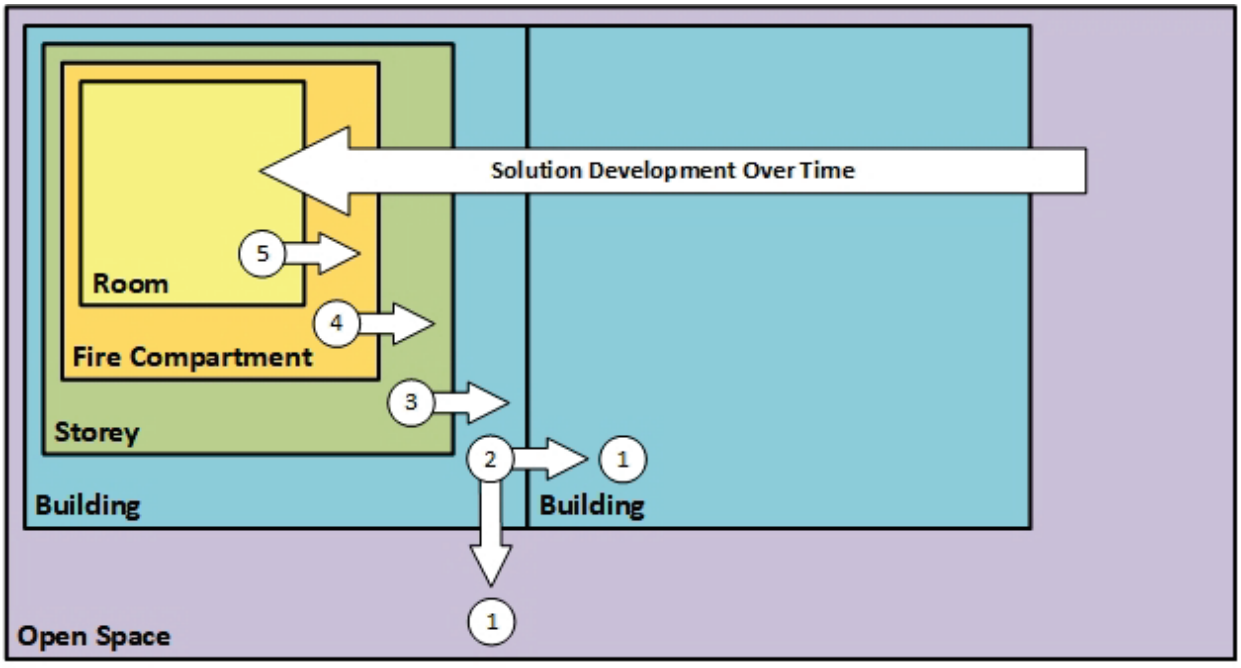


Figure 6-4: Building fire spread layers and evolution of solution development

These eras of development are illustrated in Figure 6-4, showing a shift in focus over time to more precisely limit the probability of fire spread. Initially, containment efforts were aimed at localized areas within cities (1), then moved to individual buildings (2), later to individual storeys (3), and more recently to individual suites (4). The spread of fire has been further minimized to individual rooms (5) through the introduction and increasing use of sprinkler systems. This illustrates the gradual shift to the regulation of smaller spaces [296], and is a case of a shifting baseline of acceptable performance embodied in the changing “unit” of regulatory control. However, the building size limits in the NBC are structured to align with the building as the “unit” of regulatory control, which as discussed earlier is an outdated concept.

The intent of all of the solutions listed above has remained the same, to limit fire growth and spread. Due to the time span over which their development occurred, however, there have been few recorded cycles of reflection. Instead, these solutions have been incrementally added together through the ratchet effect. As a result, with each new era of solution development and the predominant “test of time” approach to solution performance confirmation, the benefit of the cumulative solutions in reducing the risk of fire growth and spread has not been realized or quantified.

As part of the technical reconciliation stage in the new framework, the combined risk-reduction (reliability) impact of these strategies can be analyzed using the Fire Safety Concepts Tree (FSCT). The solutions to limit fire growth and spread, formulated around the relationship between building size limits and types of construction requirements are explored here in the context of the “manage fire” branch of the FSCT, illustrated in Figure 6-5, and in sequence of their implementation.

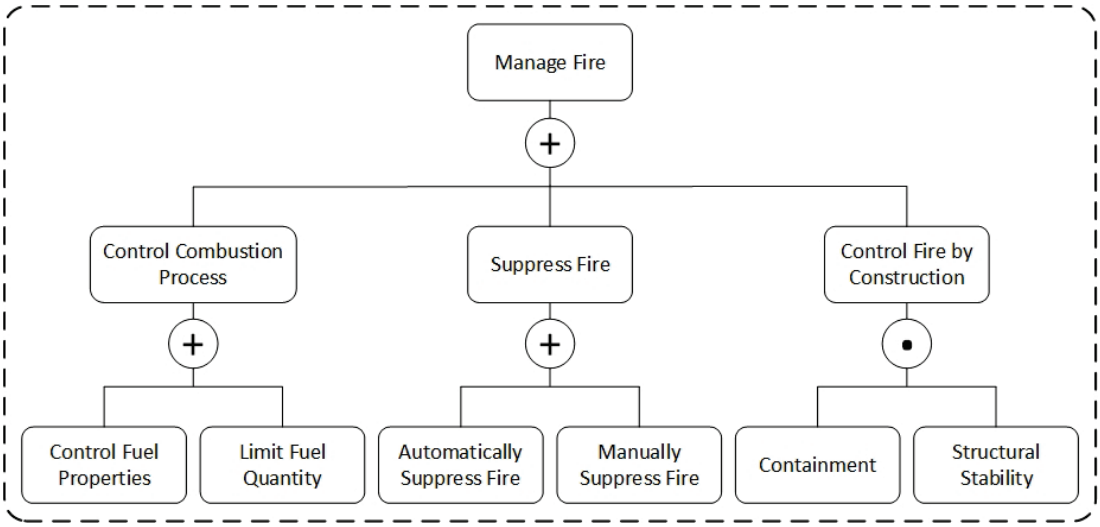


Figure 6-5: A redrawn version of the Manage Fire tree

As illustrated in Figure 6-5, the “manage fire“ node of the FSCT branches into three key strategies: “control combustion process,“ “suppress fire,“ and “control fire by construction,“ with the (+) gate indicating that the top level objective can be achieved through any one of the subordinate strategies. This affords the potential for multiple strategies to serve as backup (or redundant) to the primary strategy in achieving the top level objective where one (or more) of the other joint strategies fails to perform as intended.

The “control combustion process“ branch of the FSCT involves two key strategies: “control fuel properties“ and “limit fuel quantity,“ as illustrated in Figure 6-6. Noncombustible construction, one of the oldest strategies to limit fire growth and spread, was primarily intended to “control fuel properties,“ with the “limit fuel quantity“ option serving as a secondary strategy.

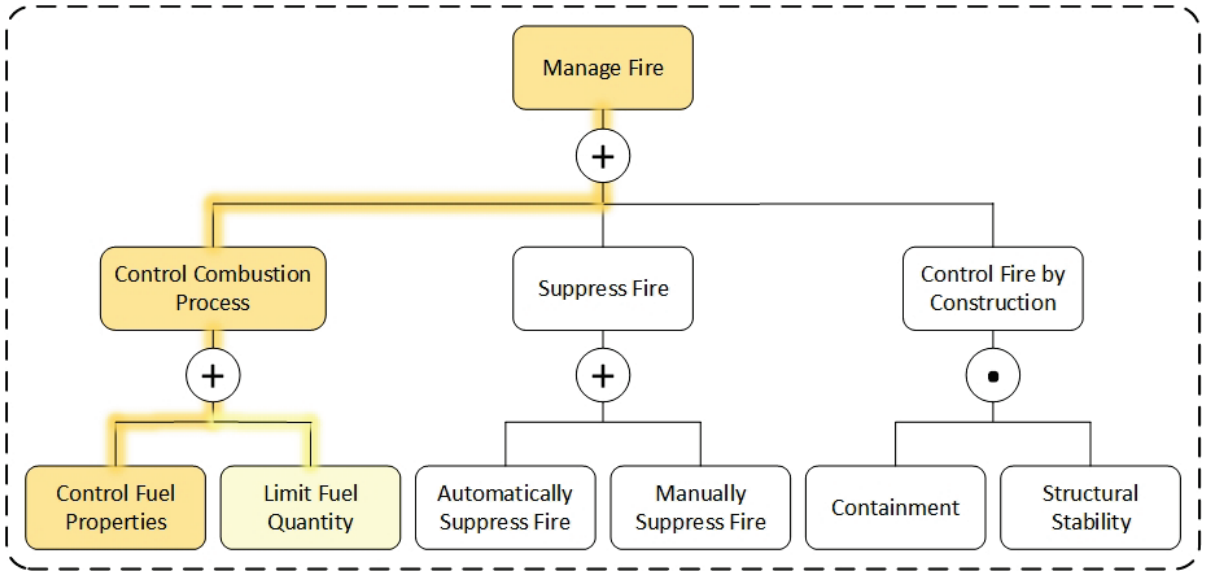


Figure 6-6: A modified version of the control combustion process tree

Over time, however, limiting the type of construction to noncombustible (fireproof) was recognized to no longer achieve an acceptable level of performance due to the presence of combustible building contents combined with increased building sizes, with result that fire sizes exceeded the capacity of the responding fire services.

Since the moveable nature of combustible building contents makes them challenging to control, the limiting of fuel quantity through regulation and control of combustible contents has not been considered a strategy to reduce the impact of fire relative to the building size limits and types of construction requirements. Instead it has been captured through the fire load as a fire hazard characteristic, as discussed earlier.

Following a review of the damage from the Baltimore conflagration in 1904, noncombustible (fireproof) construction was again shown to be ineffective, leading to the subsequent development of fire separations and fire-resistive construction.

The “control fire by construction“ branch is illustrated in Figure 6-7. It includes the strategies of “containment” and “structural stability” connected by an “and“ (•) gate. This indicates that they must be considered together to achieve the parent objective of “control fire by construction.“ The objective of this branch was intended to be achieved by correlating the “burn-out” of the combustible contents associated with building use (occupancy) to the fire-resistance provided to bounding and supporting construction. Together, these were intended to provide fire containment and also some consideration of the challenges that might be posed by increasing building size, should it result in fires exceeding the capability of a responding fire service to control.

The “suppress fire“ branch of the FSCT includes two strategies: “automatically suppress fire“ and “manually suppress fire.“ This section focuses on the “manually suppress fire” strategy, illustrated in Figure 6-8, intended to be achieved through reliance on fire service intervention in the event of a fire. This

strategy was developed to address the shortcomings of noncombustible construction in limiting fire growth and spread.

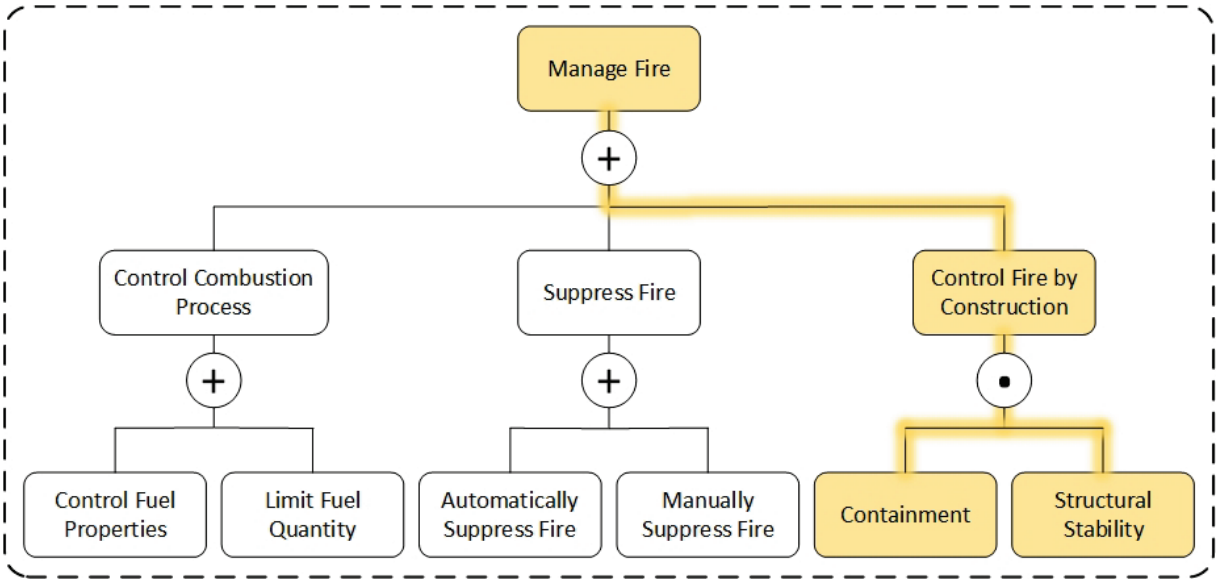


Figure 6-7: A modified version of the control fire by construction tree

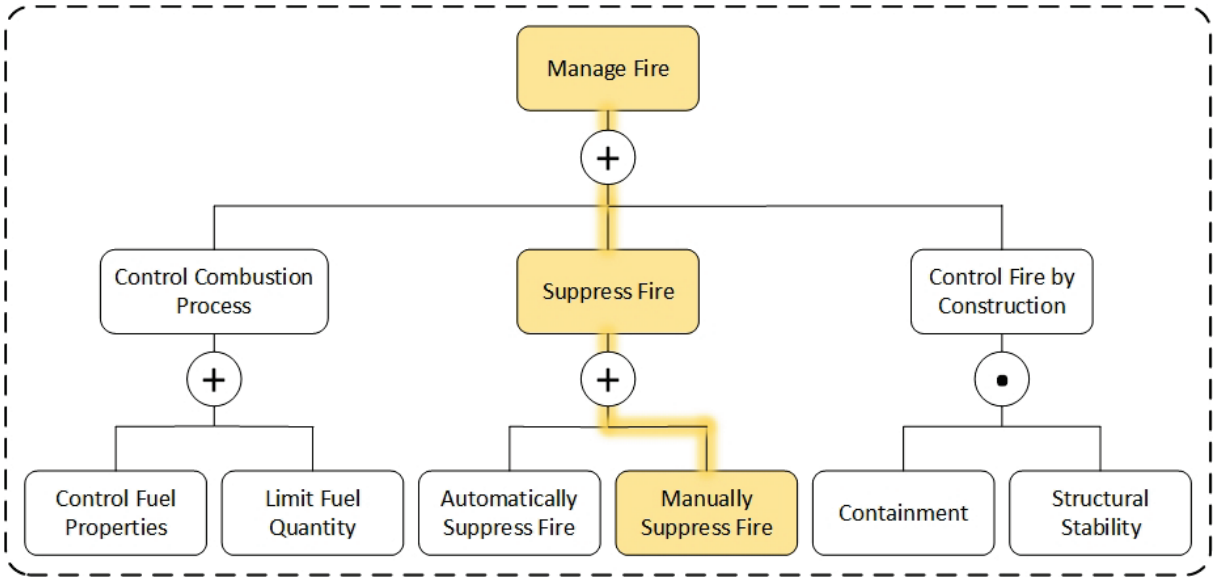


Figure 6-8: A modified version of the manually suppress fire tree

Explicit requirement for specific fire service intervention is beyond the scope of the NBC as a regulatory measure. However, the notes to Part 3 of the 2020 NBC [21] state that fire service intervention has been assumed in the development of the fire and life safety regulations, and in particular, the limitation of building size. In this context, while not required in the NBC, fire service intervention is considered a key strategy in support of the other strategies discussed above.

Even though fire compartmentation was recognized as “performing as intended” [297] and the degree of fire compartmentation had increased over time, the combination of noncombustible construction, fire

service intervention, and fire compartmentation was considered ineffective in limiting fire growth and spread. This led to incorporation of the additional strategy of automatic sprinklers under the "automatically suppress fire" strategy, illustrated in Figure 6-9, through the provision of automatic sprinklers. The specific reasons for mandatory sprinklering of all buildings over 6 storeys and certain buildings 6 storeys or less in building height were [298]:

- To establish more efficient means of controlling fires to limit fire service costs.
- Deaths and substantial property loss in high buildings.
- Concerns of safety in highrise buildings in Ontario.

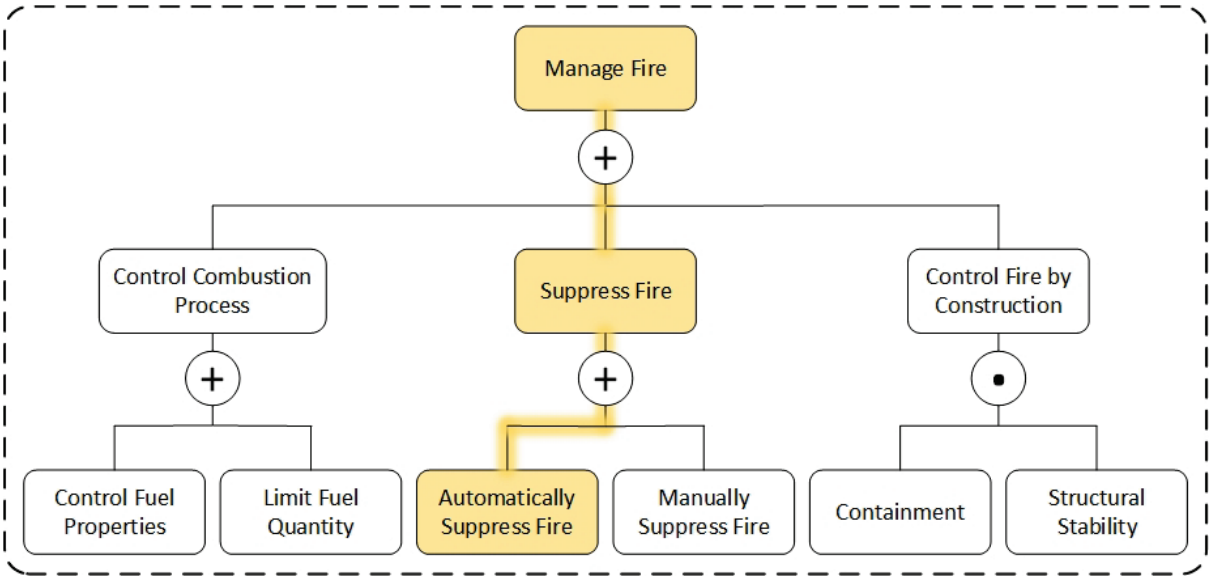


Figure 6-9: A modified version of the automatically suppress fire tree

Despite the high reliability of automatic sprinklers, estimated at 96% or greater, in limiting fire growth and spread [299], few concessions have been made in requirements derived from other strategies for managing the fire. Law (1994) discussed this issue, noting the following [144, p. 80]:

> *The evidence is considerable from a number of sources to suggest that sprinklered buildings are extremely safe from fire. It has even been suggested that a well-designed sprinkler system with a very high level of reliability could be defensibly installed as the only fire safety measure in a building. This type of radical approach would clearly take a long time to be accepted, but even at present, the relaxations in fire safety measures for sprinklered buildings rarely reflect the high degree of enhanced safety.*

Ferguson provided a similar perspective on sprinkler performance and their importance in managing a fire, as previously discussed in Sections 3.2.5 and 4.4, and reiterated here for context [182, p. 11]:

> *Despite the higher factor of safety in larger buildings it is the practice in many building by-laws to take further precautions by restricting the combustible load and requiring non-bearing partitions, interior trim and even furniture to be non-combustible and* ***sometimes sprinklers are required on top of all this*** *[emphasis added]. To the author of this paper*

> *this appears to be a malpractice. The correct way to regulate is to assess the risk and apply regulations accordingly. It should be unnecessary as a sequel to apply further requirements to diminish the risk. If it is necessary,* ***these further regulations should have been considered as part of the initial risk*** *[emphasis added].*

The cumulative impact of the high reliability of sprinkler systems, in conjunction with fire compartmentation and fire service intervention, may diminish the importance of limiting combustibility of building components even if sprinklers have increased the baseline of acceptable performance in modern buildings. Nearly all fires in sprinklered buildings are expected to be controlled by the sprinkler system. As such, it could be argued that combustibility of the building components is an insignificant factor in managing a fire. In the rare event that a fire is not controlled by the sprinkler system, it is expected to be contained by fire compartmentation, facilitating eventual control by a responding fire service, if necessary.

The combination of noncombustible construction, fire compartmentation, sprinklers, and fire service intervention collectively achieves the objective of "manage fire," or limiting fire growth and spread. Any one of these strategies could be employed alone to address the top level objective of managing the fire; however, the degree of reliability associated with each of these strategies must also be evaluated in a technical reconciliation of requirements in the NBC.

It has been noted that the reliability of fire safety systems is not as robustly defined as reliability of other systems that may have a more precise understanding of failure rate [334]. This is primarily due to the complex interactions between these systems and a fire, where the failure of specific fire safety systems is difficult to establish in isolation. However, recent statistical analyses of fire losses have correlated regulatory strategies, such as fire compartmentation and sprinkler protection, with key fire growth and spread mechanisms that have resulted in fire losses [209, 210, 335-338].

A recent study, comparing fire severity outcomes in apartment buildings constructed of combustible and noncombustible construction materials [339], examined the impact of the type of construction on the severity of fire outcomes in apartment buildings [339]. The study analyzed thousands of fires in 1 through 6 storey apartment buildings that occurred between 2005 and 2019 in British Columbia, Alberta, and Manitoba. In buildings equipped with sprinklers and smoke alarms, the study found the following [339]:

- The presence of working smoke alarms and sprinklers was significant in reducing the severity of a fire outcome.
- Smoke alarms and sprinklers both reduced the odds of the fire spreading beyond the room of fire origin and the need for extinguishment by the fire department and the fire spreading beyond the room of origin.
- Sprinklers were found to reduce the injury rate.
- Type of construction of an appropriately constructed structure did not impact its fire performance in terms of injuries, requiring extinguishment by a fire department, or the fire spreading beyond the room of origin.

These results highlight the significant role of sprinklers as the primary factor in reducing the risk of fire growth and spread. By extension, they suggest that, at least in sprinklered buildings with smoke alarms, the impact of fire risk reduction through the type of construction appears statistically insignificant. This reinforces the conclusions in [114] and discussed in Section 6.2.3, which argued that while noncombustible construction will always be a solution to address the hazard of fire with respect to building size, it is certainly not the only solution. From the above discussion then, the combined historical and technical reconciliation of these factors, through the proposed new framework, leads to the very important question, and necessary discussion for future modification of the NBC, as to the conditions under which, if any, it is necessary to limit the type of construction as a fire risk reduction strategy for sprinkler protected and fire compartmented buildings. If the limit on type of construction were to be removed, the ancillary discussion, of course, would be to define the "acceptable" level of performance required by the sprinkler protection and fire compartmentation in the corresponding buildings.

6.4 Modified IRCC Framework Integration

The historical basis of the building size limits and types of construction requirements, supplemented by the information detailed in other historical sources [46], can be used to populate the modified IRCC hierarchy. A comprehensive detailing of this information is beyond the scope of this thesis, which is limited to demonstrating the efficacy of the framework for building code analysis and modification outlined in Chapter 4. The following provides an example of the incorporation of historical information (Section 6.2) to populate levels 4 and 5 of the modified IRCC hierarchy for office buildings. Information for Levels 1 to 3 has already been included in the objective-based framework of the 2020 NBC [21].

6.4.1 Level 4: Performance or Risk Groups

When populating the IRCC hierarchy, it is important to identify the performance or risk groups that are critical to that section of the NBC that is being analyzed. In this example, an important risk group can be extracted from the intent statement related to the required fire protection between differing major occupancies within the same building which reads [131, p. 2]:

> *from one major occupancy to an adjacent major occupancy* ***having a different degree of fire risk [emphasis added]****.*

The degree of fire risk referred to in this statement is specific to the fire load associated with the types of occupancy on each side of the separation. As a parameter then, fire load is more aptly considered to be a risk (hazard) characteristic of a building which can be defined as a function of building (or compartment) use (occupancy). Likewise, combustible construction is also considered to be a risk (hazard) characteristic of the building given that the construction in this instance may also contribute to fire growth and spread. In contrast, noncombustible construction is considered a solution, or alternative, that mitigates the hazard of combustible construction. Additional risk (hazard) characteristics of a building include the building height and area, normally referenced as a function of the ability of a responding fire service to access and

control fire from spreading to adjacent buildings (for buildings of combustible construction), or from one storey to another storey. When these hazard characteristics are grouped together, the risk groups can be summarized as follows:

1) The uses (group of occupancies).
2) The type of construction (group of construction types).
3) Building size (group of building sizes).

These characteristics are identified in a given set of requirements in the NBC, as shown in the example below [21, Div. B, pp. 3-65, 3-66]. The occupancy is highlighted in red text, the type of construction is highlighted in green text (note this is also part of the solution), and the building size and area considerations are highlighted in blue text.

3.2.2.59. Group D, up to 6 Storeys, Sprinklered, Noncombustible Construction

1) A building classified as Group D is permitted to conform to Sentence (2) provided

a) except as permitted by Sentences 3.2.2.7.(1) and 3.2.2.18.(2), the building is sprinklered throughout,
b) it is not more than 6 storeys in building height, and
c) it has a building area
i) that is not limited if the building is not more than 2 storeys in building height,
ii) not more than 14 400 m² if 3 storeys in building height,
iii) not more than 10 800 m² if 4 storeys in building height,
iv) not more than 8 640 m² if 5 storeys in building height, or
v) not more than 7 200 m² if 6 storeys in building height.

2) Except as permitted by Article 3.2.2.16., the building referred to in Sentence (1) shall be of noncombustible construction, and

a) floor assemblies shall be fire separations with a fire-resistance rating not less than 1 h,
b) mezzanines shall have a fire-resistance rating not less than 1 h, and
c) loadbearing walls, columns and arches shall have a fire-resistance rating not less than that required for the supported assembly.

Generally, as this is done, a series of solutions to the risk factors will also form part of the current requirements in the NBC, so these should be noted. The solution to the risk factors (hazards) detailed above are identified in Clause 3.2.2.59.(1)(a) requiring sprinklers, and Sentence 3.2.2.59.(2) requiring noncombustible construction and fire separations with specific fire-resistance ratings. Finally, it is critical at this stage in the analysis to document any implicit solutions that may not be directly specified. In this case, fire service intervention is an additional solution not identified in the requirement, but implicit in the overall basis for requirements in the NBC [21].

With the risk and performance groups identified through Level 4 of the IRCC, the next stage is to consider Level 5 of the IRCC in which performance and risk criteria are specified. To continue the present case study, the performance/risk criteria implicit to building size and construction requirements are detailed in the following section.

6.4.2 Level 5: Performance or Risk Criteria

The performance/risk criteria implicit in the building size limits and construction requirements of the NBC are compiled and further assessed during this stage of analysis. First, the multiple semi-quantitative criteria associated with each key stage of fire growth and spread are extracted from the historical analysis in Section 6.2. Fulfilment of these criteria has led to a set of redundant strategies to limit ultimate fire size and building collapse. The strategies are not intended to be applied independently, but instead as a set of criteria to achieve a level of reliability summarized below:

1) **Sprinklers:** intended to limit fire from transitioning from early growth stages through flashover to a fully involved compartment. Sprinklers should contain fire growth to localized burning and the room of origin.
2) **Fire Compartmentation:** intended to provide fire barriers between compartments that have a fire-resistance rating correlated to the fuel load fire severity. Compartmentation should allow burn-out of combustibles within the compartment without a fire spreading to adjacent compartments.
3) **Limit Combustibility:** intended to limit the contribution of combustible construction materials to fire growth and spread. Structural stability of the building should be maintained for long enough to allow burn-out of combustibles within a compartment or storey without a fire spreading to adjacent areas.
4) **Fire Service Intervention:** limit the height and area of buildings of combustible construction (or unprotected construction) to a size that, assuming the building becomes completely involved in a fire, the responding fire service would be able to control the fire from the exterior and limit fire from spreading to adjacent buildings. For buildings larger than the capability of a fire service to control if completely involved, the construction must be such as to contain the fire to the storey of origin and to a much more limited size so that a responding fire service can enter the building, attend to the fire floor, and control the fire.

The criteria currently embodied in the NBC are structured to provide semi-qualitative performance-based guidance and requirements for fire safety design due to their historical basis and a lack of understanding of risk characterization and quantification at the time(s) of their development. Further, they have evolved through implementation of a design and subsequent measure of performance using the “test of time” to assess the functioning of that design under fire conditions. In contrast, the proposed new risk-based framework allows existing, or new, performance measures to be taken in their historical context and then combined with more in depth technical analysis to re-evaluate and reconcile designs and their fire performance within the quantified IRCC risk framework. With this approach, the present “binary” outcome expectation that a design that meets or does not meet the NBC requirements will exhibit acceptable or

non-acceptable fire safety performance would be replaced with a method by which to assess a design based on a probability distribution of outcomes as a function of key variables related to fire safety for that design.

6.5 Conclusion and Recommendations

This case study has demonstrated the use of the new framework to identify the historical basis of the requirements around building size limits and types of construction currently in the NBC. The historical information was then utilized to populate Levels 4 and 5 of the modified IRCC Framework, either in an unmodified form or in combination with technical reconciliation of certain aspects of the requirements. Populating Levels 1 to 5 of the modified IRCC Framework allows for the reconsideration of the existing requirement(s) (Level 6A) and the development of a parallel performance requirement (Level 6B). Given the significant advances in knowledge, capabilities, materials, and methods since the original development of the building size limits and construction requirements, even the preliminary assessment in this case study highlight potential reconsideration of the following:

1) The fire severity of occupancies needs to be recharacterized, not through fire loads as a function of type of occupancy, but instead via specification of design fires using the quantity, energy density, and configuration of combustible material,
2) Fire service capability needs to be re-evaluated and quantified in terms of ability to control an ultimate size of fire and ability to access and control fire within buildings to better establish ultimate building/fire compartment size.
3) Material properties and methods of protection of combustible materials need to be better defined and understood to allow technical assessment of their interactions with different fire environments and potentially facilitate broader use in construction.
4) The contribution of multiple fire protective strategies in determining overall system reliability must be quantified, particularly in light of the effectiveness of automatic sprinklers in limiting fire growth and spread at an early stage of development. For example, more in depth technical consideration of sprinklers and their impact on particular fire environments could lead to greater allowance of combustible materials or reduced fire compartmentation.
5) A holistic method(s) must be developed to characterize and quantify the risk of fire growth and spread as a function of critical factors related to building construction. In contrast to the present “test of time” approach and prolonged cycles of reflection, this would lead toward greater flexibility in development and assessment of construction requirements and prediction of fire safety outcomes across a broader range of buildings.

Chapter 7
Case Study - Spatial Separation

This final case study examines spatial separation requirements of the NBC. It provides a more complex test of the utility of the proposed framework as there is a much broader base of historical and technical context embodied in these requirements than in many of the others. In general, the spatial separation requirements began due to the conflagrations that plagued many cities up to the early 1900s. Radiant heat was identified as the dominant fire spread mechanism in these events, as it preheated and ignited combustible materials at a distance from the fire source. Early solutions designed to limit the spread of fire via radiation recognized that separation distances were needed between buildings, supplemented by use of noncombustible exterior construction. Today, these same requirements are reflected through the spatial separation requirements detailed in Subsection 3.2.3., "Spatial Separation and Exposure Protection" of the 2020 NBC [21]. They are examined in the context of the proposed new framework in this chapter.

7.1 Specification Overview

The spatial separation requirements in the 2020 NBC are primarily concerned with limiting the spread of fire between buildings by requiring minimum distances to a boundary line (i.e., property line) with those distances linked to the percentage of "unprotected" openings in a building face [Sentences 3.2.3.1.(1), 9.10.14.2.(2) and 9.10.15.4.(1) of the 2020 NBC]. The percentage of openings permitted is determined using four look-up tables in Part 3 [Tables 3.2.3.1.-B to -E] and two look-up tables in Part 9 [Tables 9.10.14.4.-A and 9.10.15.4.] of the 2020 NBC. This case study is focused on the Part 3 tables. The current tables contain prescriptive values of the percentage of unprotected openings allowed in a building or fire compartment face as a function of:

- whether or not sprinklers are provided,
- type of fire compartment occupancy,
- area of exposing building face and ratio of length to width of that face, and
- a limiting distance between the building face and a boundary line.

An example table is included in Figure 7-1. The key table parameters are highlighted in the inset and each parameter and its link to building design is discussed in more detail in the following sections.

7.1.1 Sprinklers

The four key Part 3 spatial separation tables include two for unsprinklered fire compartments [Tables 3.2.3.1.-B and -C of the 2020 NBC] and two for sprinklered fire compartments [Tables 3.2.3.1.-D and -E of

the 2020 NBC]. Sprinklered fire compartments are permitted to have a greater area of unprotected openings than unsprinklered fire compartments to recognize the benefit of sprinklers in reducing fire risk.

Exposing Building Face		Area of *Unprotected Opening* for groups A, C, D, and F, Division 3 Occupancies, %																								
Max.	Ratio	*Limiting Distance*, m																								
Area, m²	(L/H or H/L)	0	1.2	1.5	2	2.5	3	4	5	6	7	8	9	10	11	12	13	14	16	18	20	25	30	35	40	45	50
10	Less than 3:1	0	8	10	18	29	46	91	100																		
	3:1 to 10:1	0	8	12	21	33	50	96	100																		
	over 10:1	0	11	18	32	46	68	100																			
15	Less than 3:1	0	7	9	14	22	33	63	100																		
	3:1 to 10:1	0	8	10	17	25	37	67	100																		
	over 10:1	0	10	15	26	39	53	87	100																		
20	Less than 3:1	0	7	9	12	18	26	49	81	100																	
	3:1 to 10:1	0	8	10	15	21	30	53	85	100																	
	over 10:1	0	9	14	23	33	45	72	100																		
25	Less than 3:1	0	7	8	11	16	23	41	66	98	100																
	3:1 to 10:1	0	8	9	13	19	26	45	70	100																	
	over 10:1	0	9	13	21	30	39	62	90	100																	
30	Less than 3:1	0	7	8	11	15	20	35	56	83	100																
	3:1 to 10:1	0	7	9	12	17	23	39	61	88	100																
	over 10:1	0	8	12	19	27	36	56	79	100																	
40	Less than 3:1	0	7	8	10	13	17	28	44	64	89	100															
	3:1 to 10:1	0	7	8	11	15	20	32	48	69	93	100															
	over 10:1	0	8	11	17	24	31	47	66	88	100																
50	Less than 3:1	0	7	8	9	12	15	24	37	53	72	96	100														
	3:1 to 10:1	0	7	8	10	14	18	28	41	57	77	100															
	over 10:1	0	8	10	15	21	28	41	57	76	97	100															
60	Less than 3:1	0	7	8	9	11	14	21	32	45	62	81	100														
	3:1 to 10:1	0	7	8	10	13	16	25	36	49	66	85	100														
	over 10:1	0	8	10	14	20	25	38	51	67	85	100															
80	Less than 3:1	0	7	7	8	10	12	18	26	36	48	62	79	98	100												
	3:1 to 10:1	0	7	8	9	11	14	21	29	40	52	67	84	100													
	over 10:1	0	8	9	13	17	22	32	44	56	70	86	100														
100	Less than 3:1	0	7	7	8	9	11	16	22	30	40	51	65	80	97	100											
	3:1 to 10:1	0	7	8	9	11	13	18	25	34	44	56	69	84	100												
	over 10:1	0	7	9	12	16	20	29	39	49	61	74	89	100													

		0	1.2	1.5
30	Less than 3:1	0	7	8
	3:1 to 10:1	0	7	9
	over 10:1	0	8	12

Figure 7-1: A modified version of Table 3.2.3.1.-B of the 2020 NBC

7.1.2 Fire Compartment Occupancy

The occupancy classifications, Groups A through F, in the 2020 NBC are divided into two groups for the determination of the spatial separation requirements. These groups are as follows:

- **Low Hazard:** assembly (A), detention and treatment (B), residential (C), business (D) and low hazard industrial (F3).
- **High Hazard:** mercantile (E), medium and high hazard industrial (F1 and F2).

The spatial separation tables are then divided into two “low hazard” tables [Tables 3.2.3.1.-B and -D of the 2020 NBC] and two “high hazard” tables [Tables 3.2.3.1.-C and -E of the 2020 NBC]; both sets of tables account for sprinklered and unsprinklered compartments.

7.1.3 Exposing Building Face (EBF) Area and Ratio

The exposing building face area is included as a column along the left-hand side of each table (see Figure 7-1) with the “exposing building face” defined as [21, Div. A, p. 1-7]:

that part of the exterior wall of a building that faces one direction and is located between ground level and the ceiling of its top storey or, where a building is divided into fire compartments, the exterior wall of a fire compartment that faces one direction.

This definition is illustrated in Figure 7-2, showing the exposing building face in dark green. Note that the face of the attic space above does not form part of the exposing building face. The entire exposing building face area can be subdivided as a function of fire compartments, as illustrated in Figure 7-3, so that each subdivision becomes the "exposing building face" area and the permitted percentage of unprotected openings can then be determined for each fire compartment subdivision area. This approach is generally used as it tends to result in an increase of the permitted percentage of unprotected openings over using the entire building face area.

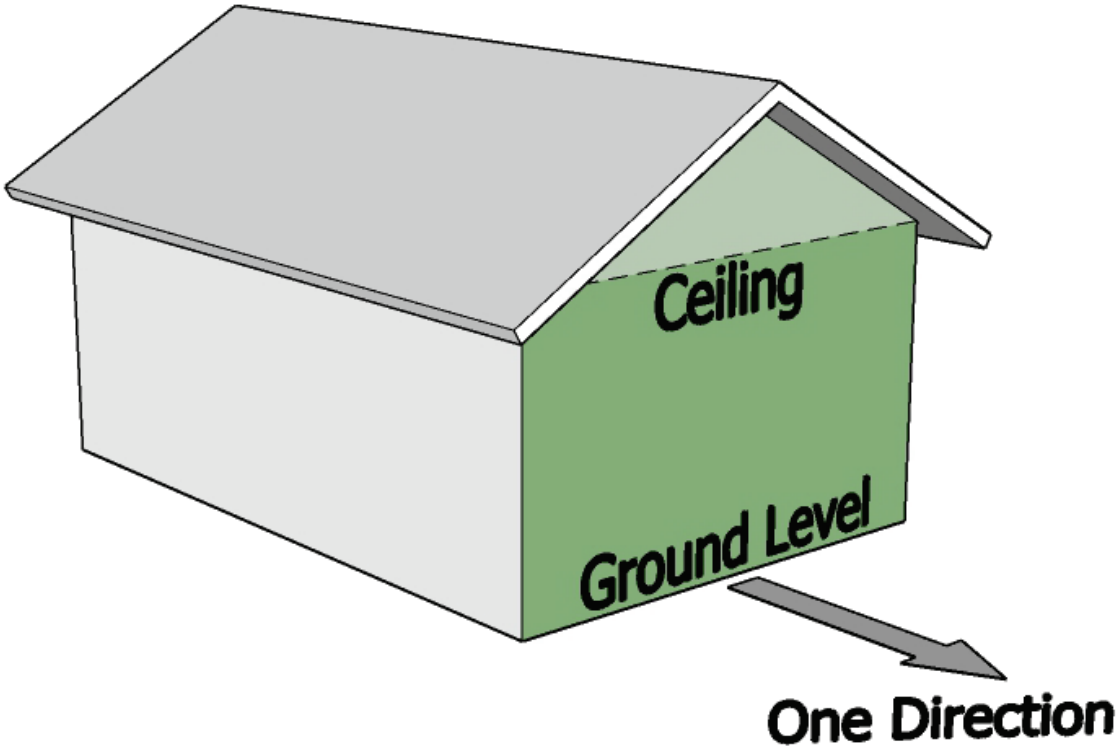


Figure 7-2: Exposing building face

The ratio of the length to width of the exposing building face, illustrated in Figure 7-4, is another input along the left-hand side of the unsprinklered tables in the column next to the exposing building face area. The ratio is based on the choice of exposing building face area, as discussed above, and will therefore be the length-to-width ratio of either the entire building face or the bounds of a fire compartment in that face, depending on the approach used. The exposing building length-to-width ratio is not a required input for the sprinklered tables.

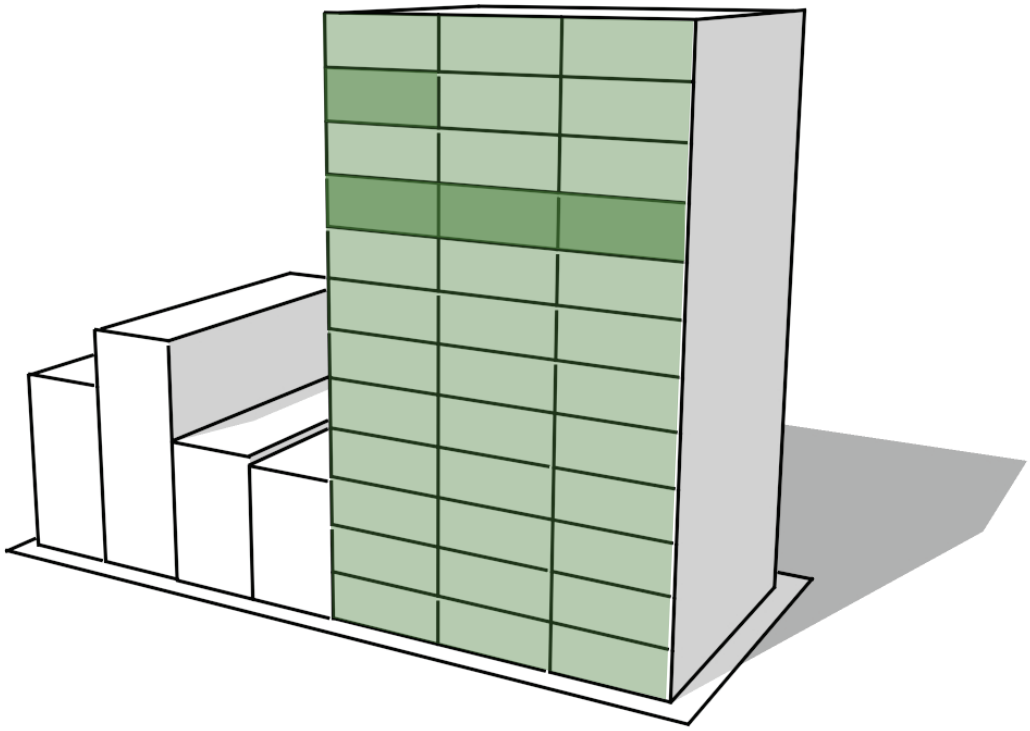


Figure 7-3: Exposing building face

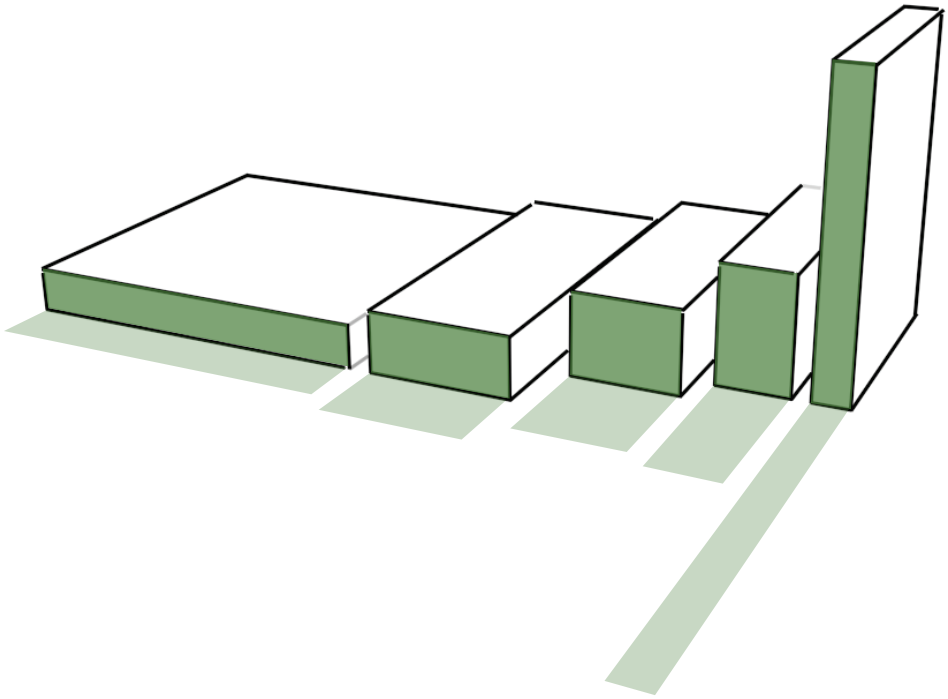


Figure 7-4: Exposing building face configuration - Ratio

7.1.4 Limiting Distance

The limiting distance is listed in a row along the top of each spatial separation table, and although it forms the basis for “spatial separation” requirements, it is an input rather than an output in the tables. This is due to the tables focusing on aiding designers to determine the percentage of openings in a building face as their output to provide a more flexible design parameter than the perpendicular distance to a property boundary. The 2020 NBC defines the “limiting distance” as follows [21, Div. A, p. 1-9]:

> *the distance from an exposing building face to a property line, the centre line of a street, lane or public thoroughfare, or to an imaginary line between 2 buildings or fire compartments on the same property, measured at right angles to the exposing building face.*

The limiting distance is illustrated in Figure 7-5, which shows three buildings. The building on the left (A) is on a separate property. The building on the right (C) is on the same property as the centre building (B). As illustrated in Figure 7-5, the limiting distance is approximately the halfway point between these buildings, shown by the arrows.

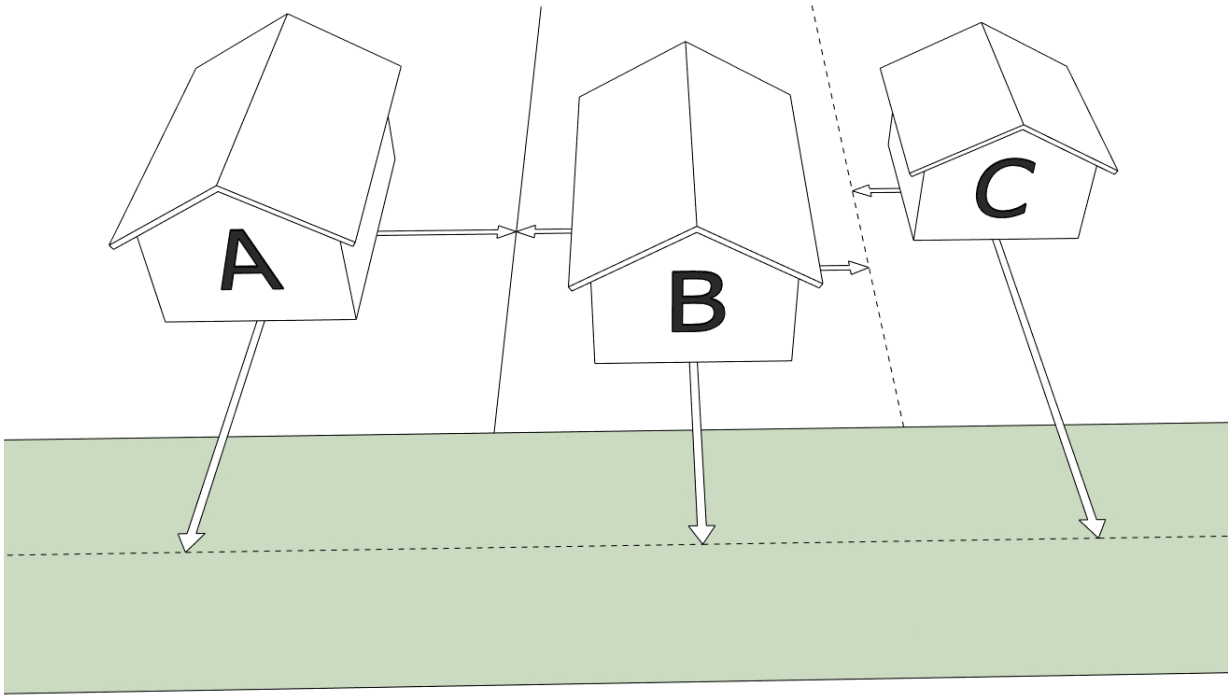


Figure 7-5: Limiting distance

7.1.5 Percentage of Unprotected Openings

Values for percentage of unprotected openings are included in each spatial separation table for all buildings except houses, where they are expressed as a percentage of glazed openings. The 2020 NBC defines the “unprotected opening” as follows [21, Div. A, p. 1-13]:

a doorway, window or opening other than one equipped with a closure having the required fire-protection rating, or any part of a wall forming part of the exposing building face that has a fire-resistance rating less than that required for the exposing building face.

Examples of unprotected openings are highlighted in green in Figure 7-6. The 2020 NBC does not define glazed openings, but the handbook to Part 9 of the NBC describes a glazed opening as follows [340, p. 151]:

The area of glazed openings is measured to the rough opening of the window or door, not to the edges of the glazing.

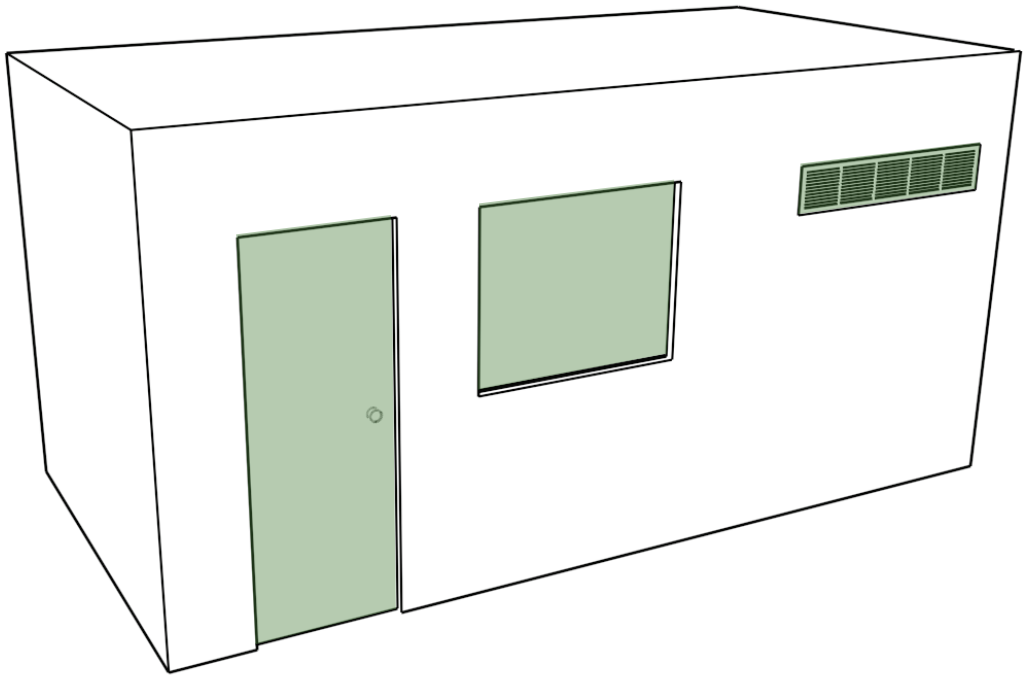


Figure 7-6: Unprotected openings

7.1.6 Table Use

The use of the spatial separation tables requires the input parameters defined above. For example, for a building with an exposing building face area of 18 m², exposing building face length to width ratio of 4:1, and limiting distance of 3 m, the permitted percentage of unprotected openings is 30%, as illustrated in Figure 7-7.

Linear interpolation of table values is permitted in practice [341], although this is not explicitly stated in the NBC. Using the same values from the example above and the interpolation equations included in Appendix A, a more precise percentage of unprotected openings in the case above is 32.8%, 2.8% greater than that determined directly from the spatial separation table. This illustrates the impact of the

simplification of a complex solution to generate the existing spatial separation look-up table values in the NBC.

Exposing Building Face		Area of *Unprotected Opening* for gr											
Max.	Ratio	*Limit*											
Area, m²	(L/H or H/L)	0	1.2	1.5	2	2.5	(3)	4	5	6	7	8	9
10	Less than 3:1	0	8	10	18	29	46	91	100				
	3:1 to 10:1	0	8	12	21	33	50	96	100				
	over 10:1	0	11	18	32	48	68	100					
15	Less than 3:1	0	7	9	14	22	33	63	100				
	3:1 to 10:1	0	8	10	17	25	37	67	100				
	over 10:1	0	10	15	26	39	53	87	100				
(20)	Less than 3:1	0	7	9	12	18	26	49	81	100			
	3:1 to 10:1	0	8	10	15	21	(30)	53	85	100			
	over 10:1	0	9	14	23	33	45	72	100				
25	Less than 3:1	0	7	8	11	16	23	41	66	98	100		
	3:1 to 10:1	0	8	9	13	19	26	45	70	100			
	over 10:1	0	9	13	21	30	39	62	90	100			

Figure 7-7: Spatial separation table use

7.1.7 Objectives, Functional Statements and Intent Statements

The objective and functional statements attributed to the spatial separation table requirements are [21]:

Objective – OP3.1 [21, Div. A, p. 2-5]: to limit the probability that, as a result of the design or construction of the building, adjacent buildings will be exposed to an unacceptable risk of damage due to fire. The risks of damage to adjacent buildings due to fire addressed in this Code are those caused by fire or explosion impacting areas beyond the building of origin.

Functional Statement – F03 [21, Div. A, p. 3-1]: To retard the effects of fire on areas beyond its point of origin.

The intent of this requirement is to [131, p. 313]:

> *To limit the probability of the spread of fire from the building to an adjacent building during the time required for emergency responders to perform their duties, which could lead to damage to adjacent buildings.*

No further basis for the spatial separation requirements is identified in the NBC. Therefore, the following section uses the proposed new historical analysis sub-framework to review and identify the historical basis of these requirements.

7.2 Historical Analysis

The historical development of the spatial separation requirements is likely one of the longest in the NBC, since it spans approximately 2000 years (briefly discussed in Section 2.1.1.) as detailed in the following sections.

7.2.1 Early Development

The driving force behind the development of early building regulations was fire spread from building to building which had resulted in significant city-wide conflagrations. Several significant conflagrations occurred in Rome in 64 AD, London in 1189 and 1666, and Canada and the US in the late 1800s and early 1900s, with the fires characterized by significant building-to-building fire spread, primarily driven by radiant heat transfer and ignition by brand spotting (airborne embers).

In response to the potential for a city-wide conflagration, buildings of combustible construction were restricted in built-up city centres. The boundaries of the restricted areas were defined with reference to particular streets (fire limits); however, this approach could be quite complex. Regulations setting fire limits were established in the City of New York as far back as the 1760s [342], and have been referenced as recently as the 1960s in Canadian city building bylaws [343]. The 1874 fire limits map of Toronto is shown in Figure 7-8.

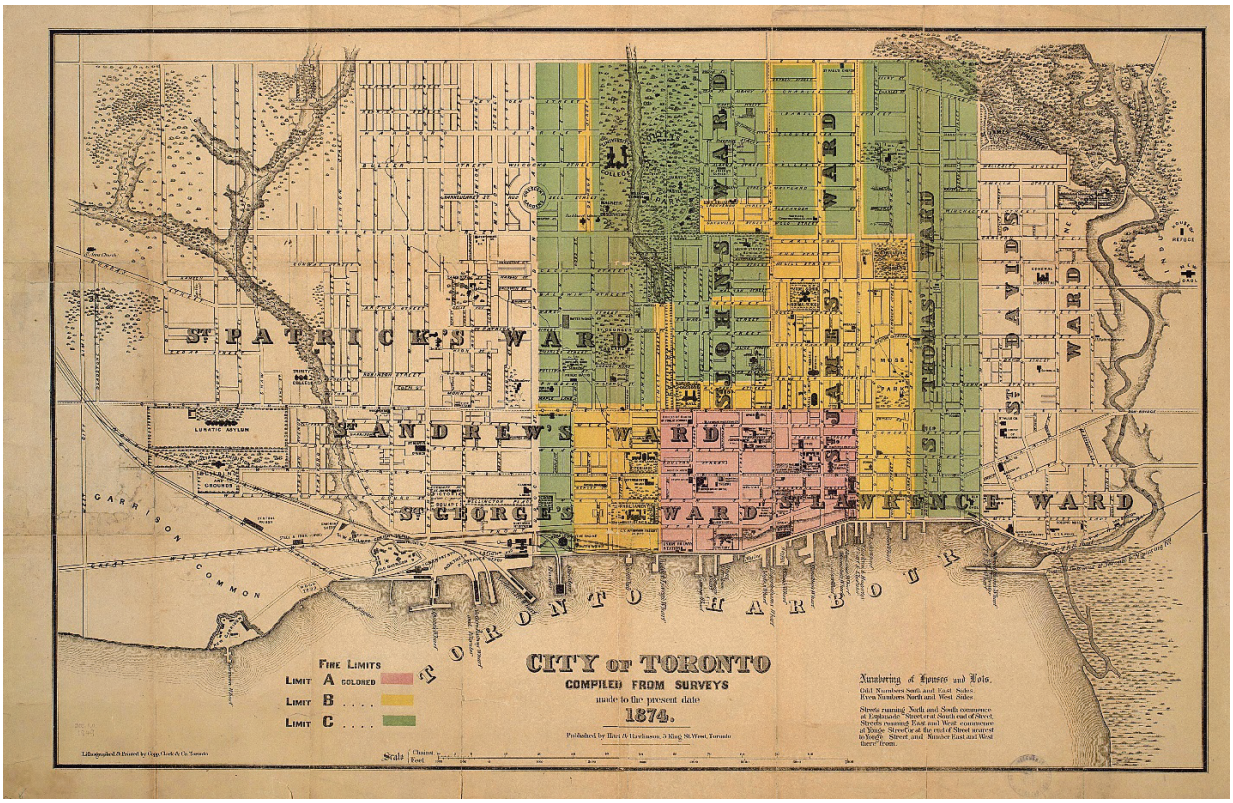


Figure 7-8: 1874 fire limits map of the City of Toronto [344]

A partial description of the “First Class Fire Limits” for the City of Calgary in 1913 illustrates the complexity of these regulations [99, pp. 94, 95]:

> *(a) The First Class Fire Limits will be property within the following limits -*
>
> *The following defined area of the City of Calgary shall be known as the First Class Fire limits, that is to say, all the area lying within the following boundaries, namely: -*
>
> *Commencing at the intersection of 6th Ave. and a point 125 feet West of 4th St. W., running easterly along 6th Ave., to the intersection of 2nd St. E. and 6th Ave., thence southerly along 2nd. St. E. to the intersection of 7th Ave. thence easterly alone 7th Ave. to the intersection of 4th St. E. thence southerly on 4th St. E. across the C.P.R. Right-of-way to the intersect ion of 11th Ave. and 4th St. E. thence westerly on 11th Ave. to the intersection of 4th St. W. thence northerly across the C.P.R. Right-of-way to the intersection of 9th Ave. thence westerly on 9th Ave to the intersection of 7th St. and 9th Ave. thence northerly on 7th St. W. to the intersection of 8th Ave. thence easterly to a point 125 feet west of 4th St. W. and 8th Ave. thence northerly to point of commencement.*
>
> *(b) Commencing at the intersection of 6th Ave. and the West line of Centre St. running westerly 125 feet thence northerly to the north line of 1st Ave and thence easterly to 125 feet east of Centre St. thence southerly to the intersection of 6th Ave.*
>
> *(c) Commencing at the intersection of 11th Ave and the west street line of 1st St. W. running westerly 125 feet thence southerly to the intersection of 17th Ave. thence easterly to 125 feet east of the easterly street line of 1st St. W. and running northerly to the intersection of 11th Ave thence west to point of commencement.*

Even with fire limits, conflagrations still occurred [12], primarily due to rapid city growth and the challenges of enforcing appropriate construction within the limits. Furthermore, the complexity of fire limit descriptors made them difficult to maintain, as illustrated by the examples above for Calgary and Toronto. As a result, fire limits are no longer utilized in a regulatory context in the NBC or the associated provincial/territorial building codes.

Insurance rating agencies recognized that a key challenge in protecting exposures within a neighbourhood or city was managing the fire hazards that extend beyond individual buildings. To address this, they set rates based not only on the characteristics of a defined “standard building” but also on those of a “standard city,” which accounted for broader factors such as firefighting capability, water supply, and exposure conditions. Therefore, assessing the exposure conditions of an individual building also necessitated an understanding of the characteristics of neighbouring buildings.

In the early 1900s, approximately 30% ($50,000,000) of all fire losses were a result of exposure fires [345]. To address such a large proportion of losses, the insurance rating system (Schedule) addressed building exposure in great detail with formulas and tables. The consideration of individual building exposure risk and associated insurance rates was complicated by the exposure risk to and from neighbouring buildings, in addition to all the factors associated with the degree of exposure. Since

insurance rates were established on a comparative (ratio) basis as a function of standard building characteristics (Section 2.1.3.1) and standard city characteristics, the “cause and effect” of the exposure hazard between buildings resulted in “numerous ratios and ratios of ratios” [346, p. 3].

For analysis of separation in the context of insurance rating, Dean recommended three classifications of exposure [346]:

1) Radiated exposure: the proportion of exposure hazard from one building to adjacent buildings.
2) Absorbed exposure: the proportion of exposure hazard absorbed by a building from an adjacent building.
3) Transmitted exposure: the proportion of exposure hazard a building absorbs from one side and transmits to adjacent buildings on the other side.

He further noted that “radiated, absorbed and transmitted exposure are all modified by structure [type of construction], clear space and fire department protection” [346, p. 3]. The following additional factors were also considered in the modification of the exposure hazard in the determination of insurance rates:

- occupancy classification,
- exposure configuration (wall length, width and angle), and
- provision of sprinkler protection.

A standard exposure rate was established and then modified as a function of the factors above for the building of interest, as well as the neighbouring buildings. In this manner, the insurance rating schedule identified key exposure risk factors based on fire loss statistics that would carry forward into regulatory development.

7.2.2 1941 NBC

The 1941 NBC included a reference to “fire zones,” structured similarly to fire limits, as outlined above. Three zones were defined [105]: Zone 1, being the most built-up area, had the most restrictive construction, requiring primarily noncombustible buildings [105]. Zone 2 served as an intermediate zone, predominantly featuring mid-rise buildings and acted as a buffer between Zones 1 and 3. Zone 3, which included one- and two-family dwellings and small retail buildings, permitted any construction type that complied with the 1941 NBC.

While the zone-based approach was derived from the earlier, and at the time, well established fire limits strategy, it was also too complicated to apply and to maintain in regulations. To address these complexities, the 1941 NBC also limited exterior wall construction and percentage of aggregate area of openings as a function of the distance to a property boundary and the location of the exterior wall (i.e., front, rear). In this way, then, while the 1941 NBC maintained concepts similar to fire limits, it also introduced an approach that did not depend on defined fire limits or on knowledge of the location and construction of neighbouring buildings. As such, it moved away from the fire limits and insurance rating approaches and

instead provided a “building independent” means to address exposure risk, where only the characteristics of the building at hand were required. These approaches persisted until the 1953 NBC, where a more scientific-based approach was adopted through physical and spatial fire separation requirements to limit fire spread to within a building. As a result, zone-based requirements were considered redundant.

7.2.3 1953 NBC: Science-Based Approach

During the Second World War, the UK undertook “Post-War Building Studies” at the request of professional and other institutions to address problems expected to impact peace-time (post-war) buildings [347]. These studies addressed a variety of building issues and construction types. One of the reports titled, “Post-War Building Studies No. 20, Fire Grading of Buildings, Part I, General Principles and Structural Precautions,” was published in 1946 and was intended to [347, p. 6]:

> *review the underlying principles of fire protection in buildings, so far as existing knowledge permits, and to present the results in the form of recommendations.*

This included an examination of the exposure hazard and building independent strategies to limit fire spread between buildings. There was limited knowledge and data at the time to quantify the exposure fire hazard, which was qualitatively characterized through identification of the key modes of fire spread and factors impacting the degree of hazard. The key modes of fire spread were identified to be radiated heat, direct flame impingement, and flying brands.

It was determined that the hazards of direct flame impingement and flying brands could be addressed through limits on type of exterior construction, whereas radiated heat was considered the more dominant hazard requiring further regulatory development. The factors considered key to the magnitude of the exposure hazard from radiated heat were building occupancy, building size, type of construction, amount of window openings, and distance between the buildings [347].

A method to quantify the degree of exposure hazard was developed by measuring temperatures at various distances from a fire and comparing them to the standard time-temperature curve used in determination of fire-resistance ratings. The appropriate grade of protection could then be provided through space separation between buildings, wall and roof covering construction, protection of openings, sprinkler protection, and/or firefighting intervention [347].

The post-war building studies advanced understanding of the key physical parameters underlying exposure hazards and identified key fire safety strategies to mitigate their impact.

A subsequent UK study, “Radiation from Building Fires,” in 1950 [109] further developed the concepts introduced in the post-war study through the quantification of several factors associated with the magnitude of radiant heat exposure from a fire, expressed in Equation 7-1 [109].

$$I = \phi \cdot \varepsilon^* \cdot T^4 \qquad \text{Equation 7-1}$$

Where:

I = Intensity of radiation (kW/m²)
ϕ = Configuration factor
ε^* = Coefficient of emission[11] (kW/m²·K⁴)
T = Emissive source temperature (K)

Applying this equation to a building fire where heat radiates from window openings, the intensity of radiation at a point (I) is a function of the configuration of the point relative to the window (ϕ), fire temperature (T), and coefficient of emission (ε^*). Assuming constant fire temperature and emissivity for all fires, the radiant intensity is then primarily governed by the configuration factor. The configuration factor ranges between 0 and 1 and represents the fraction of heat from a source (fire) to a point (exposed), determined as a function of the geometrical configuration and distance between them.

The temperature of a building fire was assumed at the time to be 1000 °C, and the emissivity was assumed to be that of a "black body." These assumptions have since been validated through testing [349]. The critical configuration factor was then established through experiments that measured the temperature of a gold disk at a distance from a fire. Temperature was then related to observed heat effects on a wood surface located in proximity to the gold disc. The recorded temperatures and observed radiant heat impact on the wood surface are listed in Table 7-1 [109].

Table 7-1: Recorded temperatures and observed wood surface heat effects

Gold Disc Temperature (°C)	**Configuration Factor**	**Wood Surface Observation [109, p. 4]**
100	0.031	"slight flow of resin occurred over the heated surface of the timber"
150	0.056	"considerable flow of resin"
200	0.082	"severe charring of the whole exposed surface"

The gold disc temperature of 150 °C was selected as a reasonable maximum exposure below which wood was considered unlikely to ignite. As shown in Table 7-1, the critical configuration factor of 0.056 was associated with this threshold. Both the assumed fire temperature and associated critical configuration factor were validated through observations of burn damage to wood window frames in two fire incidents [109].

The number and variation of potential window configurations were considered to be a complication in the practical application of the critical configuration concept. This was addressed by implementing an assumption that the entire exterior wall of the building be treated as a single source of radiation. The

[11] Note that at the time of preparation of the study of "Radiation of Building Fires," the emissivity (ε) and the Stefan-Boltzmann constant (σ) were considered together in the coefficient of emission (ε^*) [348].

radiant intensity associated with that wall was then reduced by the percentage of the wall area that contained windows in that exterior face. This is the “grey radiator approximation.”

Between 1953 and 1957, the UK Department of Scientific and Industrial Research and Fire Offices’ Committee and the Joint Fire Research Organization conducted further studies on configuration factors [350, 351], the ignition of wood [352, 353], and enhancements to the gold disc radiometer for more accurate heat flux measurements [354]. These studies determined that the piloted ignition threshold for wood was 0.3 cal/cm²·s (12.5 kW/m²) [352].

Based on the recommendations in the UK National Building Study of “Radiation from Building Fires” [109], the 1953 NBC further departed from the 1941 NBC approach of controlling fire exposure hazards through fire zones/limits. Instead, it shifted to the building independent approach based on radiant intensity of the fire, whereby building separation distances were derived as a function of fuel load and corresponding fire-resistance ratings. This was achieved by establishing source temperatures as a function of the time-temperature curve and then determining distances at which wood materials are not likely to ignite when exposed to these source temperatures. The results of this assessment are shown in Table 7-2 [108, 355].

Table 7-2: Correlation between fire-resistance and distance

Fire Load (lbs/ft²)	Equivalent Fire-Resistance	Absolute Distance (ft)	Distance to Lot Line (ft)
10	1-hour	30	15
20	2-hours	40	20
30	3-hours	50	25

The 1953 NBC allowed the application of these solutions either individually or in combination to limit fire spread between buildings. For example, according to Table 7-2, a residential building (Group C) with a 10 lb/ft² fuel load would require a 1-hour exterior wall fire-resistance rating (for burn-out) if there was no separation to the lot line. If there was a 15 ft distance to the lot line, no exterior wall fire-resistance rating would be necessary. The 1953 NBC also permitted combinations of a fire-resistance rated exterior wall and separation distance.

Openings were also permitted in the exterior walls of buildings for up to 20% of the exterior wall area when an additional spatial separation equal to half the distance specified in Table 7-2 was provided, or up to 100%, when the separation distance exceeded those specified in Table 7-2. For example, a residential building (Group C) with 20% openings in its exterior wall required a 1-hour fire-resistance rating and a 7.5 ft distance from the property line.

This new regulatory approach was based on application of contemporary advancements in scientific knowledge around radiant heat transfer, allowing the development of a building independent approach to spatial separation. Further advancements to this approach were then developed and incorporated into later versions of the NBC through full scale testing, discussed in more detail in the following section.

7.2.4 1960 NBC: St. Lawrence Burn Tests

A series of burn tests were undertaken in the late 1950s in abandoned structures expropriated by the Ontario Hydro Electric Power Commission during the development of the St. Lawrence Power project [356]. These tests, the St. Lawrence burn tests, informed further development of the NBC by examining fire growth and spread within buildings with particular focus on occupant survivability, ventilation rates, and spread of fire by radiant heat [357]. Prior to planned flooding for the project in 1958, the Fire Section of the Division of Building Research of the National Research Council conducted burn tests in eight full-scale buildings in the village of Aultsville, located on the north bank of the St. Lawrence River [357]. The fire tests were conducted in six two storey houses and two larger structures (a school and community hall) [357]. Members of the Joint Fire Research Organization (JFRO) of the UK participated in the testing and analysis of the results [358]. Of particular interest with respect to spatial separation requirements within the NBC are those portions of the tests related to the spread of fire by radiant heat [357]. In this context, relevant results include:

- Radiation intensity at a distance from the fire source.
- Radiant temperature at the openings of a burning building.
- The flame front distance from the openings in a building face.

These results will be discussed here since the spatial separation requirements of the NBC were almost exclusively based on these results, specifically from fire tests conducted in Building Nos. 4 and 5. These were residential buildings (Figure 7-9 and Figure 7-11 respectively), two storeys in height, with similar areas. The test layouts for Building Nos. 4 and 5 are shown in Figure 7-10 and Figure 7-12 respectively. Each layout shows the ground floor on the left and the “first” floor (second storey) on the right. The walls are highlighted in grey, the window openings are highlighted in blue, and the exterior doors are highlighted in green.

All windows and exterior doors in Building No. 4 were closed at the start of the test. The back exterior door on the ground floor of Building No. 5 was open at the start of the test.

The combustible fire load for Building Nos. 4 and 5 is listed in Table 7-3, representing the average residential fire loading at the time [251], was concentrated in the living room of each building respectively. These locations are highlighted orange in Figure 7-10 and Figure 7-12. The fire load of the combustible interior finish in Building No. 5 was not quantified, nor was any fuel load due to floor material reported for either building. The recorded fuel load consisted of two hemlock based wood cribs with a density of 29 lb/ft^3 for a combined weight of 670 lbs. A photograph of one of the cribs is shown in Figure 7-13. Crumpled paper in the base of the wood cribs was ignited using rolled-up paper. The timer for each test was not started until it was confirmed that ignition of the cribs had occurred and fire was established [357].



Figure 7-9: Building No. 4 [359]

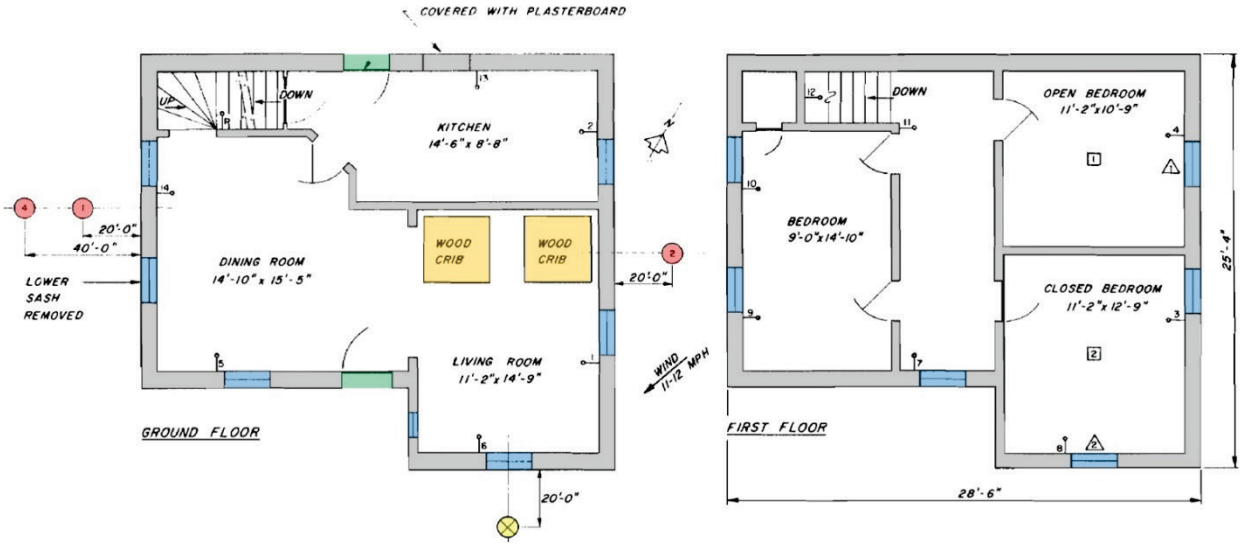


Figure 7-10: Burn No. 4 layout [357]



Figure 7-11: Building No. 5 [360]

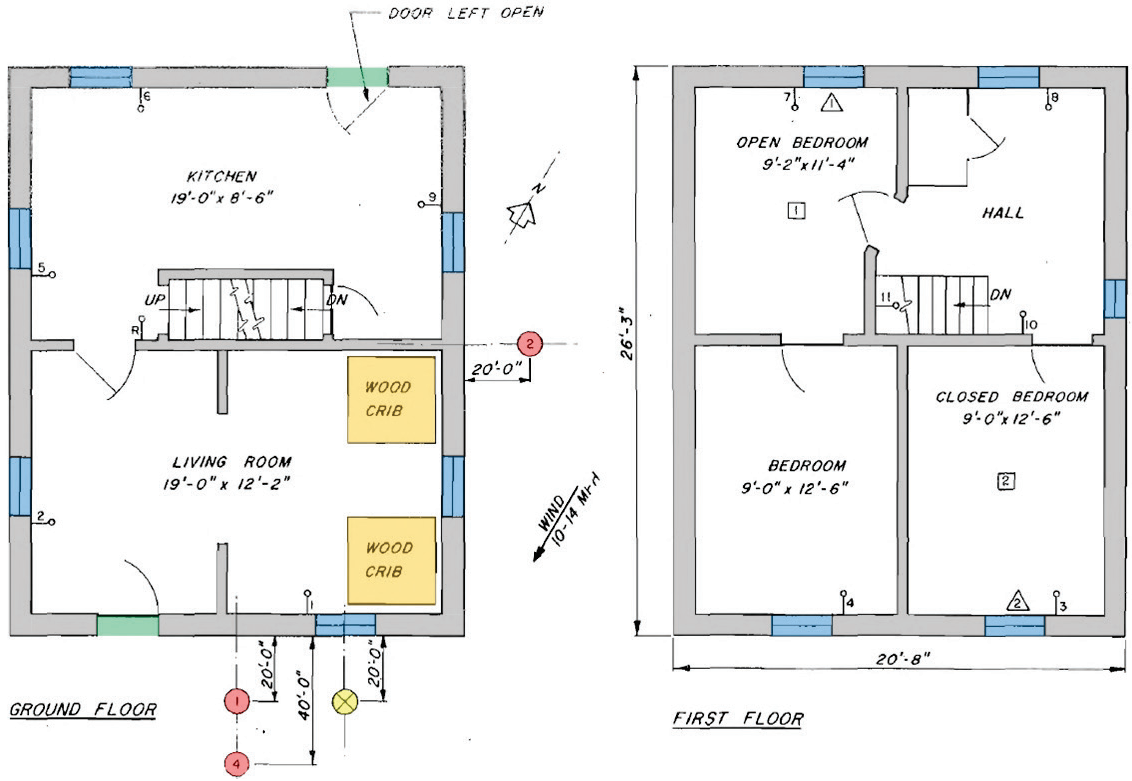


Figure 7-12: Burn No. 5 layout [357]

Table 7-3: Fire load

Building No.	**Net Floor Area, Room of Origin (ft²)**	**Wood Crib Fire Load (lb/ft²)**	**Average Survey Fire Load (lb/ft²)** [251]
4	Dining room – 209 Living room – 165 Total - 374	1.8	3.5
5	Living room – 227	3.0	3.9



Figure 7-13: Fire load – wood cribs [361]

The British JFRO developed [354], provided, and operated radiometers, shown in Figure 7-14, to measure the radiant heat from the fires in each of the burn tests [357, 362]. These consisted of two gold receiving discs in a heavy brass body that limited the rate of rise of the body temperature relative to the gold discs [362]. The primary blackened gold disc was located behind a thin mica cover and had a thermocouple attached. A second gold disk was mounted within the sensor body as a cold junction. Given the custom nature of the radiometers and short supply timeline, their sensitivity to wind was not examined prior to the tests [362].

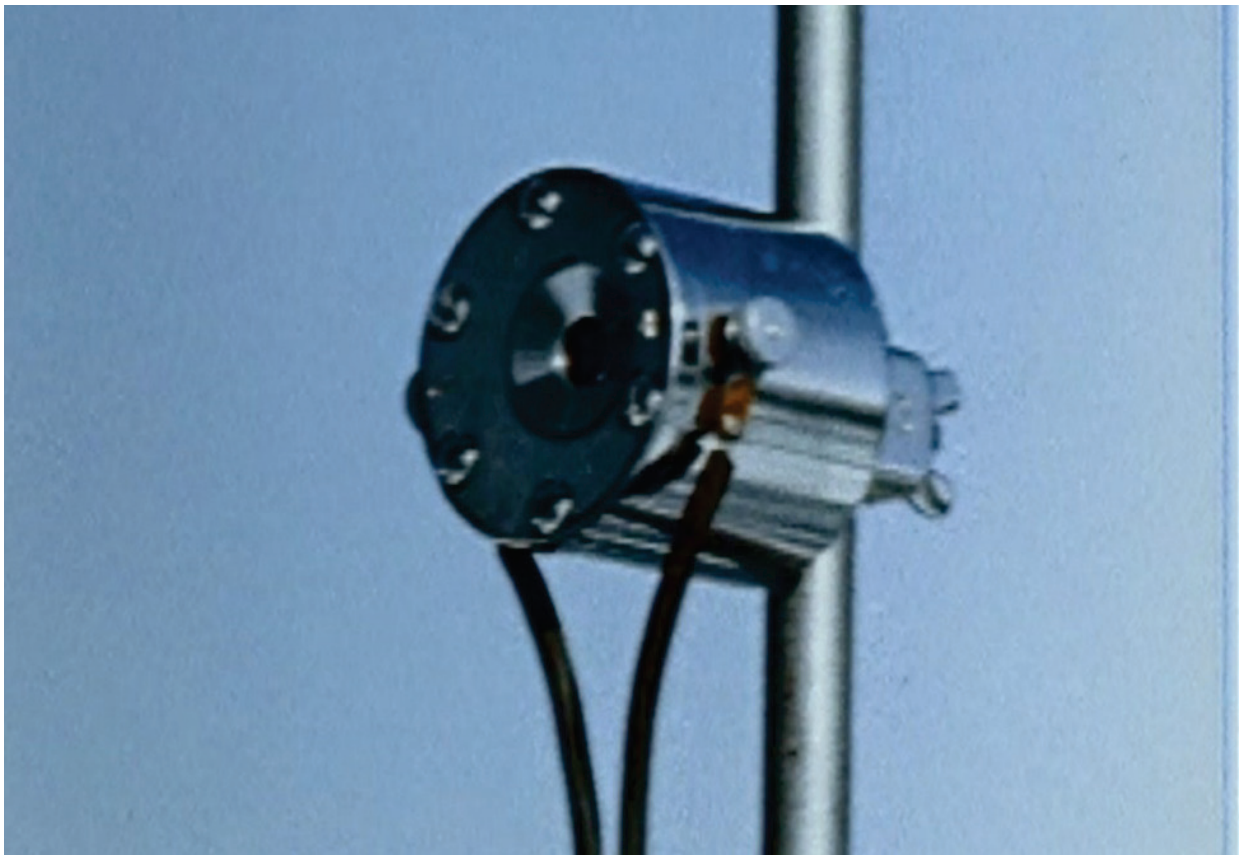


Figure 7-14: Radiometer [361]

The location of the radiometers relative to Building Nos. 4 and 5 are shown highlighted red in Figure 7-10 and Figure 7-12 respectively. They were located at the centre of each wall they faced, and were mounted on stands at 10 feet in height for those located 40 feet from the test building face, and at 15 feet in height for those located 20 feet from the test building face.

Thermopile radiometers were also used “to measure the equivalent black body temperature of a window where the fire started” [349, p. 5]. These are highlighted yellow (circle with an X in the centre) in Figure 7-10 and Figure 7-12.

Thermocouples were installed within the compartments in Buildings 4 and 5 to measure temperature, as indicated by the combined circle and lines symbol (o--), shown adjacent to walls in Figure 7-10 and Figure 7-12, respectively. Each thermocouple was positioned 4 feet above the floor and 8 inches from the wall [357]. The thermocouples located at the base of each stair were positioned at ceiling level.

The environmental conditions were recorded during each test and are detailed in Table 7-4. For Building No. 5, it was noted that “the weather had deteriorated badly” [357, p. 24], resulting in frequent wind gusts as the test progressed.

Table 7-4: Environmental conditions during testing

Building No.	Temperature (°F)	Relative Humidity (%)	Wind	
			Direction	Speed (mph)
4	20	60	NE	11-12
5	18	95	N	10-14 (frequent gusts)

7.2.4.1 Test Results

Fire tests were conducted in Building Nos. 4 and 5 on January 15 and 16, 1958, respectively. Instrumentation installed in the test buildings captured data on temperature, smoke, gas concentration, ventilation rate, and sound [349, 357, 362-368]. The National Film Board of Canada filmed the tests, while visual observations were conducted by staff from the Fire Section of the Division of Building Research at NRC.

Results of these tests were documented in reports, which include data plots but without listings of the original raw data. Therefore, to extract information from the plots for this analysis, a software tool, WebPlotDigitizer [369], was employed to enable additional analysis of the historical data.

General Results and Observations

The fire developed rapidly in Building No. 5 and spread to involve the entire structure within a short period of time in comparison to the fire in Building No. 4. For context, a side-by-side comparison showing exterior fire extension from each building at 11 minutes is shown in Figure 7-15 and at almost 16 minutes in Figure 7-16.



(a) (b)

Figure 7-15: 11 minutes, (a) Building No. 4 [359], (b) Building No. 5 [360]



(a) (b)

Figure 7-16: 15 minutes, 49 seconds, (a) Building No. 4 [359], (b) Building No. 5 [360]

Key time-based observations made by NRC Fire Section staff are detailed in Table 7-5 [357].

Table 7-5: Key visual observations

Key Observation	**Time (min:sec)**	
	Building No. 4	**Building No. 5**
Flame coming out of front living room Window	11:00	08:00
Exterior cladding ignited	13:00	08:25
Ceiling temperature at foot of stairs is 900 °F	11:00	02:30
Front wall completely involved in fire	31:30	14:00
Flame front extension (The flame front for Building No. 5 at approximately 11 minutes is shown in Figure 7-17.)	32:00 (10 ft)	09:15 (4 ft) 11:00 (7 ft) 12:00 (10 ft) 15:00 (15 ft)

In addition to these, the following general observations were noted [368]:

- Buildings lined with combustible material in the testing had radiation levels twice as high as those with noncombustible linings.
- If 'I' represents the radiation intensity at a distance from a building and 'F' is the configuration factor of the openings at the measurement point, then the ratio 'I/F' provides a convenient means to compare radiation levels across different buildings.
- During peak radiation periods, the radiant heat directly emitted from openings in the exterior walls was significantly lower than that emitted from the flames above and around the windows.

- Peak radiation levels were recorded after approximately 16 minutes.
- Wind had an impact on the radiant heat levels, but the results were insufficient to quantify the effects. Recorded wind speeds ranging from 10 to 14 mph could have significantly impacted the burning rate.
- Combustible exterior siding did not appreciably increase the maximum radiation levels.



Figure 7-17: Building No. 5 flame front at approximately 11 minutes [360]

Room Temperatures

Figure 7-18 shows the temperature results for thermocouples located above the wood cribs, at the foot of the stairs leading to the upper floor, and throughout the ground floor. Temperature data for Building No. 5 is represented in red, while Building No. 4 is shown in blue. Solid lines represent the temperature above the wood cribs, which is similar for both tests. Dashed lines indicate the temperature at ceiling level at the foot of the stairs to the upper level.

The stair temperature in Building No. 5 is comparable to that in Building No. 4 during the first 1 to 2 minutes. However, by 6 minutes, the temperature in Building No. 5 has increased to approximately 1000 °F (538 °C), which is double the temperature recorded in Building No. 4. A similar trend is observed in the general floor area, where the temperature in Building No. 5 is roughly twice that of Building No. 4, although it remains lower than the temperature measured at the foot of the stair. This result aligns with

expectations, as the general floor area temperature represents an average of all thermocouples on the ground floor.

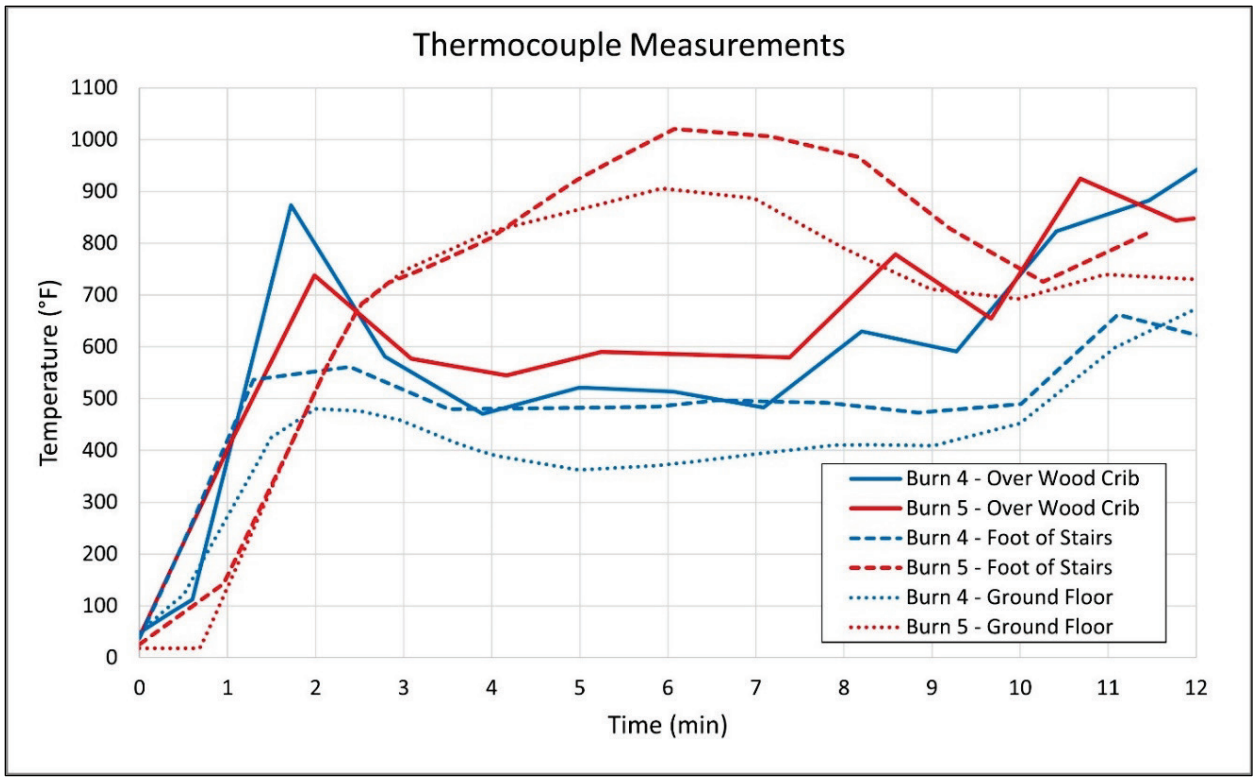


Figure 7-18: Plot of room temperatures

Radiant Temperature of Openings

The results of the thermopile radiometers were analyzed to establish the radiant temperature of window openings during the tests. It was found that the temperatures ranged between approx. 200 and 1000 °C as a function of the degree of fire development and degree of smoke obscuration at the window opening. The radiant temperature of window openings for buildings with combustible interior finish reached higher values sooner than for buildings with noncombustible interior finish [349]. The radiant temperature for Building No. 5 was also generally lower as a result of smoke obscuration at the openings during the test.

The calculated radiant temperature reached 1003 °C in one test (Building No. 2) for a brief period of time but remained below 1000 °C for the remainder of the test and in all other tests [349]. These results validate the assumption outlined in Section 7.2.3, that windows in a fully involved compartment fire can be assumed to radiate heat as a black body at 1000 °C [349].

Incident Heat Flux

The results from the radiometers located 20 ft and 40 ft from the front of Building Nos. 4 and 5 are shown in Figure 7-19. Results for Building No. 5 are shown in red, and those for Building No. 4 are shown in blue. Solid lines indicate readings at 20 ft, while dashed lines represent readings at 40 ft from the front of each building. As expected, the measured radiant intensities at 40 ft are lower than those at 20 ft, consistent

with the inverse square law, since measured radiant intensity decreases proportionally to the square of the distance from the fire. The radiant intensity measured during Building No. 4 tests are approximately half of those measured for Building No. 5, with delayed growth and peak phases compared to the results for Building No. 5. These values are later used to determine the radiant emissivity of the fire using the geometrical relationship between the radiometer and the openings in the building façades (configuration factor).

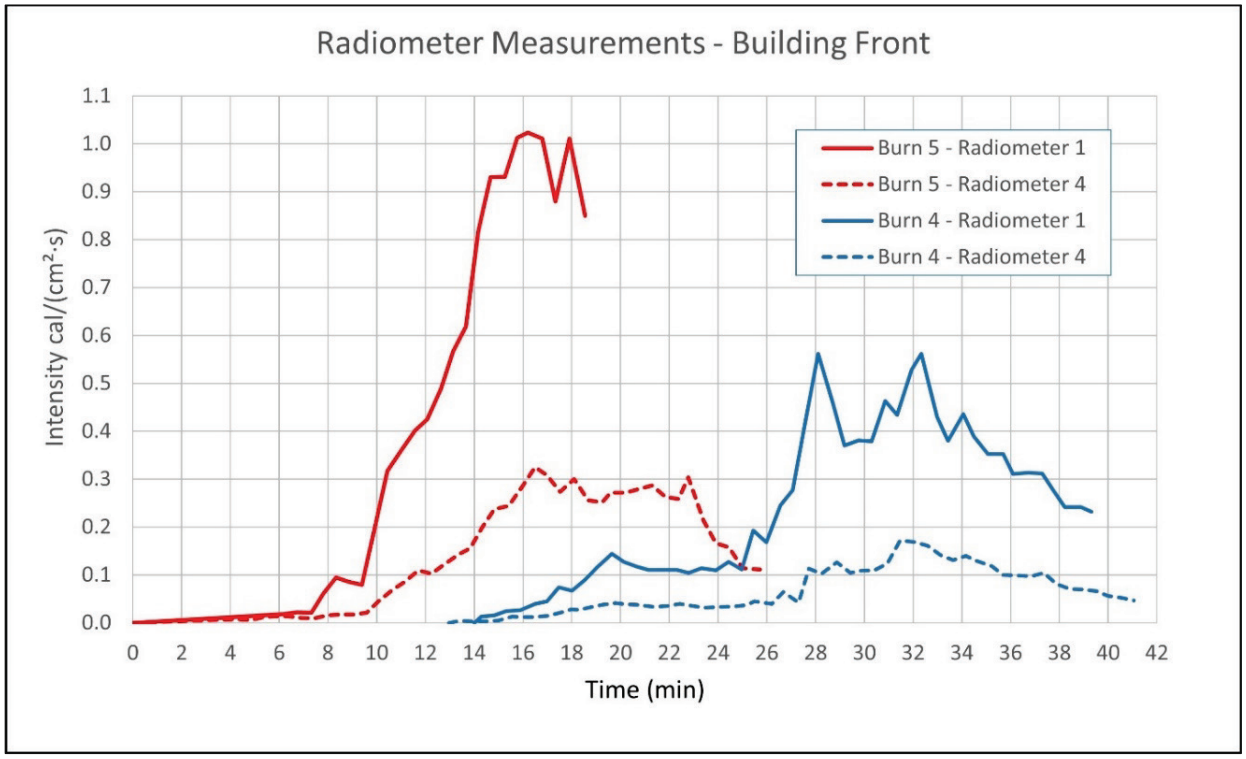


Figure 7-19: Plot of heat flux at radiometers

7.2.4.2 Regulation Development

Results of the tests in Building Nos. 4 and 5 were used in the development of the spatial separation requirements in the NBC, with intent to provide a more technical basis for the building separation requirements than used in the 1953 NBC. However, the detailed results from the tests were complex and needed to be simplified and then expressed in a concise regulatory format that could be applied broadly to building design and construction. This required a series of assumptions, simplifications, and analyses of the data, presented here in a format consistent with the regulatory risk paradigm that was proposed in Section 4.2, for ease of discussion in the following sections. In this context, the steps undertaken in the original analysis entailed defining:

1) the radiant emissive power of the fire (characterization of the hazard),
2) the incident radiant heat exposure below which a building is not likely to ignite, to define the acceptable threshold exposure value (characterization of the exposed), and

3) a simplified means to analyze the relationship between the radiant emissive power and the incident heat flux at a distance from a burning building (relationship between the hazard and the exposed), in order to develop the final spatial separation regulations put forward in the NBC at that time.

Characterization of the Hazard (Source Radiant Emissive Power)

The exposure hazard was characterized through analysis of the radiant emissive power from the openings in the face of each test building. This was taken as the black body temperature of the openings, assuming that the openings were the only emitting source. However, this was not considered representative of the real exposure due to the degree of flame extension from the openings observed during the tests. Instead, the exposure hazard was characterized based on analysis of the radiometer measurements accounting for the position of the radiometer relative to the building face. To fully analyze the measurements, an understanding of the geometrical relationship between the flaming zone of the fire and the radiometer was required; however, determination of this was challenging due to the varying flame area and extension over time, as illustrated for Building No. 5 in Figure 7-16(b) and Figure 7-17. Thus, the analysis was simplified by assuming that the heat flux measured by each radiometer originated only from the openings in the face of each building (i.e., windows and doors), to allow a simpler geometrical representation of the fire (emitting source).

With the assumption that the radiant emissive power originates solely from the openings, a straightforward geometrical (configuration factor) analysis was undertaken. Configuration factors between the openings in the face of each building and the radiometer were calculated and coupled with the measured radiometer data to determine the emissive power at the openings. The geometrical configuration factors used in this analysis are shown in Table 7-6 [368, 370].

Table 7-6: Calculated configuration factors for Building Nos. 4 and 5

Building No.	Radiometer No.	Configuration Factor
4	1 (20 ft)	0.032
	4 (40 ft)	0.011
5	1 (20 ft)	0.027
	4 (40 ft)	0.008

These configuration factors were confirmed[12] based on scaled measurements from the test layouts (Figure 7-12) and the locations of Radiometers 1 and 4 (yellow and orange, respectively), and radiometer 2 (green), in combination with photogrammetry using a tool in SketchUp 2023 [371] and shown in Figure 7-20. The full analysis is included in Appendix B.

[12] The same exercise was not undertaken for Building No. 4, but is assumed to be similarly valid.

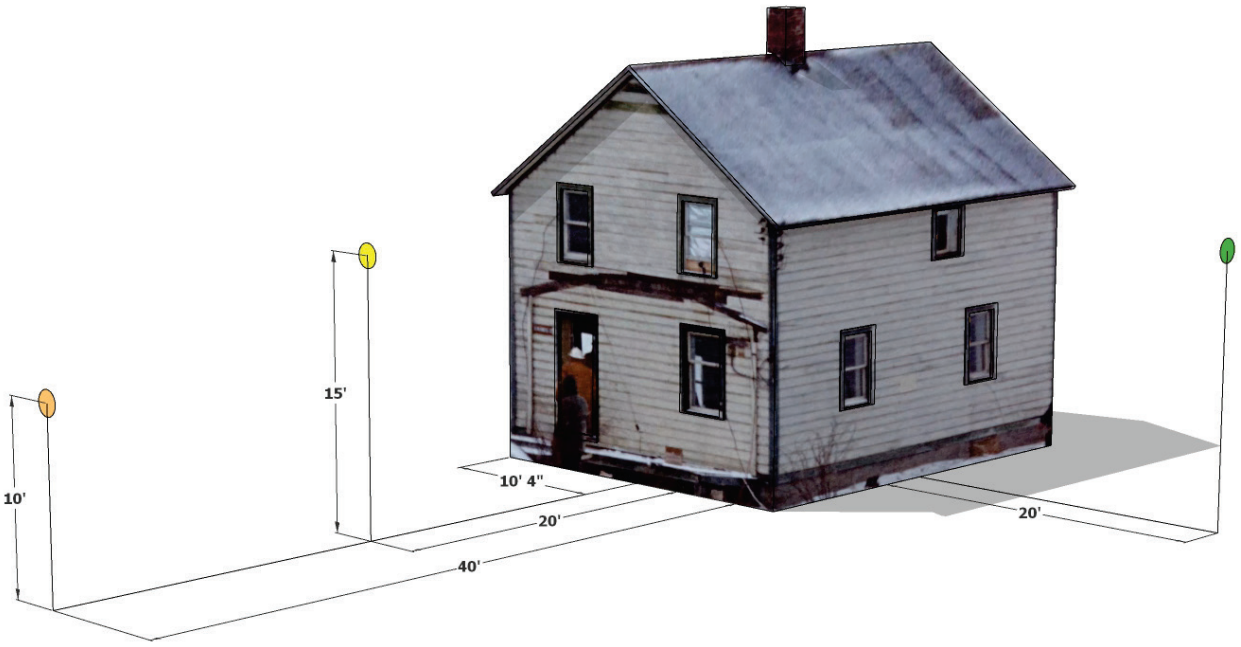


Figure 7-20: SketchUp 2023 model of Building No. 5

The simplified approach used in the analysis resulted in artificially high estimations of the radiant emissive power and corresponding black body temperatures, higher than the 1,000 °C from each opening, but it was retained due to the simplicity of application in the context of regulatory development. This has subsequently resulted in confusion over representative flame and fire temperatures, leading to definition of unrealistic peak temperatures in building fires. At least one subsequent regulatory guide [372] referenced a peak temperature of 1311 °C in the St. Lawrence burn tests, a value that has since been removed following a "Public Input" submission by the author of this thesis describing the origin of the artificially high radiant emissive power values and the underlying assumption (simplification) [373].

The radiometer data was analyzed to determine the values of radiant emissive power of the openings in test Building Nos. 4 and 5 using the above configuration factors and Equation 7-2, with resulting values plotted in Figure 7-21.

$$E = \frac{I_r}{\phi_o} \qquad \text{Equation 7-2}$$

Where:

E = Emissive power of the openings (cal/cm²·s)
I_r = Radiometer measurement (cal/cm²·s)
ϕ_o = Configuration factor of the openings to the radiometer (Table 7-6)

As can be seen in Figure 7-21, once corrected for the configuration of the radiometer relative to the building openings, consistent flux levels were obtained using data from Radiometers 1 and 4 since they both measured the incident radiant heat flux from the same face of each building.

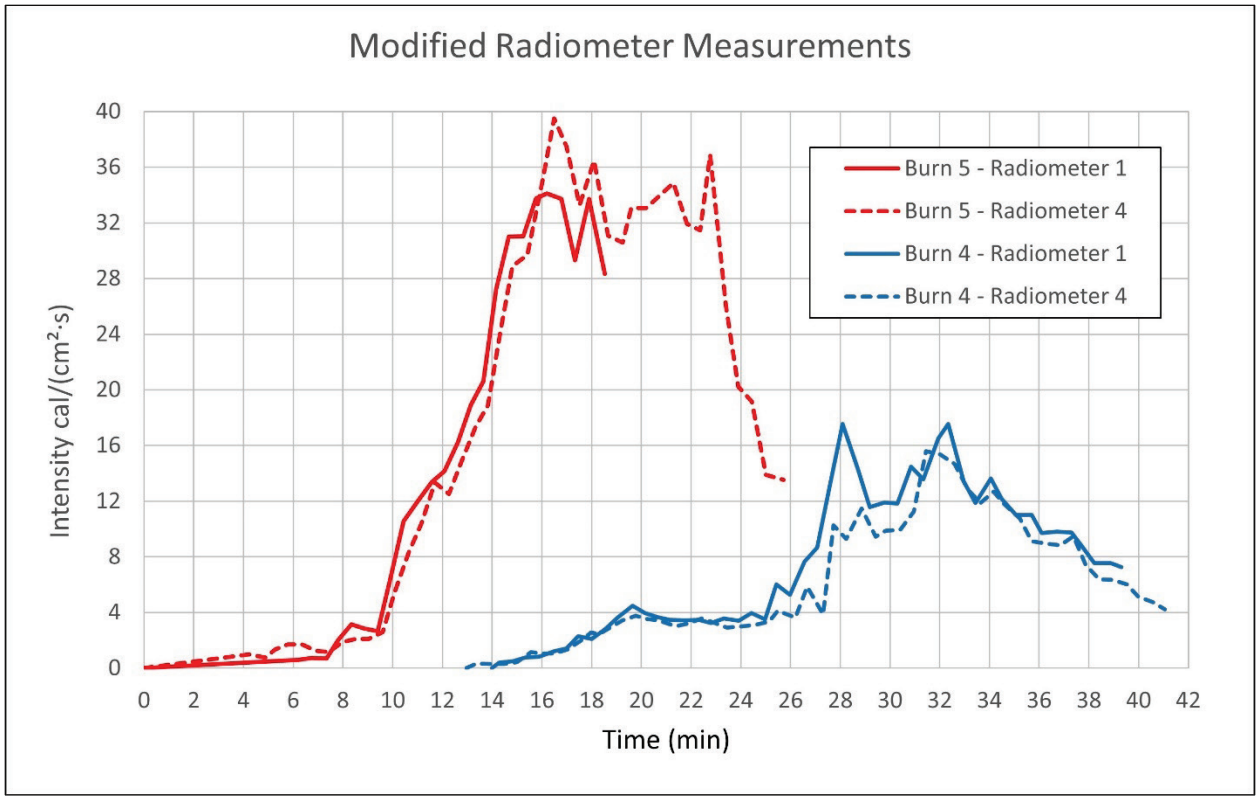


Figure 7-21: Plot of the radiant emissive power of the openings

The radiant emissive power values obtained from the initial phase of analysis were then used to determine a degree of fire exposure that could adequately characterize fire hazard with respect to "safe" distances between buildings. Initially, the peak measured values of radiant emissive power were used; however, this resulted in the necessity for impractical distances between building openings and the adjacent building face. To refine the estimate toward specification of more practical distances between buildings, another significant assumption was made. This was that a fire department was expected to arrive and control an exposure fire within 10 to 11 minutes. To align with this simplification, the time trace of the measured radiant emissive power was re-examined and a value of radiant emissive power corresponding to the time 10/11 minutes after ignition was determined. For the Building No. 5 fire, this assumption resulted in a value of source radiant emissive power of 8.5 cal/cm²·s (356 kW/m²), as shown in Figure 7-22 by the intersection of the green solid and dotted lines at times of 10 and 11 minutes and the averaging of the corresponding values of radiant emissive power.

The fire in Building No. 5 was considered to be significant, largely attributed to the combustible interior lining material. The source emissive power from an opening as determined using the method above was therefore considered to represent a "high hazard" exposure condition for purposes of regulation development. Further, it was noted the peak value in the Building No. 5 fire was approximately twice that calculated based on the data measured during the fire in Building No. 4, which had a noncombustible interior lining. Therefore, for purposes of regulation development, half of the 10/11 minute value

calculated for the fire in Building No. 5, a value of 4.25 cal/cm²·s (178 kW/m²), was considered to represent the radiant emissive power from an opening for a "low hazard" exposure condition.

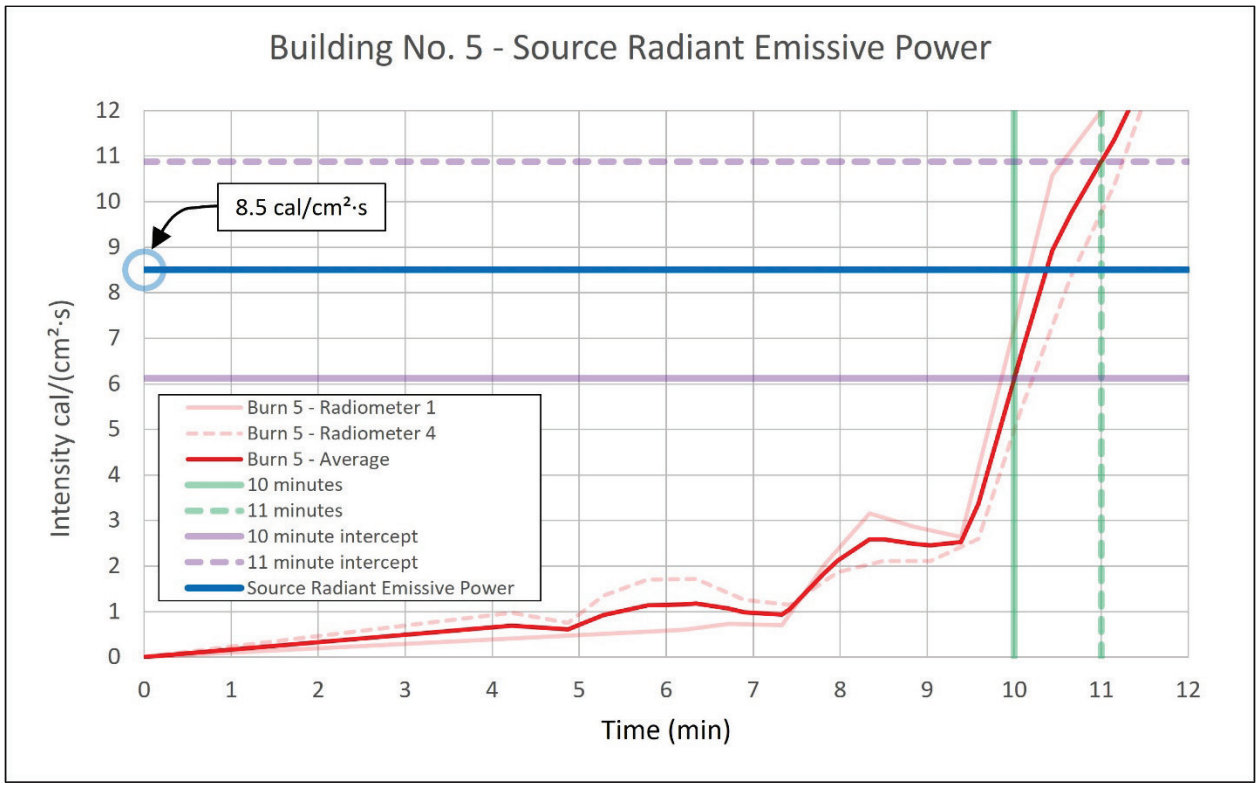


Figure 7-22: Building No. 5 radiant emissive power of the openings at 10 to 11 minutes

Characterization of the Exposed (Critical Incident Heat Flux)

A "critical" incident radiant heat flux criteria by which to set and judge "acceptable" building separation distances was then determined. This was based on the potential for ignition of construction materials on an exposed building. At the time, wood was considered to be an abundant building material with the lowest ignition temperature and associated ignition heat flux, based on previous UK studies across several species of wood [352, 353, 370]. These studies identified representative incident heat flux exposures for piloted and non-piloted ignition of wood as listed in Table 7-7.

Table 7-7: Critical heat flux for wood ignition

Ignition Mechanism	Ignition Intensity (cal/cm²·s)
Pilot Ignition	0.3 (12.5 kW/m²)
Spontaneous Ignition	0.8 (33.5 kW/m²)

The value for piloted ignition was selected as the critical heat flux criterion. This was further supported by experience from actual fire events where sparks and flying brands were observed to be emitted from the fire, passing nearby adjacent structures and acting as a potential pilot ignition source [370]. Therefore,

the critical heat flux criteria used in the determination of the spatial separation requirements of the NBC was taken as the value for the piloted ignition of wood, or 0.3 cal/cm²·s (12.5 kW/m²).

Using this value of critical heat flux, a critical configuration factor could then be determined to express a geometrical relationship between a source emissive power of the fire and the critical heat flux required to ignite an adjacent structure. This is expressed in Equation 7-3.

$$I_{crit} = \phi_{crit} \cdot E \qquad \text{Equation 7-3}$$

Where:

I_{crit} = Critical incident heat flux (cal/cm²·s)
ϕ_{crit} = Critical configuration factor
E = Emissive power of the openings (cal/cm²·s)

Rearranging Equation 7-3 to solve for the critical configuration factor results in Equation 7-4.

$$\Phi_{crit} = \frac{I_{crit}}{\mathrm{E}} \qquad \text{Equation 7-4}$$

Substituting the critical incident heat flux for wood (0.3 cal/cm²·s) and the emissive power for the "high" (8.5 cal/cm²·s [356 kW/m²]) and "low" (4.25 cal/cm²·s [178 kW/m²]) hazard exposure conditions results in the critical configuration factors summarized in Table 7-8.

Table 7-8: Critical configuration factors

Hazard Level	**Critical Configuration Factor**
Low	0.070
High	0.035

It can then be specified that if the configuration factor from the exposing building face to a point of interest is less than the critical configuration factor, the incident heat flux at that point will remain below 0.3 cal/cm²·s (12.5 kW/m²), and the distance to the point relative to the openings is considered acceptable. Conversely, if the configuration factor exceeds the critical value, the heat flux will exceed 0.3 cal/cm²·s (12.5 kW/m²). In such cases, either the area and/or configuration of openings would need to be adjusted, or the distance from the exposing building face to the point of interest would need to be increased to be acceptable.

Relationship Between the Hazard and Exposed

The next step in the analysis was to quantify how to determine a relationship (configuration factor) between the emitting fire source (hazard) and the point of interest (exposed) [374]. When done rigorously, based upon theoretical determination of configuration factors for radiation heat transfer from individual openings, this can become mathematically complex and thus challenging to apply within a simplified regulatory framework. In development of values for the NBC, therefore, the determination was simplified

to use the “grey radiator approximation” using a single basic planar configuration factor with a simplified representation of the distance between buildings.

The “grey radiator approximation” simplified the calculation of configuration factor by taking the percentage of the total plane area of the exposing face (%UPO) that consisted of openings and multiplying it by the configuration factor found based on the entire exposing face plane (ϕ_{plane}). This approximation resulted in a single value for an “effective” configuration factor [375-377] to account for the openings in the exposing face, although it was an approximation of the actual configuration factor expressed in Equation 7-5. It was recognized at the time that the accuracy of this approximation relied on an even distribution of openings over the exposing face, and that the applicability of the simplified value diminished at close distances to the point of interest (often a property boundary) and with a reduced percentage of openings in the exposing face of the building [378].

$$\%\mathrm{UPO} \cdot \phi_{plane} = \phi_{eff} \qquad \text{Equation 7-5}$$

Where:

$\%\mathrm{UPO}$ = Percentage unprotected openings in the exposing plane (%)
ϕ_{plane} = Configuration factor of the exposing plane
ϕ_{eff} = Effective (grey) configuration factor representing the openings in the exposing plane

Figure 7-23 illustrates the grey radiator simplification, showing Exposing Plane 1 with two openings and the actual configuration factor for radiant heat transfer to the exposed point shown in red. Exposing Plane 2 represents the application of the grey radiator approximation to the openings in Exposing plane 1, where the area represented by the openings is divided into an infinite number of smaller areas that are evenly distributed over the face of the plane [378] and the approximated configuration factor for radiant heat transfer to the exposed point is shown in pink. It should be noted that, unless an exposing building face contains 100% openings, the grey radiator approximation will, in most cases, produce an effective configuration factor that is less than the total configuration factor that would be calculated based on a sum of the configuration factors of the actual openings, as expressed in Equation 7-6.

$$\phi_{bf1} = \phi_1 + \phi_2$$
$$\phi_{bf2} = 20\% \cdot \phi_{p2} \qquad \text{Equation 7-6}$$
$$\phi_{bf1} > \phi_{bf2}$$

Where:

ϕ_{bf1} = Total (actual) configuration factor from building face 1
ϕ_{bf2} = Total (grey) configuration factor from building face 2
ϕ_1 = Configuration factor of opening 1 in building face 1
ϕ_2 = Configuration factor of opening 2 in building face 1
ϕ_{p2} = Configuration factor of the plane of building face 2

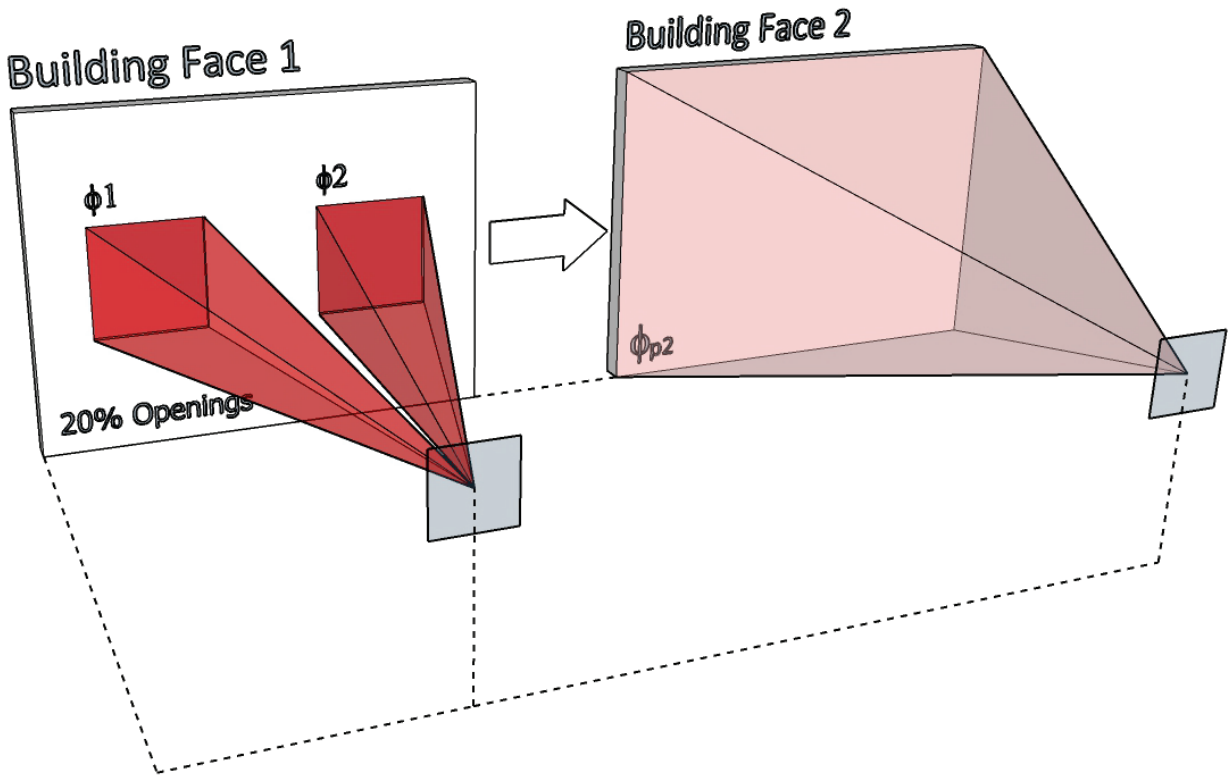


Figure 7-23: Grey radiator approximation

Despite its recognized limitations, described at the time as “minor inconsistencies inherent in [the] approach” [378, p. 1], the grey radiator approximation was utilized as a fundamental methodology in the development of the values in the spatial separation tables. This was largely due to the simplicity of the approach, as well as the absence of a more accurate or practical alternative method available at the time.

The next step in the development of the tables was the establishment of the method by which to calculate the configuration factor between the exposing “grey radiator” plane and the point of interest, as illustrated in Figure 7-24. This calculation, expressed in Equation 7-7 to Equation 7-9 [350, 379], was further simplified assuming [375]:

1. The exposing source is a rectangular vertical plane.
2. The exposed point of interest is parallel to and directly opposite the centre of the exposing plane.

$$\phi_{plane} = \frac{2}{\pi}\left[\sqrt{\frac{\frac{T}{S}}{\frac{T}{S}+4}}\tan^{-1}\left(\sqrt{\frac{T\cdot S}{\frac{T}{S}+4}}\right)+\sqrt{\frac{T\cdot S}{T\cdot S+4}}\tan^{-1}\left(\sqrt{\frac{\frac{T}{S}}{T\cdot S+4}}\right)\right] \quad \text{Equation 7-7}$$

$$\mathrm{T} = \frac{A}{d^2} = \frac{h\cdot w}{d^2} \quad \text{Equation 7-8}$$

$$\mathrm{S} = \max\left[\frac{h}{w},\frac{w}{h}\right] \quad \text{Equation 7-9}$$

Where:

ϕ_{plane} = Planar configuration factor
h = Exposing plane height (m)
w = Exposing plane width (m)
d = Distance from the exposing plane (m)
π = 3.14159

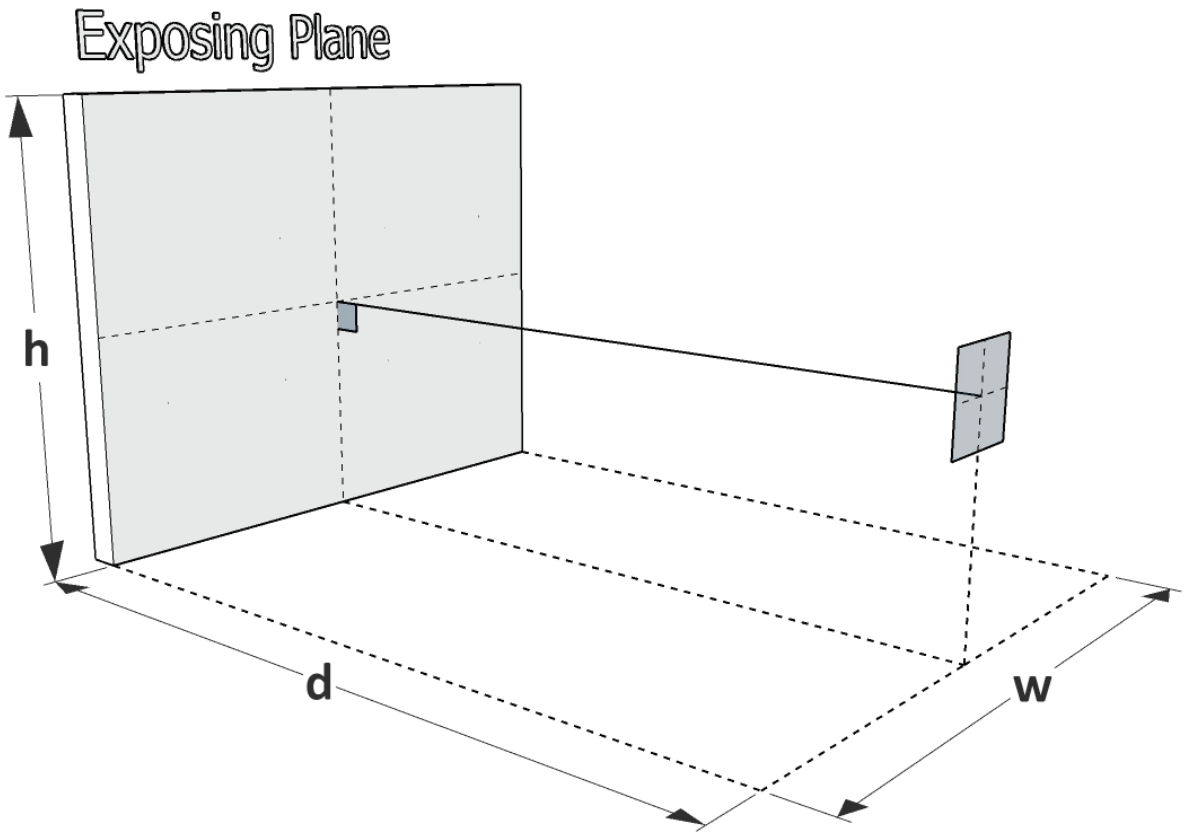


Figure 7-24: Basic planar configuration factor geometry

The key variables in Equation 7-7 were the area and aspect ratio of the source plane, and the distance between the source plane and the receiver. The height and width of the source were defined as the entire height and width of the face of the building of interest, or where that building is divided into fire compartments, the height and width of the face of each fire compartment. This approach recognized the benefits of fire compartmentation in containing a fire to a localized area of a building and therefore limiting its potential for exposure to neighbouring buildings.

The distance to be used in Equation 7-8 to define the horizontal separation between the source and the receiver was modified to account for the flame front observed during the St. Lawrence burn tests in Building Nos. 4 and 5 [357]. Horizontal flame front extensions of 5 ft and 7 ft from the window openings were defined for the low and high hazard exposure conditions, respectively, despite the fact that radiant intensity due to the flame front extension in the St. Lawrence burn tests had been incorporated into the

calculations of radiant emissive power. This modification of the distance between the radiator and target in the configuration factor calculation effectively reduced the distance between the source and the point of interest and was justified as follows [370, p. 10]:

> *This policy has been adopted firstly because the horizontal projections of flames from windows will not follow a linear geometrical relationship and secondly because firefighting becomes progressively more difficult with reduction in space separation.*

The two values for flame front extension were later averaged to a value of 6 ft (1.8288 m) [380], which was then applied to both low and high hazard exposure conditions.

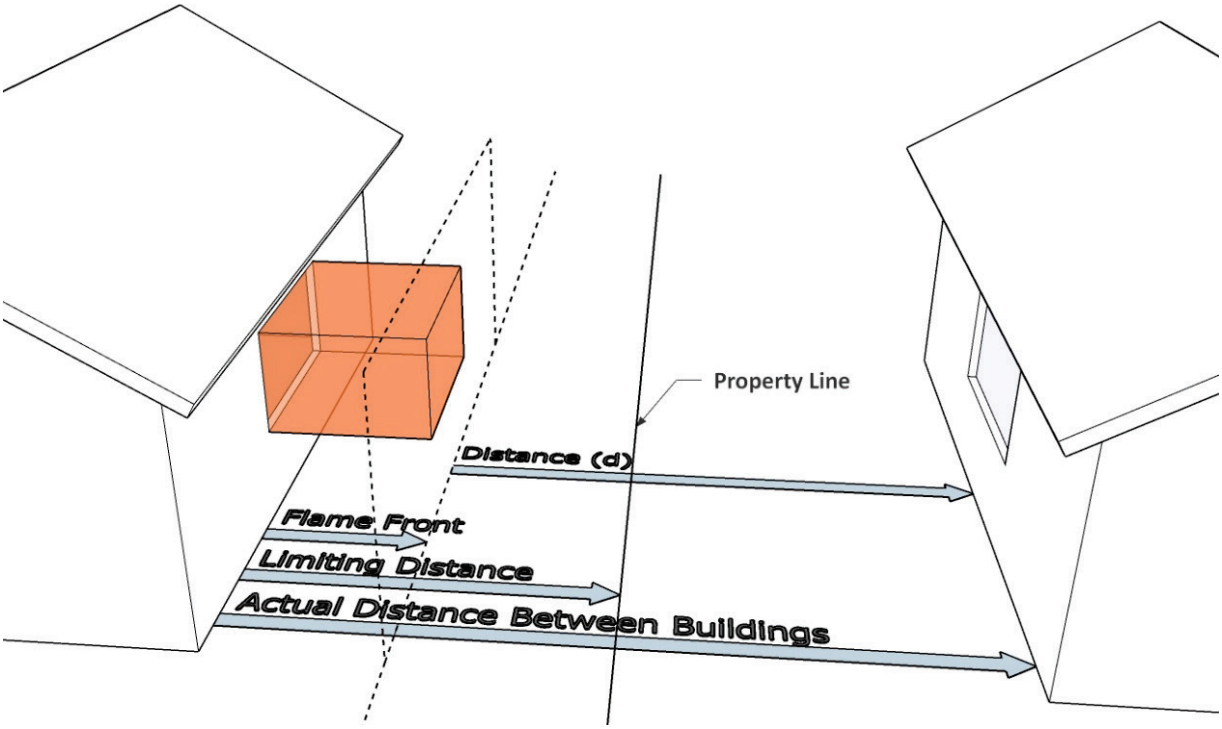


Figure 7-25: Exposing plane distances

The actual distance between buildings was further modified through the definition of a "limiting distance," developed to address earlier challenges associated with fire limits and insurance rating approaches that required knowledge of neighbouring building location relative to the building of interest. The modification was first introduced in the 1941 NBC and further refined in the 1953 NBC to regulate distances of buildings to a defined property boundary (or similar bounding line), recognizing that in most design situations the distance between a building and its property boundary is known, while the distance to neighbouring buildings may not be. This "limiting distance," incorporating the flame front factor, indirectly represented the "safe" distance between the flame front and a notional neighbouring building. It is expressed in Equation 7-10 and illustrated in Figure 7-25.

$$\mathrm{LD} = \frac{d + ff}{2} \qquad \text{Equation 7-10}$$

Where:

LD = Limiting distance (m)
d = Theoretical distance between the flame front and a notional building (m)
ff = Flame front factor (6 ft or 1.8288 m)

Equation 7-10 can be re-arranged, as shown in Equation 7-11, to calculate the distance, which is then used to determine the associated configuration factor in Equation 7-7 and Equation 7-8.

$$\mathrm{d} = 2 \cdot LD - ff \qquad \text{Equation 7-11}$$

Determination of the limiting distance in this manner introduces a "mirror boundary condition" for building separations, where it is assumed that the building located opposite the building on fire is of equal exposure risk. As a result of these modifications, the distance used in determination of the configuration factor may not be the actual distance between buildings, depending on the exposure characteristics of the building located opposite. While this is a beneficial simplification, it breaks down when the actual building opposite has a different exposure risk than that of the building on fire, due to a difference in occupancy, size, configuration, sprinklering, or a combination thereof. This can be a significant issue, as shown in Figure 7-26, where a large building is located opposite a small one. In the figure, the critical heat flux boundary from a fire in the larger building is shown in orange, and encompasses the smaller building. The critical heat flux boundary from a fire in the smaller building is shown in yellow and does not even extend to the larger building. The NBC warns of the potential for this condition in the following note [21, Div. B, p. 3-236]:

> *The Code requirements that deal with reducing the probability of building-to-building fire spread were originally developed based on the assumption that the exposing building faces of adjacent buildings are of similar size and configuration, and are equidistant from the shared property line. Where buildings are of different sizes, the smaller building may be subject to a higher heat flux in the event of a fire compared to the larger building. Where buildings are closely spaced and not equidistant from the property line, the construction of the building with the greater limiting distance does not recognize the proximity of the building with the lesser limiting distance.*

Defining the exposing building face based on fire compartment boundaries, rather than on the entire building face, to some extent mitigates the probability of such a discrepancy of exposure on opposite sides of a boundary. It also aligns with the trend in the regulatory development of the NBC, which has progressively increased the degree of fire compartmentation.

The spatial separation requirements of the NBC were then structured such that the percentage of unprotected openings permitted in an exposing building face could be calculated based on the configuration factor of the plane of the exposing face and the critical configuration factor associated with the occupancy of the associated building or fire compartment, as per Equation 7-12.

$$\%\text{UPO} = 100 \cdot \left(\frac{\phi_{crit}}{\phi_{plane}} \right)$$ Equation 7-12

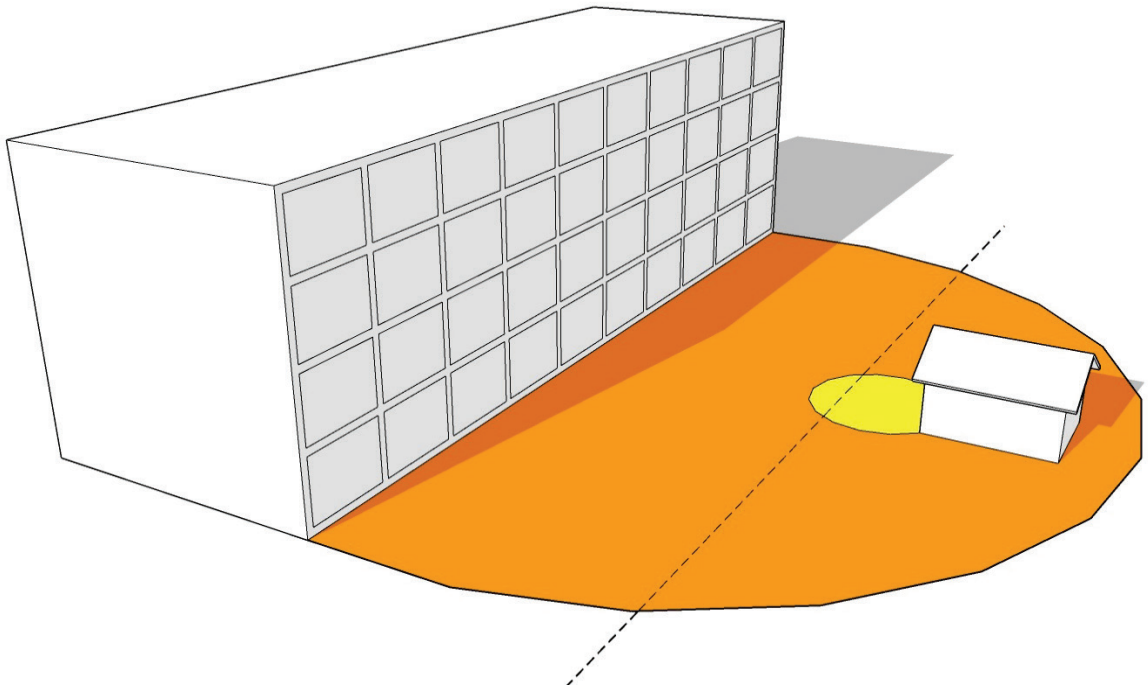


Figure 7-26: Mirror boundary condition

A final step in the simplification of the approach for regulatory use involved the tabulation of a set of discrete values for the permitted percentage of unprotected openings as a function of building (fire compartment) occupancy, exposing face aspect ratio, area, and limiting distance. As a result, direct use of the tables provides imprecise estimates for the percentage of unprotected openings unless the input values exactly match the predefined table entries. When values do not align, designers are required to use the closest table value or may be permitted to utilize linear interpolation of the table values. The more detailed calculations behind the tables are not included in the NBC or associated guidance documentation and, thus, are not generally known or understood, leaving designers and authorities to rely on the tabular estimation methods. Appendix C provides further details of the full methodology that was historically used to derive the NBC spatial separation tables (Equation 7-7 to Equation 7-9, Equation 7-11 and Equation 7-12).

7.2.5 1965 to 2020 NBC: Further Development

Key changes to the spatial separation requirements, following those originally developed from the St. Lawrence Burn tests for the 1960 NBC, are discussed next to further the historical analysis of the provisions as they exist today. For the sake of simplicity, and in contrast to the other historical analyses outlined in

this thesis, the following changes to the spatial separation requirements are more easily discussed in the next sections according to subject matter, rather than following a strict chronological summary.

7.2.5.1 Re-Examination of Concentration of Openings and the Enclosing Rectangle

The JFRO assisted in planning the St. Lawrence burn tests, as well as supplying test equipment and personnel to attend the burns and later analyze the data. In fact, Mr. J.H. McGuire, who was heavily involved in the radiometer measurements, actually transitioned from JFRO to the Fire Section of the Division of Building Research at the National Research Council of Canada in 1959 and continued to be involved in the work [362, 370]. He acknowledged the assistance of Margaret Law, who remained at JFRO, "for much of the analysis of the [radiometer] results" [362, p. 5]. Thus, staff at JFRO were likely very familiar with the results, interpretation, and regulatory application of the results from the St. Lawrence burn tests. Subsequently, researchers at the JFRO in the UK continued investigating variables associated with radiant heat exposure from building fires and associated spatial separation distances [381-383]. This included additional full-scale testing, research, and analysis conducted through the 1960s [383].

Based on their findings, the JFRO introduced the "enclosing rectangle concept" to address the limitations of the grey radiator approximation [382, 384]. This concept requires that, instead of basing spatial separation calculations on the entire building or fire compartment face areas, the emitting source should be defined as the smallest rectangle, or rectangles, that enclose all openings. This is illustrated in Figure 7-27 with the UK-based enclosing rectangle shown on the left, encompassing the openings in the blue shaded area. The NBC-based grey radiator approach is shown on the right, encompassing the openings within the entire building face. In this way, the enclosing rectangle concept still used a grey radiator approximation, but one that was more precisely aligned with the boundaries of the openings.

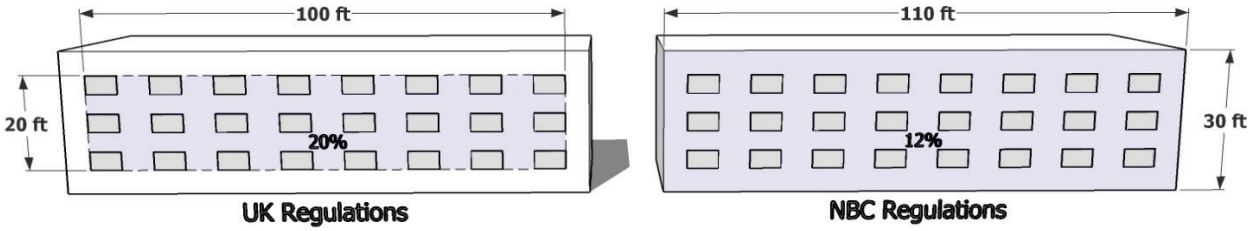


Figure 7-27: Enclosing rectangle example 1

The enclosing rectangle concept is also able to address separate localized concentrations of openings, as illustrated in Figure 7-28. The example building on the left features two concentrations of openings, each having its own enclosing rectangle. In contrast, the example building on the right utilizes the NBC grey radiator approximation [146] that includes the entire building face area and does not properly account for the effects of radiation from localized concentrations of openings. In using separate enclosing rectangles on the same building face, the more restrictive configuration factor of the two rectangles governs in establishing the separation distance.

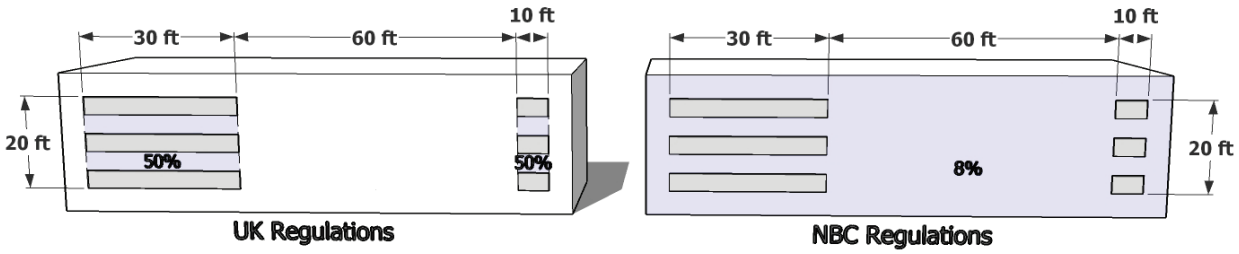


Figure 7-28: Enclosing rectangle example 2

While the UK-based enclosing rectangle approach mitigates the generalized effects of the grey radiator approximation through more concise bounding of the openings on a building or fire compartment face, its application is inherently more complex compared to the grey radiator approximation. This was recognized during re-examination of the spatial separation requirements for the 1965 and 1970 NBC [385], where concern was expressed regarding the potential negative impact of allowing the use of grouped versus evenly distributed openings in an exposing building face. Instead of immediate changes, it was recommended that the British work in development of the enclosing rectangle concept be examined for use in the NBC spatial separation requirements [384]. Following the examination, modifications to the 1960 NBC spatial separation requirements to include this concept were proposed but not adopted as a change to the 1970 NBC [386], likely due to the complexity of the approach and the continued opinion that local concentrations of openings do not create an issue of concern [387] in connection with spatial separation calculations using the original grey radiator approximation. Until the 2005 NBC [129], the permitted percentage of unprotected openings continued to be based on the grey radiator approximation, with no provision to address concentration of unprotected openings in an exposing building face, despite continued concern that localized concentrations of openings were known to impact the effectiveness of this approximation [388-390].

This changed following several fires in the City of Calgary where fire had spread from one building to another [391]. A change was proposed to the 2005 NBC to regulate the concentration of unprotected openings and better address the limitations of the grey radiator approximation at closer limiting distances to a property boundary [392]. An NRC discussion paper investigated the impact of opening concentration on the configuration factor due to the grey radiator approximation by analyzing a single rectangular opening in an exposing building face to establish a formula for the maximum opening area as a function of limiting distance and the flame front factor [376]. This initially involved solving for the ratio of exposing area to (separation distance)^2 ('T' in Equation 7-7) using the low hazard critical configuration factor of 0.07. Changing the aspect ratio (S) between the values of 0.3 and 1.0 was found to have a negligible impact on configuration factor (ϕ) [376] in Equation 7-7, and was therefore set to a value of 1. With these values, 'T' was found to have a value of 0.24. This value was then substituted into Equation 7-8 to solve for exposing area (A) as a function of distance (d), as shown in Equation 7-13.

$$A = 0.24 \cdot d^2 \qquad \text{Equation 7-13}$$

Equation 7-11 was then substituted into Equation 7-13, along with the original low hazard flame front extension factor of 1.5 m (5 ft) [357], to express the exposing area as a function of limiting distance, as shown in Equation 7-14. This equation defines the maximum permitted single area of unprotected openings as a function of limiting distance.

$$A = 0.24 \cdot (2 \cdot LD - 1.5)^2 \qquad \text{Equation 7-14}$$

The applicability of Equation 7-14 was bounded within a limiting distance range of 1.2 m to 2.0 m, based on the understanding that the impact of localized concentrations of openings diminishes with increased limiting distance [376]. Following this, a table of opening areas was calculated as a function of this range of limiting distances, as shown in Table 7-9.

Table 7-9: Maximum area of individual unprotected openings with flame front extension factor of 1.5 m

Limiting Distance (m)	**Maximum Area of Individual Unprotected Opening (m²)**
1.2	0.19
1.5	0.54
2.0	1.50

However, at the time (and still today) the NBC required that a bedroom egress window have a minimum area of 0.35 m², and there was concern that introducing the window area limit of 0.19 m², would in some cases, result in conflicting requirements. The flame front factor value in Equation 7-14 was therefore arbitrarily lowered to 1.2 m to produce a result that would align the minimum limiting distance of 1.2 m with the minimum area required for a bedroom egress window of 0.35 m². The modified version is expressed in Equation 7-15, and the corresponding table of discrete values are included in Table 7-10.

$$A = 0.24 \cdot (2 \cdot LD - 1.2)^2 \qquad \text{Equation 7-15}$$

Table 7-10: Maximum area of individual unprotected openings

Limiting Distance (m)	**Maximum Area of Individual Unprotected Opening (m²)**
1.2	0.35
1.5	0.78
2.0	1.88

Equation 7-15 and Table 7-10 were introduced into the 2010 NBC for unsprinklered buildings. In recognition of the reliability of sprinklers in limiting fire growth and spread [299], it was also determined that these requirements do not need to be applied to sprinklered buildings. In addition to specifying the

maximum area of individual openings, the NBC also requires a minimum separation between openings serving the same room, to maintain uniformity in the spacing of openings in a building face [21].

Despite these changes, the limitations in the use of the grey radiator approximation for determining spatial separation distances between larger exposing building faces with limiting distances greater than 2 m remain unaddressed, and the impact of this is not currently known. For such cases, the enclosing rectangle concept offers a more scalable approach to address these limitations.

It should also be noted that the new requirement was derived using the low hazard critical configuration factor of 0.07 and flame front factor of 1.5 m (5 ft), which was modified downward to 1.2 m, and applied equally to low and high hazard occupancies, without accounting for known increased severity of fire associated with high hazard conditions. These limitations point to further opportunity for technical reconciliation of the grey radiator approximation, which is examined and discussed in more detail later in this case study.

7.2.5.2 Fire Department Response Time

Prior to the 1970 NBC [117], the presumption of fire service intervention that had been used to justify the lower radiant emissive power used in the development of the spatial separation requirements was not explicitly stated in the requirements. However, the following advisory note was included in both the 1965 and 1970 NBCs, providing context for the appropriate application of the requirements [117, p. 86]:

> *The requirements of this Article are based on the assumption that properly equipped fire-fighting services are available. The limiting distances required herein can be relied upon only when a fire is in its incipient stages. Where a properly equipped fire-fighting service is not available, the required distances should be double the distances specified.*

This note was proposed to be changed in the 1975 NBC to include regulatory language stating that "It has been found that periods of some 10 to 30 minutes usually elapse between the outbreak of flaming combustion" [388, p. 83], and arrival of the fire department, which was revised and then added as an interim change to the 1970 NBC [393]. The specific requirement was worded as follows [183, p. 87]:

> *In respect to the building under consideration where firefighting facilities and protective wetting facilities are not available within 10 min. of the alarm being received, the limiting distance required by Article 3.2.3.1. shall be doubled.*

Other than editorial revisions, this requirement remained unchanged until the 2005 NBC [129]. In response to the same Calgary fire incidents noted earlier [391], a change was proposed to the 2005 NBC to clarify how it should be applied, introduce performance metrics, and provide an exemption for sprinklered buildings [146]. The updated requirement, which remains unchanged today, is as follows [21, Div. B, p. 3-79]:

> *8) A limiting distance equal to half the actual limiting distance shall be used as input to Tables 3.2.3.1.-B and 3.2.3.1.-C, where*

a) the time from receipt of notification of a fire by the fire department until the arrival of the first fire department vehicle at the building exceeds 10 min in 10% or more of all fire department calls to the building, and

b) any storey in the building is not sprinklered.

As a result of this requirement, buildings located in areas with longer fire department response times, such as rural areas or new neighbourhood developments, must either reduce the allowable percentage of unprotected openings in exterior walls or be separated by increased distances to maintain the same opening area. In addition, the practical application of this requirement has presented challenges, particularly in defining what constitutes "the first fire department vehicle" and in obtaining and interpreting the data necessary to quantify local fire department arrival time thresholds [394]. As with the grey radiator approximation, these challenges provide an opportunity for technical reconciliation of the fire department response time requirement in future versions of the NBC, which is also addressed in more detail later in this case study.

7.2.5.3 Sprinkler Tables

The 1965 through 1990 versions of the NBC permitted the percentage of unprotected openings to be double the table value when a building was equipped with a sprinkler system [111]. During consideration of mandatory sprinklering of all Part 3 buildings in the 1990s, new spatial separation tables specific to sprinklered buildings were introduced. These recognized the reliability of sprinklers in reducing the probability of fire growth and spread, and in particular, fire spread as a result of exposure [299]. Minor simplifications of the underlying calculations for the permitted percentage of unprotected openings were implemented into Equation 7-7 to Equation 7-9, Equation 7-11 and Equation 7-12 with technical support through reference to explanatory language in NFPA 80A [373].

Through this, an upper limit to the area of the exposing building face was introduced as a function of the minimum permitted length of a sprinkler design area [299, 395]. The length is calculated as shown in Equation 7-16 [396], where the sprinkler design area is established based on the occupancy classifications per NFPA 13 classifications, as shown in Table 7-11 [396].

$$\mathrm{L}_s = 1.2 \cdot \sqrt{A_s} \qquad \text{Equation 7-16}$$

Where:

L_s = Minimum length of sprinkler design area parallel to the branch lines (m)

A_s = Sprinkler design area[13] (m²)

[13] The sprinkler design area is the hydraulically most remote set of sprinkler heads within a specified area by which the hydraulic design of the entire sprinkler system is determined.

Table 7-11: NFPA 13 areas and minimum lengths of sprinkler operation

Hazard Level (NBC)	Hazard Level (NFPA 13) [396]	Area of Sprinkler Operation (m^2) [396]	Minimum Length of Sprinkler Design Area (m)
Low	Light and Ordinary Hazard	139 (rounded to 140)	14.2 (rounded to 15)
High	Extra Hazard	232 (rounded to 240)	18.6 (rounded to 19)

In the development of the NBC spatial separation tables for buildings equipped with a sprinkler system, a maximum compartment height of 10 m was assumed [299], without rationale. When this was applied with the minimum lengths of sprinkler design area, exposing building face areas of 150 m^2 and 190 m^2 (rounded to 200 m^2) were determined for low and high hazard exposures respectively. These were then used as the upper limits on the area of "exposing building face" included in the sprinklered spatial separation tables, on the assumption that sprinklers will control the ultimate fire size to be within these limits.

The second simplification was that the ratio of the height to width ('S' in Equation 7-7 and Equation 7-9) of all sprinklered buildings was defined to be a value of 3 since only limited changes to the permitted percentage of unprotected openings were anticipated for aspect ratios above that value [299].

New sprinklered spatial separation table values were then established using these simplifications in combination with linear interpolation of the existing unsprinklered table values, leading to even further differences between the new values in the spatial separation tables for sprinklered buildings and those that would be calculated using the fundamental underlying equations.

7.2.6 Summary of Historical Basis

The historical analysis of the spatial separation requirements presented in this case study highlights the potential complexities involved in determining the bases for, and subsequently tracking the development of, changing requirements within a building code over time. As a conclusion to such an analysis, it is useful to identify the key historical information within the context of the elements of the proposed regulatory risk paradigm. This information is presented in tabular form in Table 7-12, although alternative formats may be used depending on the complexity of findings in a given historical analysis.

Table 7-12: Summary of the historical basis of the spatial separation requirements

Hazard:	Building to building fire spread as a result of the following: 1. Full room (fire compartment) involvement in fire. 2. Flame extension out of all the openings in a building or fire compartment face. 3. Emissive power from the openings of 178 kW/m^2 for low hazard occupancies and 356 kW/m^2 for high hazard occupancies,

	presuming fire department intervention within 10-11 minutes of the start of a fire.
Exposed:	Ignition of building materials, with wood considered the most vulnerable, can occur at a pilot ignition heat flux of 12.5 kW/m² in the presence of an ignition source such as a brand or ember.
Relationship:	Configuration factor of an exposing building face and a hypothetical neighbouring building with the following assumptions and simplifications: 1. A grey radiator approximation of the openings in the exposing building face to a single exposing plane. 2. The configuration factor of the single exposing plane is measured to a point of interest that is centred on and parallel to the plane. 3. The distance between the exposing plane and point of interest is: a. reduced by a flame front factor of 1.8288 m (6 ft), and b. then modified through a mirror boundary concept to be measured as a function of a property boundary. 4. The permitted percentage of unprotected openings are specified in tabular format with further simplifications for the tables that apply to sprinklered buildings.
Regulatory Solution:	Specification of the permitted percentage of unprotected openings in an exposing building face depends on building occupancy, provision of sprinklers, the exposing building face area, the ratio of exposing building face height and width (unsprinklered), and distance to a property boundary.
Acceptable Performance:	Limit the incident heat flux on a notional neighbouring building to be less than 12.5 kW/m².

It is clear from the historical analysis above that the spatial separation requirements in the current (2020) NBC are primarily based on the results of the St. Lawrence burn tests. Since then, few substantive changes have been made, with revisions largely focused on addressing the grey radiator approximation, fire department response times, and simplifications for sprinklered buildings. Over the same time period, additional testing and associated studies have been conducted in Canada, the United Kingdom, the United States, and other jurisdictions to further investigate the influence of key factors on the radiant heat exposure from burning buildings. These studies have contributed to the development and revision of regulations in the United Kingdom and other international jurisdictions to address technical shortcomings in earlier analyses of the St. Lawrence burn test results and to incorporate the evolving understanding of

fire development within compartments and flame extension/radiation through openings in exterior walls. The results from these studies and corresponding changes to international regulations are therefore used here as a basis for technical reconciliation of the spatial separation requirements of the 2020 NBC, to demonstrate use of the technical reconciliation sub-framework proposed in the new regulatory risk framework that forms the subject of this thesis.

7.3 Technical Reconciliation

The technical reconciliation of the spatial separation requirements of this case study begins with an assessment of the technical rationale that underlies the historical development of those requirements. In the 2020 NBC, these were primarily derived from the results of a single fire test (Building No. 5) discussed above. During this test, the weather had deteriorated, including sustained high wind speeds and frequent wind gusts across the window openings adjacent to the wood cribs, as shown in Figure 7-29, illustrating a cross-ventilation effect.

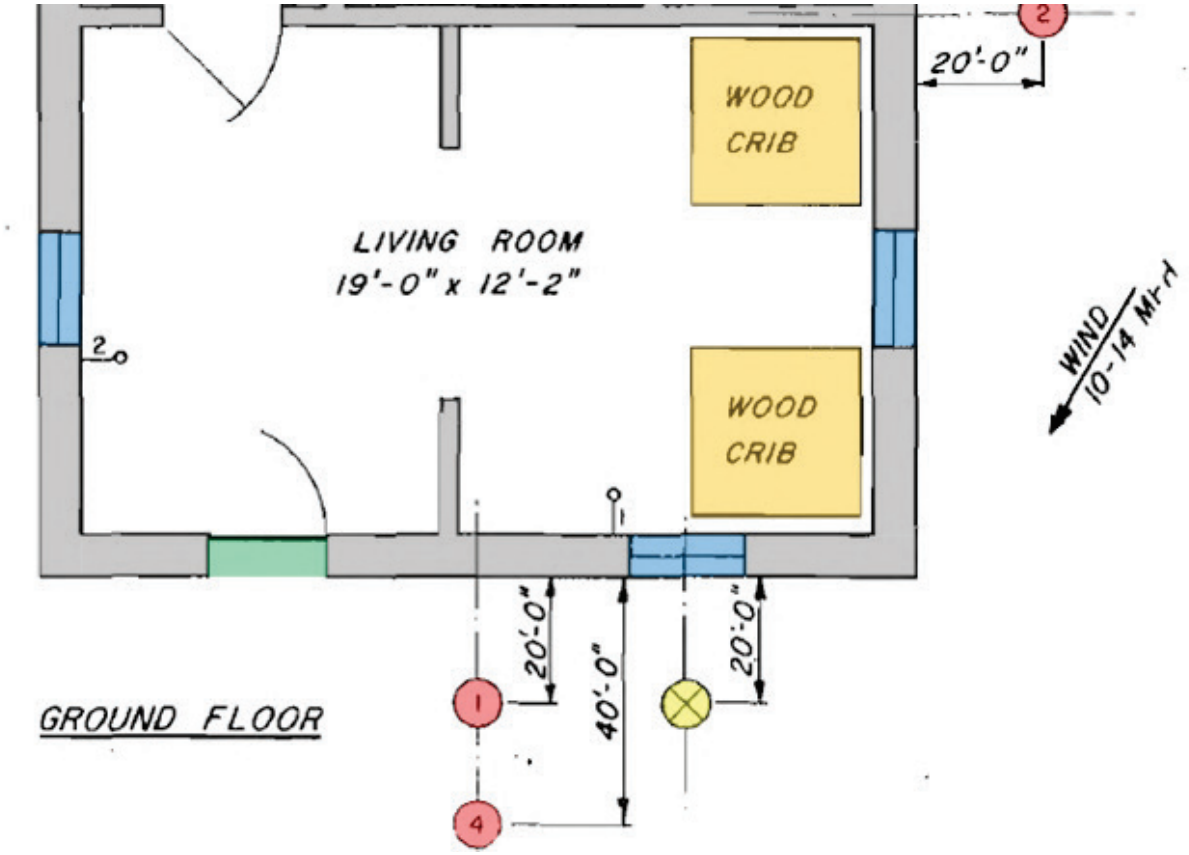


Figure 7-29: Cross-ventilation [357]

The variable wind conditions during the test would have influenced the radiometer measurements of radiant heat and may also have had a significant effect on the burning rate, although the available data are insufficient to quantify these impacts [368]. In addition, the combustible interior lining materials present in this building [362] would have contributed to fire intensity and severity. Despite these

limitations, the original data underlying the spatial separation requirements have not been re-examined. Instead, the main changes have focused on reassessing the original grey radiator approximation that was initially applied, and clarifying assumptions related to fire department response times, both of which were recognized issues at the time of the St. Lawrence burn tests.

Since these burns, additional testing and analyses have been conducted for the development of similar regulations in other jurisdictions. The data, interpretation, and analysis from these efforts could support further changes to the NBC spatial separation requirements. In recognition of these advancements, and to address other outdated aspects of the spatial separation requirements, the following sections present changes that can be made based on a more in-depth technical reconciliation of the key fundamental elements underlying the development of the spatial separation requirements, using the proposed new framework.

7.3.1 Table Value Errors

The first step in the technical reconciliation is the identification of errors in the calculated spatial separation table values [Tables 3.2.3.1.-B and 3.2.3.1.-C of the 2020 NBC]. Equation 7-7 to Equation 7-9 were used to examine the values in the tables and an error was found in the "high hazard" table [Table 3.2.3.1.-C of the 2020 NBC]. Specifically, the entry that uses an exposing building face area of 2000 m², an aspect ratio of 1, and a limiting distance of 50 m, should be listed as 57%, whereas the 2020 NBC table value is 56%. While inconsequential in terms of fire hazard impact, this error should be corrected to align the table values with those calculated using the original equations underlying their derivation, and in doing so, facilitate future use of those equations as an alternative to the table values without raising concerns about inconsistency.

Additional inconsistencies are found in the values contained in the sprinklered spatial separation tables [Tables 3.2.3.1.-D and 3.2.3.1.-E of the 2020 NBC]. As discussed earlier, these tables were developed by doubling the values corresponding to an aspect ratio of 3, as listed in the unsprinklered tables [Tables 3.2.3.1.-B and 3.2.3.1.-C]. However, the values listed in the unsprinklered tables are rounded off relative to the final calculated values to simplify their use. Thus, the simple doubling of values from the unsprinklered table to derive the spatial separation entries for sprinklered buildings introduced additional rounding errors, further exacerbating the differences between the actual, equation-based values and the already increased or decreased values in the unsprinklered tables. The resulting error in allowed percentage of unprotected openings for a given limiting distance and exposing building face area can be as much as 1% in many cases.

The rounding errors are more pronounced in Table 3.2.3.1.-E, particularly for the "Exposing Building Face" area of 200 m². This area has no direct counterpart in Table 3.2.3.1.-C, so the values were derived based on linear interpolation of values from the corresponding areas of 150 m² and 250 m² in Table 3.2.3.1.-C, and the interpolated values were then doubled. This approach compounded the rounding errors, resulting in discrepancies of 2% to 5% when compared to values that would have been calculated

based on Equation 7-7 to Equation 7-9. A detailed comparison of the calculated versus actual table values is included in Appendix G.

These errors were identified and corrected. The corrected values were determined using the fundamental equations and then submitted as a code change request to Codes Canada (CCR 1183) by the author of this thesis [397]. The submission was reviewed by the Standing Committee on Fire Protection, developed into proposed code changes [398, 399], and issued for public comment. Following the public comment period, the changes were accepted for inclusion in the yet to be published 2025 NBC, attesting to the import of the proposed technical reconciliation stage of the framework.

7.3.2 Fire Department Response Time

During development of the spatial separation requirements, it was presumed that fire service intervention would occur within approximately 10 to 11 minutes of the start of a fire, in order to keep values of required building separation to within practical limits. In doing this, the radiometer data corresponding to that approximate time was used to characterize the “high” hazard source fire radiant emissive power as 356 kW/m² (8.5 cal/cm²·s). A time of 10 minutes was then defined as the conservative time limit for presumed fire service intervention. Although this time was used to determine key fire severity parameters measured during the more severe Building No. 5 fire test (“high” hazard), these values were then algebraically reduced in developing characteristics for “low” hazard occupancies, without taking into account how the development of a low hazard fire might differ from a more severe fire during the first minutes after ignition. The specific reason for doing this was not recorded, but it was likely for purposes of regulatory simplification. Technical reconciliation using the proposed new framework can be used for a re-evaluation of the assumptions and simplifications made with respect to fire size and times for fire service intervention.

Given the intensity of the Building No. 5 fire, use of the fire characteristics at 10/11 minutes after ignition from this fire as a basis for determining values of those for fires in “low” hazard occupancies represents an overly conservative approach. It is also inconsistent with the approach used for other parameters, where results from tests in Building No. 4 and Building No. 5 were balanced. The averaging of the flame front extension factor from 7 ft for “high” hazard and 5 ft for “low” hazard to 6 ft for both cases is one such example.

The ”low” hazard emissive power used in the development of the spatial separation requirements was established through a comparison of the results from Building No. 4 and Building No. 5, which showed that the peak value of estimated emissive power for Building No. 4 was approximately half that of Building No. 5. However, in applying this simplification and determining a value of emissive power for a low hazard fire, the measured value for emissive power determined from the Building No. 5 (high hazard) test at a time of 10/11 minutes after ignition was simply divided by 2, without taking into account differences in the fire growth times for the lower hazard fire in the Building No. 4 test. As shown in Figure 7-30, the time required to reach a source radiant emissive power of 4.25 cal/cm²·s specified for the low hazard fire was 19.7 minutes. This would be the allowed fire department response time consistent with the specified value

of radiant emissive power of 4.25 cal/cm²·s, which is approximately twice the time required to reach the specified emissive power level taken as representative of the high hazard fire in Building No. 5.

Considering these two bounding times, along with the approach taken in averaging the flame front extension factor, a representative value for fire department response time that could be applied to both "low" and "high" hazard occupancies is 15 minutes.

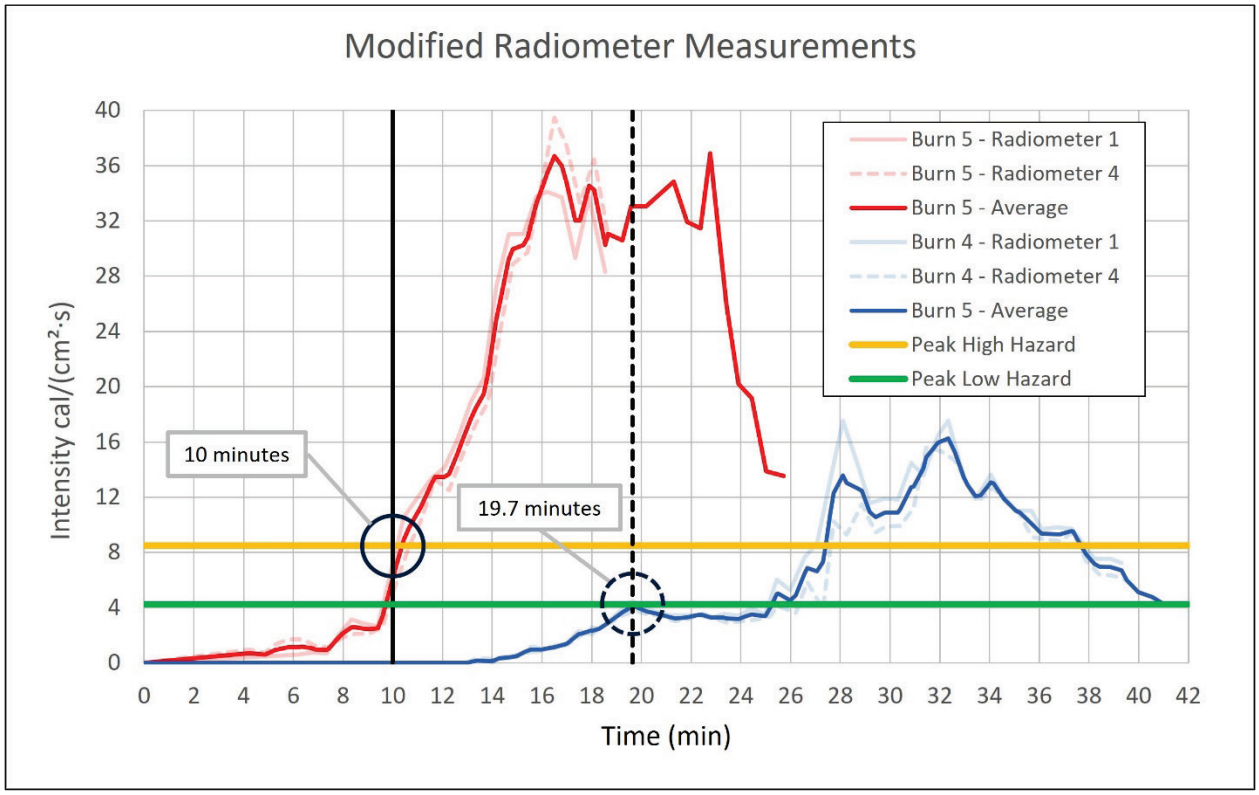


Figure 7-30: Building Nos. 4 and 5 radiant emissive power times

Similar time frames have been referenced by NRC staff, as detailed in Table 7-13, including those involved in the St. Lawrence burn tests, with such references made within the period between the occurrence of those tests and the early 1980s. This period also encompasses the original inclusion of the 10 minutes as a requirement in the 1970 NBC [393].

Table 7-13: Referenced Peak Radiant Intensity Times

Date	Time Commentary	Reference
1959	"the high levels of radiation referred to were only attained between 16 and 35 minutes from the start of the fire"	[370, p. 8]
1961	"The radiation levels which have been adopted in the National Building Code assume that fire fighting services will be available from 16 to 25 minutes after the start of a fire."	[400, p. 4]

Date	Time Commentary	Reference
1964	“the distances required in the National Building Code are such that the tolerable level of radiation would be reached within 20 minutes of the start of a fire”	[295, p. 32]
1975	“It has been found that periods of 10 to 30 min. usually elapse between the outbreak of flaming combustion in a building and the attainment of high radiation levels.”	[183, p. 87]
1982	“the use of radiation levels that would not be exceeded during the first fifteen minutes of a developing fire”	[380, App. S, p. 1]

The lower bound of the time ranges listed in Table 7-13 generally aligns with the 15 minute value determined through a technical reconciliation of the original data behind the spatial separation requirements above, and therefore supports its use as a more appropriate value to be acceptable for fire service intervention time in the context of the spatial separation requirements.

7.3.3 Grey Radiator Approximation and Opening Clustering

In the original formulation of the spatial separation requirements in the NBC, the grey radiator approximation was chosen as a basis for the radiation heat transfer calculations, since it significantly simplifies the calculation of the configuration factor for an exposing building face. This was particularly true for building exposures with more than one opening. It was claimed to provide a reasonable approximation of the radiant emissive power of those openings; however, as McGuire noted, this approach will “rarely lead to the exact solution” [375, p. 4]. The limitation is particularly evident in cases involving large exposing building faces with short limiting distances, a low permitted percentage of unprotected openings, or even with minimal clustering of openings in the building or fire compartment face. As such, this should also be re-examined in a technical reconciliation using the proposed new framework.

When calculated from theory, the configuration factor from the actual openings in an exposing building face to a point of interest is typically higher than that calculated using the corresponding grey radiator plane. This discrepancy increases as any clustering of openings becomes more pronounced. Thus, a key issue to be re-examined is the uncertainty or error inherent in estimates of the allowed opening area for a given exposing building face area, aspect ratio, and limiting distance, using the grey radiator approximation versus a more in-depth theoretical analysis, for the situation of clustering of openings on an exposing building or fire compartment face. This is examined through a systematic analysis of each permitted percentage value in Table 3.2.3.1.-B of the 2020 NBC using a hypothetical exposing fire compartment face for each of these values, defined based on the corresponding exposing fire compartment face area, aspect ratio, and limiting distance. Three scenarios are defined for each hypothetical fire compartment face (i.e., table entry), whereby the area established from the permitted percentage of unprotected openings is subdivided into 1, 3, and 9 separate openings, distributed across

the exposing fire compartment face, as illustrated for one example in Figure 7-31. A fourth reference scenario is defined, using a grey radiator approximation that includes 10,000 openings spaced equally over the fire compartment face.

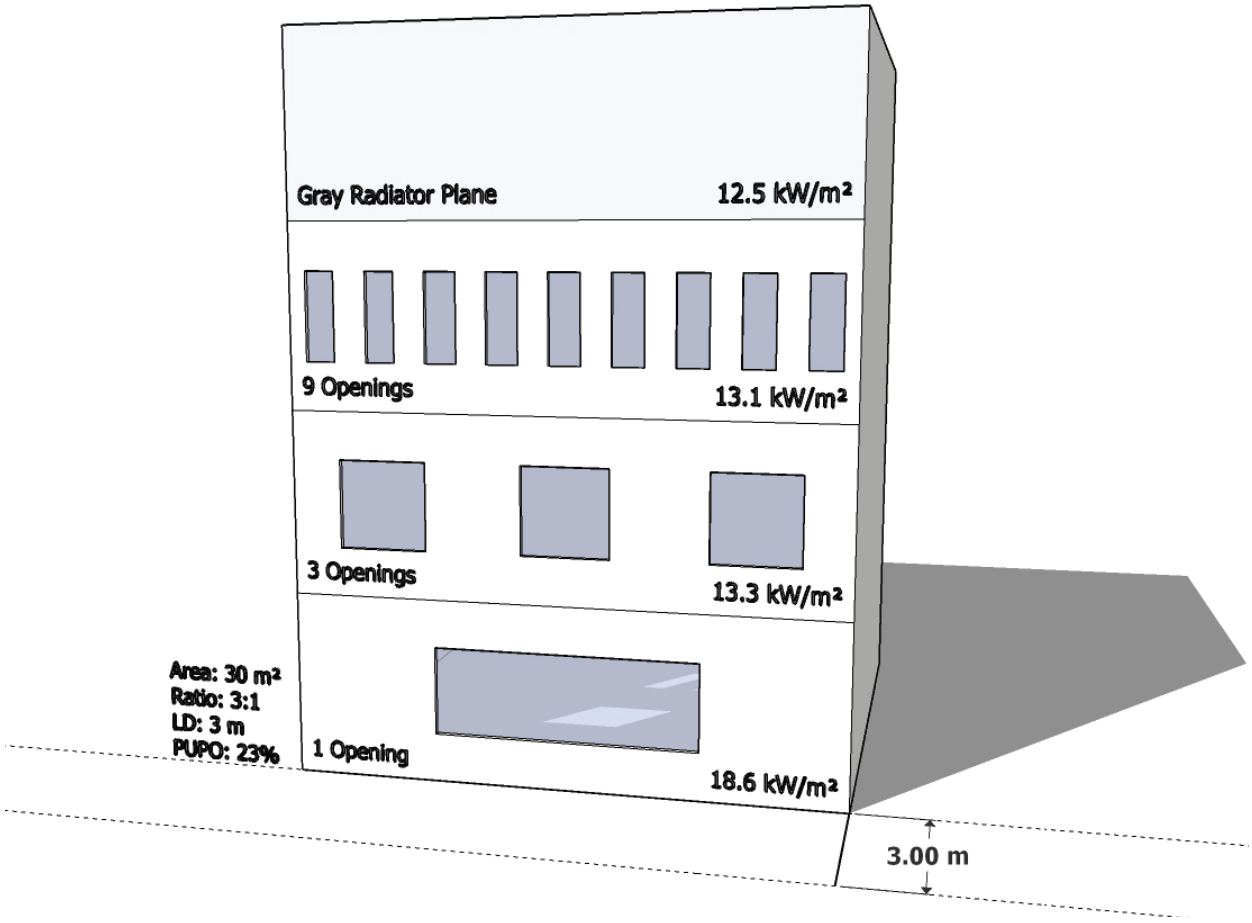


Figure 7-31: Grey radiator assessment opening distribution

The configuration factor is calculated for each individual opening in each hypothetical fire compartment face using Equation 7-17 to a point of interest (y_p, z_p), located at a distance (d) from, and centered on, the fire compartment face, as illustrated in Figure 7-32. Equation 7-17 is more complex than the configuration factor equation used in the development of the NBC spatial separation tables (Equation 7-7), by accounting for an opening that is offset from the point of interest. The configuration factors calculated for each opening are then summed over the fire compartment face using Equation 7-18 to calculate the total configuration factor at the point of interest from all openings in that face.

$$\phi_{i,o} = \frac{1}{2\pi}\left\{\frac{C}{G}\left(ArcTan\left[\frac{A}{G}\right] - ArcTan\left[\frac{B}{G}\right]\right) + \frac{D}{H}\left(ArcTan\left[\frac{B}{H}\right] - ArcTan\left[\frac{A}{H}\right]\right) + \frac{A}{E}\left(ArcTan\left[\frac{C}{E}\right] - ArcTan\left[\frac{D}{E}\right]\right) + \frac{B}{F}\left(ArcTan\left[\frac{D}{F}\right] - ArcTan\left[\frac{C}{F}\right]\right)\right\} \quad \text{Equation 7-17}$$

Where:

$\phi_{i,o}$ = Configuration factor of an individual opening

$E = \sqrt{d^2 + A^2}$

$F = \sqrt{d^2 + B^2}$

$G = \sqrt{d^2 + C^2}$

$H = \sqrt{d^2 + D^2}$

$A = y_1 - y_p$

$B = y_2 - y_p$

$C = z_1 - z_p$

$D = z_2 - z_p$

d = Perpendicular distance between the opening and the point of interest (m)

y_1 = Horizontal starting coordinate of the opening (m)

y_2 = Horizontal ending coordinate of the opening (m)

y_p = Horizontal coordinate of the point of interest (m)

z_1 = Vertical starting coordinate of the opening (m)

z_2 = Vertical ending coordinate of the opening (m)

z_p = Vertical coordinate of the point of interest (m)

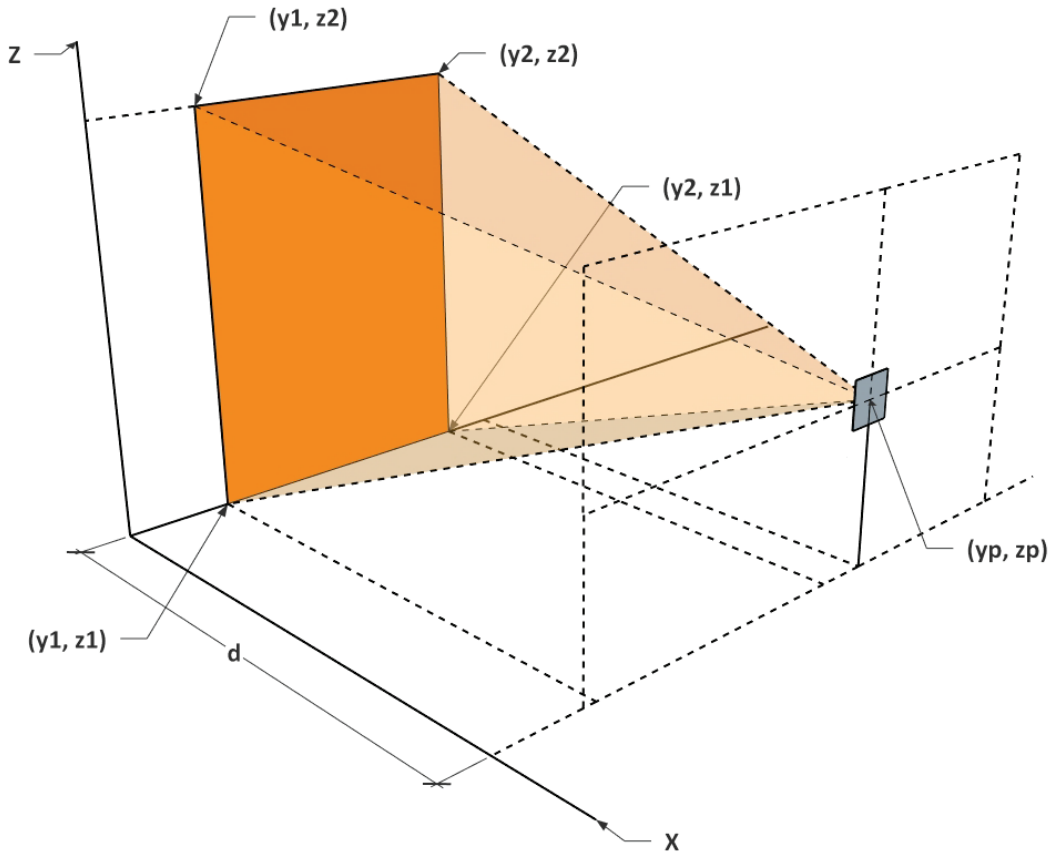


Figure 7-32: Configuration factor at a point of interest, offset from the centre of the opening

$$\phi_t = \sum_{i=1}^{n} \phi_{i,o}$$ Equation 7-18

Where:

ϕ_t = Total configuration factor at the point of interest from all openings in the exposing fire compartment face

n = Total number of openings in the exposing fire compartment face

i = Specific openings in the exposing fire compartment face

The heat flux at the point of interest from all the openings is then calculated using Equation 7-19, based on the radiant emissive power derived from the St. Lawrence burns, which underlie the spatial separation table values for low hazard occupancies, along with the total configuration factor for all the openings in the hypothetical fire compartment face, as calculated above.

$$q" = \phi_t \cdot Em$$ Equation 7-19

Where:

$q"$ = Incident heat flux at the point of interest (kW/m²)

Em = St. Lawrence burn test radiant emissive power (178 kW/m²)

The results for incident heat flux from the openings in each hypothetical exposing fire compartment face are categorized into four heat flux ranges, as provided in the colour legend in Table 7-14. A rating of green, according to the table, indicates a heat flux value from the specified exposing fire compartment face to the adjacent building that is below the acceptable value upon which the NBC spatial separation tables were calculated. A rating of yellow is above the acceptable heat flux level, but below the autoignition heat flux value for wood [213]. A rating of orange is up to a value that the current NBC specifies as a critical ignition heat flux threshold, to permit a combustible material to be used as part of the construction of a building required to be constructed of noncombustible materials in the NBC. A rating of red is above this threshold value. Therefore, these ranges indicate progressively higher, and thus more dangerous, levels of heat flux to the adjacent building.

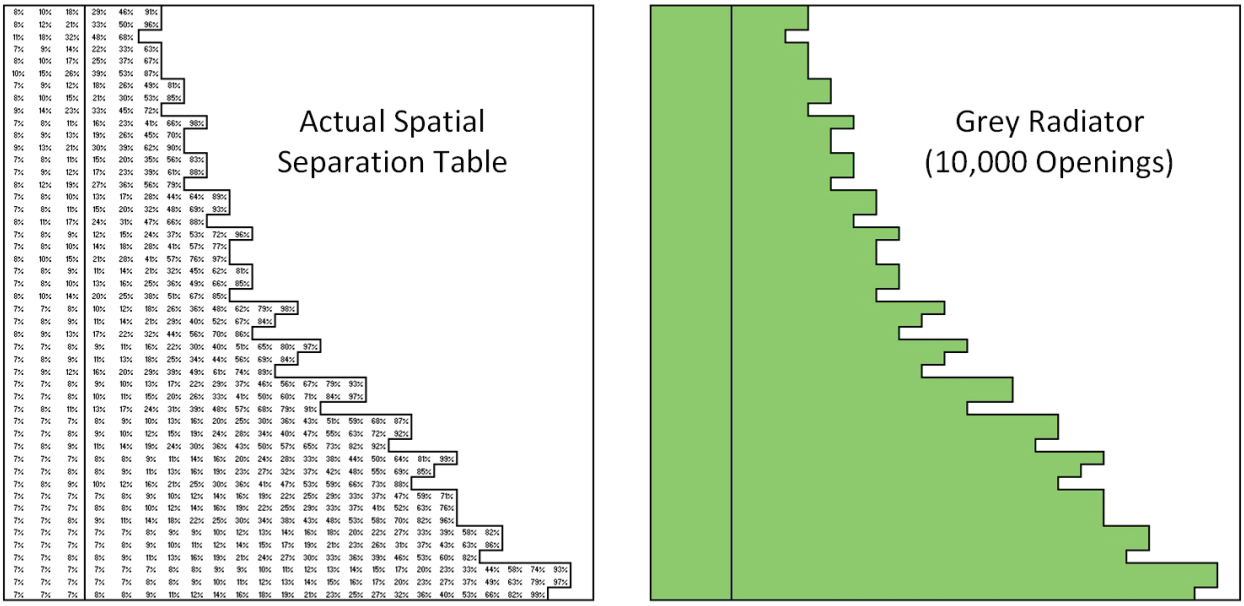
Once the calculated heat flux values have been categorized, they are presented in the same structure as the spatial separation tables, as shown in Figure 7-33(a). Results for the grey radiator approximation (reference scenario), shown in Figure 7-33(b), are all green. This result is expected, as it reflects the grey radiator approximation underlying the table values, specifically a large number of evenly distributed openings.

Figure 7-34(a) through (c) show the reconciled values of heat flux to an adjacent building for all combinations of exposing building face area, aspect ratio and limiting distance contained in the current spatial separation tables. Each subfigure shows results calculated using a different number of openings (i.e., 1, 3, 9), with the black stepped line delineating values for which the opening area on the exposing fire compartment face would be below 100%. The hatched area on the left side of each plot in Figure 7-34 corresponds to values calculated for limiting distances of 2.0 m or less. These are dealt with separately in

the current NBC, as addressed by the change implemented into the 2010 NBC, and discussed in Section 7.2.5.1.

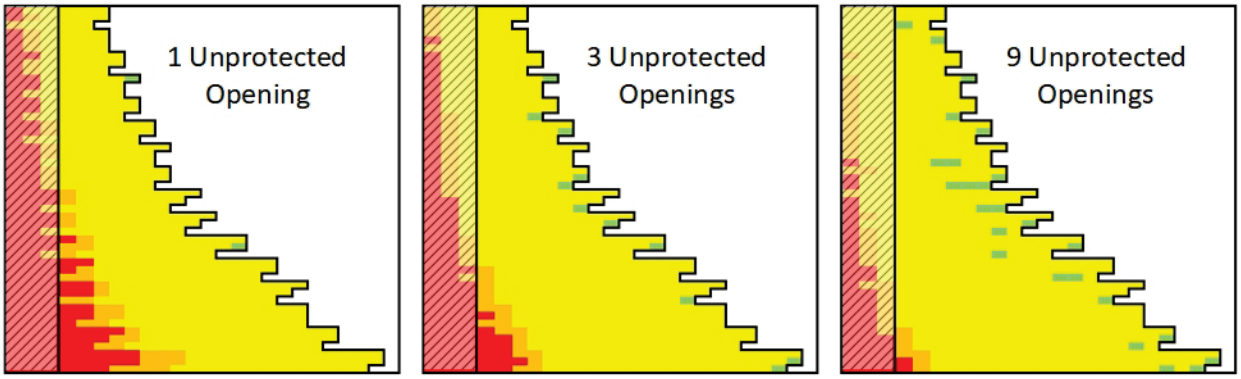
Table 7-14: Incident heat flux legend

Colour	Heat Flux Range (kW/m²)
Green	< 12.5
Yellow	12.5 to < 33.5
Orange	33.5 to < 50
Red	> 50



(a) (b)

Figure 7-33: (a) Table 3.2.3.1.-B, (b) Grey radiator assessment result for Table 3.2.3.1.-B



(a) (b) (c)

Figure 7-34: Grey radiator assessment result for Table 3.2.3.1.-B

The heat flux results shown in Figure 7-34 are nearly all higher than the critical incident heat flux of 12.5 kW/m² that forms the reference limit in the current spatial separation tables. The results also confirm McGuire's observation [375]. The most significant differences in Figure 7-34 occur for single, centrally located openings at shorter limiting distances and larger exposing building face areas, specifically in the bottom left area in all subfigures in Figure 7-34. Differences outside this range are also significant for limiting distances close to 2 m, suggesting that the 2 m limit, above which the 2020 NBC allows clustering of openings, is not adequate. These results also contrast statements noted in the historical analysis that local concentrations of openings do not create an issue of concern [387].

It follows, then, that an alternative to the grey radiator approximation is necessary to address these discrepancies. This is addressed here through further technical reconciliation of the spatial separation table values, using the enclosing rectangle approach. This approach, arising out of research by [382, 384], has been used in the UK since the 1960s, as well as in other jurisdictions such as New Zealand [206]. It was also contemplated for the NBC in the 1960s [387, 401, 402], but ultimately abandoned due to its complexity [387].

To demonstrate the implications of applying the enclosing rectangle approach and its potential improvement in accuracy over the grey radiator approximation, consider the "1 opening" example in Figure 7-31. The variables of interest in this example include the exposing fire compartment face area of 30 m², the associated aspect ratio of 1:3, and a limiting distance of 3 m (i.e., the distance to the property line). According to the current NBC spatial separation table, this configuration would allow a single centrally located unprotected opening of 6.9 m² (23%). The radiant heat flux on an adjacent building located 6 m from the single opening (i.e., twice the limiting distance) is calculated using the more fundamental configuration factor (Equation 7-17) and heat flux calculation (Equation 7-19) to be 18.6 kW/m². This result is just one instance of the broader set of results illustrated in Figure 7-34(a), and is obviously greater than the threshold value of 12.5 kW/m² that underlies the spatial separation tables.

Using the enclosing rectangle approach for this scenario requires that that the enclosing rectangle have the same bounds as the unprotected opening, meaning that the opening is then considered to be 100% of the area of the enclosing rectangle. This value, in combination with the enclosing rectangle area of 6.9 m² and aspect ratio of 3:1, are substituted into Equation *7-7*, and solving for distance results in a value of 7.1 m. Using this distance in the more accurate method represented by Equation 7-17 and Equation 7-19 results in a heat flux of 12.5 kW/m² at the neighbouring building. This value aligns with the threshold criteria upon which the NBC spatial separation tables are intended to be based, supporting the enclosed rectangle approach for this case.

Similar results are expected for other single opening configurations when using the enclosing rectangle approach. For scenarios involving multiple openings or clusters of openings, the enclosing rectangle approach utilizes a more precise version of the grey radiator approximation than the approximation based on the full fire compartment face area used in the NBC. The results of the set of examples, illustrated in Figure 7-31 and with enclosing rectangles in red in Figure 7-35, are included in Table 7-15 for the grey radiator approximation (NBC), the enclosing rectangle approach, and the fundamental approach, as was

used above for the detailed analysis. For each approach, values include the distance between an exposing fire compartment face and the adjacent building considered to be “acceptable” for that approach, and the actual heat flux at the adjacent building face based on Equation 7-17 and Equation 7-19. With the exception of the example with 10,000 evenly spaced openings, the actual heat flux based on the grey radiator approximation exceeds the critical heat flux of 12.5 kW/m². In contrast, the enclosing rectangle approach provides results that are more accurate than the NBC grey radiator results and, in some cases, more conservative than the actual heat flux values based on the fundamental approach.

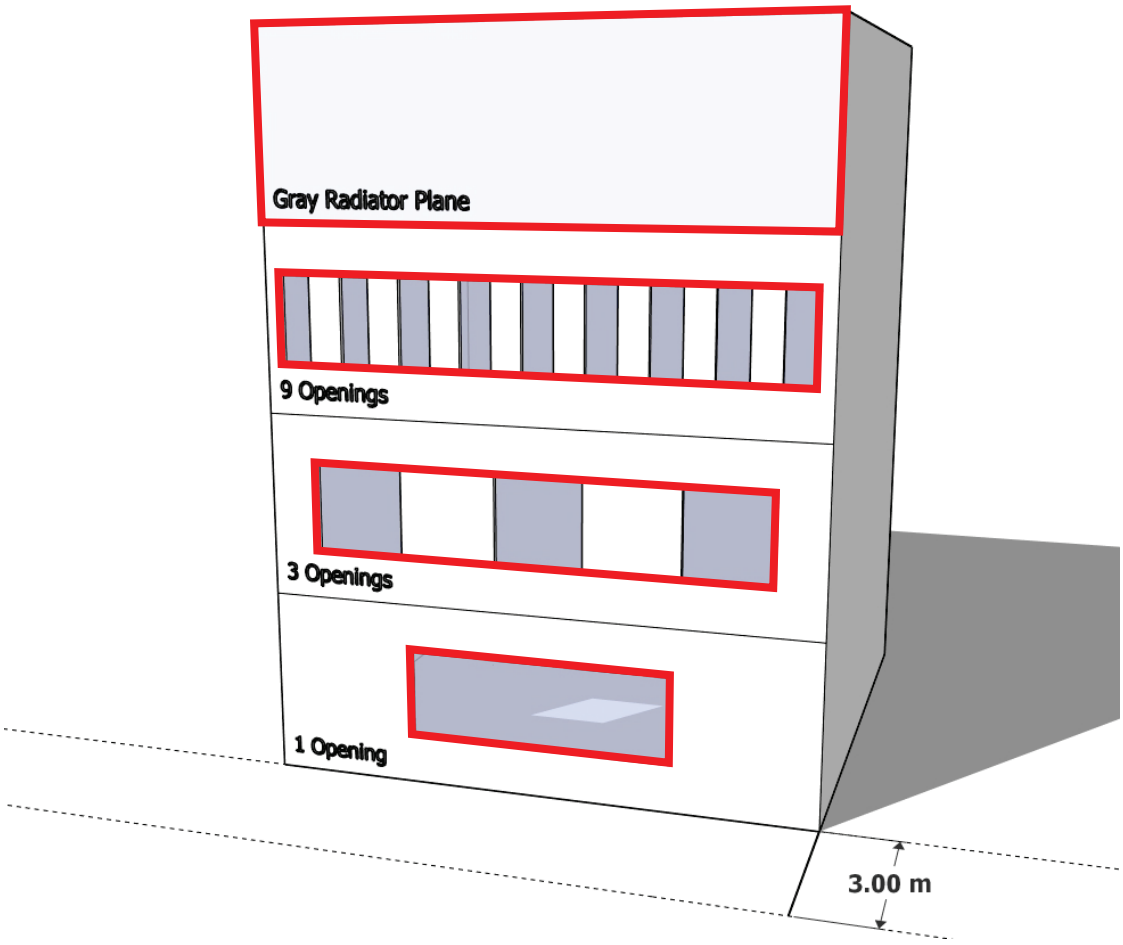


Figure 7-35: Enclosed rectangle assessment

Table 7-15: Comparison of the grey radiator approach to enclosed rectangle and fundamental approaches

Scenario	Grey Radiator Approximation (NBC)		Enclosing Rectangle Approach		Fundamental Approach (Equation 7-17 and Equation 7-19)	
	Distance (m)	Actual Heat Flux (kW/m²)	Distance (m)	Actual Heat Flux (kW/m²)	Distance (m)	Actual Heat Flux (kW/m²)
1 opening	6.00	18.63	7.09	12.50	7.09	12.50

Scenario	Grey Radiator Approximation (NBC)		Enclosing Rectangle Approach		Fundamental Approach (Equation 7-17 and Equation 7-19)	
	Distance (m)	Actual Heat Flux (kW/m²)	Distance (m)	Actual Heat Flux (kW/m²)	Distance (m)	Actual Heat Flux (kW/m²)
3 openings	6.00	13.27	6.52	11.36	6.19	12.50
9 openings	6.00	13.11	6.28	12.06	6.16	12.50
10,000 openings	6.00	12.50	6.00	12.50	6.00	12.50

From this analysis, it is clear that, while the enclosing rectangle approach is more complex than the NBC grey radiator approximation, it provides more accurate and generally more conservative results, even in comparison to the more fundamental approach.

The impact of the use of the grey radiator approximation on the acceptable level of performance, determined using the spatial separation tables in the present NBC, merits some further discussion at this point, since these tables set the benchmark against which to judge the acceptability of an alternative solution design. Thus, a design that complies with the spatial separation table values is considered an acceptable solution, even though, as presented in Figure 7-34, such a design can have combinations of exposing face area, aspect ratio, and limiting distance that result in critical heat flux values to the adjacent building well above the intended threshold of 12.5 kW/m².

Consider again the "1 opening" example in Figure 7-31, which, as calculated above, would permit a single 6.9 m² (23%) centrally located unprotected opening as the "acceptable solution" benchmark for design. Again, using the theoretical calculations above, as might be used in development of a performance-based design, the incident heat flux from this opening to an adjacent building is 18.6 kW/m². Since the proponent of an alternative design for a speciality building is required to demonstrate equivalent performance to the NBC spatial separation acceptable solution, the acceptable performance of an alternative solution would be 18.6 kW/m² in this case, rather than the critical incident heat flux of 12.5 kW/m² upon which the acceptable solution table values were originally based. This is supported by the 2020 NBC, which states the following for establishing the acceptable level of performance for an alternative solution design [21, Div. A, pp. 1-18, 1-19]:

> *[a]mong a number of possible designs satisfying acceptable solutions in Division B, the design providing the lowest level of performance should generally be considered to establish the minimum acceptable level of performance to be used in evaluating alternative solutions for compliance with the Code.*

This discrepancy is further exacerbated, as illustrated in Figure 7-34, for alternative solutions involving larger exposing building faces and shorter limiting distances, where "acceptable" incident heat flux values can exceed 100 kW/m². For context, this level of heat flux is almost three times the value that could lead to the autoignition of wood construction materials [213]. Although technically allowed, the use of such a

high incident heat flux to establish the “acceptable” level of performance for an alternative solution design would constitute malpractice due to known properties of materials. As such, it supports Bjelland’s findings that the performance associated with acceptable solutions, based on existing code requirements, does not necessarily provide a single consistent level of safety [138]. In contrast, such issues can be addressed by defining explicit acceptance criteria, such as 12.5 kW/m², against which to measure the performance of an alternative solution. Of course, this still would not address the discrepancies implicit in the spatial separation acceptable solution requirements as a result of the grey radiator approximation. These will require additional code changes, with technical support of historical analysis and technical reconciliation, that can be developed using the regulatory framework proposed in this thesis.

7.3.4 Fire Load and Flame Front

Observations during the St. Lawrence burn tests identified fire load and wind conditions as significant factors influencing the levels of thermal radiation recorded from the test buildings [368]. As the requirements were developed, the impact of fire load on radiation from the building openings was addressed through an ad hoc, magnitude-based relationship linking the combustibility of interior lining materials to measured radiant heat flux. Impacts of wind were indirectly accounted for through consideration of flame extension from openings and the addition of a flame front factor to increase the required limiting distance. This is the fourth and most substantial issue addressed during the technical reconciliation phase of the proposed new framework. For this, it is necessary to review research that was conducted after the St. Lawrence burns but is not incorporated into the present NBC spatial separation requirements.

Following the St. Lawrence burn tests, the JFRO conducted experiments measuring compartment temperatures under varying ventilation conditions, characterized by the air flow factor $A\sqrt{H}$, and fire loads ranging from 25 to 120 kg/m² (5 to 25 lb/ft²) [371], based on which they determined that the level of radiation emitted from a compartment fire was a function of both fire load and ventilation [370, 371]. Additional experiments used well-ventilated scale model rooms with varying fire loads, demonstrating that radiant intensity increased with fire load on a floor area basis [371].

Extrapolation of a correlation derived from the scale model data related a radiant intensity of 167 kW/m² (4 cal/cm²·s) to a fire load of 49 kg/m² (10 lb/ft²). This was verified in a subsequent full scale test, where a peak radiant intensity of 4.3 cal/cm²·s was measured. This corresponded to a black body temperature of 1,100 °C, which was considered a limiting maximum compartment fire temperature. These findings were broadly simplified for UK regulatory development as follows [382]:

- A peak radiant intensity of 167 kW/m² (4 cal/cm²·s) was defined for well ventilated fires in a floor area with a fire load greater than 24.4 kg/m² (5 lb/ft²) as the “normal” standard.
- A peak radiant intensity of 84 kW/m² (2 cal/cm²·s) was arbitrarily defined for a floor area with a fire load of 24.4 kg/m² (5 lb/ft²) or less, considered a low fire load.

These radiant intensities and fire loads are less than half of those that form the basis for the NBC low hazard (50 kg/m² [10 lb/ft²] and 178 kW/m²) and high hazard (100 kg/m² to 150 kg/m² [20 lb/ft² to 30 lb/ft²] and 356 kW/m²) spatial separation tables respectively. The upper limit radiant intensity of 167 kW/m² (4 cal/cm²·s), established through the JFRO tests, suggests that the high emissive power of 356 kW/m² in the St. Lawrence burn tests is more likely attributable to significant flame extension from Building No. 5 openings due to wind conditions than as a result of the fire load itself.

Similar to the NRC, the JFRO did conclude that the level of radiant heat emitted by a fire is likely to be affected by wind, which can increase the rate of burning or deflect flames from an opening [381, 382]. In contrast to the NBC spatial separation requirements, the JFRO omitted wind effects in the development of their baseline spatial separation tables in the early 1960s, pending further study [214].

In 1968, the JFRO examined [383, p. 1] "the size and thickness of flames from windows [and] the effects of wind on their size and deflection" using full scale tests in a brick-walled compartment with dimensions of 7.7 m in width, 3.7 m in depth (28.49 m² floor area), and 3 m in height under light winds, complemented by model testing in a wind tunnel [383]. The front of the compartment had two openings, each measuring 3 m wide by 1.8 m high, separated by a 0.7 m gap. A total of 19 tests were conducted, varying factors such as opening size, fire load quantity and distribution, and lining material (with one test incorporating a combustible lining). The findings confirmed prior estimates and assumptions [381, 382] used in the development of the UK spatial separation requirements. Additionally, the study made significant observations regarding geometry of flame fronts and behaviour under different conditions [383, p. 92], including that:

> *The extra radiation from flames outside the openings was not large enough to warrant altering the recommended separation distances on which present building regulations have been based.*

The referenced "present building regulations" were those discussed above, in which the radiant emissive power was based on window area and fuel load only. The study did, however, recommend further full-scale testing under higher wind conditions.

The results of model-scale testing conducted in a wind tunnel found that the orientation of the compartment relative to the wind flow influenced the intensity of radiation at the compartment opening. The full-scale implications could not be extrapolated from the small scale testing, and it was suggested that under wind conditions of up to 29 km/h, the rate of burning could change by less than 70%. In light of these findings, the St. Lawrence burns were re-analyzed, and it was speculated, without confirmation, that the difference in results (i.e., significant flame fronts in the St. Lawrence burns) was likely due to greater ventilation, and particularly cross ventilation, in Canadian homes [383].

At about the same time, the Building Research Division of the NBS in the United States conducted fire tests in three residential apartment units [249] (1967 NBS Burns). These tests used wood crib fire loads of 6 lb/ft² (29 kg/m²), with all test room interiors lined with noncombustible materials. The NBS Burn Nos. 1 and 3 included thermopile radiometers to measure radiant intensity and radiation pyrometers to measure the apparent black body temperature of the window openings. The radiometer measurements were

correlated to the sizes and configurations of the window openings, following a similar methodology as the St. Lawrence burns to determine radiant emission from the window openings alone versus that from window opening plus flame front [249].

Peak values of radiation measured during the NBS Burn tests are summarized in Table 7-16. Wind speeds were measured at 7 mph (11.3 kph) and 11 mph (17.7 kph) for Test Nos. 1 and 3, respectively. The fire room window in Test No. 1 was leeward, and in Test No. 3 was windward. The wind direction in Test No. 3 was observed to limit the development of the fire [249] and is reflected in the nearly equal values of window radiation intensity estimated from radiometer measurements and calculated based on the black body temperatures as measured by the radiation pyrometer in Test No. 3.

Table 7-16: NBS Burn test maximum radiometer results

Test No.	Fire Room		Fire Room Window		
	Blackbody Temperature (°C)	**Equivalent Intensity (kW/m²)**	**Measured Intensity, I (kW/m²)**	**Configuration Factor, F**	**Estimated[14] Window Radiation Intensity, I/F (kW/m²)**
1	899	106.8	34.1	0.1480	227.1
3	921	114.7	2.5	0.0224	111.3

The difference between values of radiation intensity in Test No. 1 shows that the radiant intensity from the fire to the radiometer is more than double that based on the window alone, likely due to flame extension from the windows. Whether this further supports the notion that wind conditions influence the radiant intensity of flames extending from the window openings, it is not clear that the differences are entirely due to the wind conditions in this test, since flame extension from a window can also occur in the absence of wind due to flaming fire gases exiting the windows.

In summary, these tests show mixed results regarding the influence of wind conditions on the flame extension, and thus radiant intensity, that might be expected from a window opening during a fire. Further, when the values used in the spatial separation tables are based on experimentally measured values of radiation from full-scale or scaled tests, they already account for the effects of wind conditions. This raises a question about the justification for including the flame front factor in the spatial separation requirements in the current NBC. To extend the present technical reconciliation, as would be done under the proposed new framework, this apparent inconsistency is re-examined based on our current science-based understanding of fire behaviour and flame front extension using methods presented in Section 3.3. Results are used to analyze safe separation distances in comparison with the more traditional approaches used in the development of the NBC spatial separation tables. Then, to place the results from the updated

[14] Estimated based on the calculated configuration factor of the openings, the measured black body temperature, and the measured radiation intensity at the radiometer.

analytical method in the context of regulatory impact, they are compared with the NBC method and with spatial separation distances determined using approaches from other international jurisdictions.

7.4 Technical Risk-Based Analysis

The key factor underlying the spatial separation requirements in the NBC is radiant heat exposure at a distance from a fire. As demonstrated in the St. Lawrence burn test results, high levels of radiant heat exposure were recorded after the fires in the living rooms transitioned through flashover to full room (compartment) involvement. These fires are characterized by high temperatures that are relatively uniform within the compartment, and by flame extension out of compartment openings [403] (Section 3.3.2.1). The magnitude of radiant heat exposure at a distance is directly related to the degree of flame extension from openings, as was particularly evident in the observations and results of Building No. 5 of the St. Lawrence tests (Section 7.2.4.1). Accordingly, the flame front extension factor was originally intended to address the nonlinear geometrical projection of flames observed during the St. Lawrence burn tests, coupled with increased difficulty in firefighting associated with reduced space between the extending flames and the adjacent building face [370]. However, the effects of the flame front were already incorporated into the artificially elevated radiant emissive power values that form the basis of the spatial separation table values. To re-analyze this complex situation and uncouple the various factors inherent in the present NBC methods, it is important to define the following stages of fire development and the radiant heat to quantitatively characterize the fire hazard. These include:

1. Ignition and established burning.
2. Localized fire growth.
3. The onset of flashover.
4. Full compartment burning.
5. Flame extension from compartment openings.

The incident heat flux at a distance from the opening(s) that could result in damage to neighbouring buildings is then calculated based on the radiant heat emitted from the opening(s) and due to flames extending from the openings. Analyzing these stages of fire development and spread for all possible building design configurations is a complex task and would require a very comprehensive generic risk assessment. Therefore, a targeted subset of situations is defined to evaluate the efficacy of the flame front factor in the existing spatial separation requirements. This subset is focused on fire development in a typical Canadian living room, assuming Stage 1 above is complete, i.e., ignition has occurred, and the fire has become established. The analysis then focuses on generating values for, and further examining, radiant heat emission at Stage 5 of fire development. The analysis is conducted through the following phases:

- **Phase 1:** modelling local fire development (Stage 2) to the predicted onset of flashover (Stage 3) using an established zone model.

- **Phase 2:** modelling full compartment burning (Stage 4) and flame extension from openings (Stage 5), using realistic models of flame extension and radiant heat exposure, to determine radiant heat flux at a distance, and comparing these values to those determined using regulatory models, including for the NBC.

These phases of fire growth and spread involve complex chemical and thermophysical processes, influenced by compartment (living room) characteristics and contents. Therefore, the stages of fire development and spread, as well as the factors influencing transitions between these stages, are governed by stochastic processes with inherently uncertain outcomes. The analytical approach to characterize these stochastic processes and the associated treatment of uncertainty are detailed in the following sections.

7.4.1 Phase 1: Fire Development to Flashover - Zone Model Analysis

Assuming ignition has occurred and localized burning is established, fire growth and spread is modelled using a zone fire model. The model approximates compartment fire and smoke development and spread by dividing the compartment into two zones, a heated, buoyant upper layer and a cooler lower layer [404], each having primarily uniform characteristics. The model balances only mass and energy between the two layers based on the fire source development, with source terms connecting the main fire room to adjacent compartments and through external boundaries to ambient.

Several publicly available zone fire models have been verified and validated to differing degrees for modelling fire growth within and between compartments. Key examples include CFAST [405], B-Risk (BRANZFIRE) [406], and Ozone [407]. Each is considered briefly for use in the present analysis.

OZone V2, developed by the University of Liege [407], was used in the research conducted by De Sanctis as part of the generic risk assessment approach to regulatory development [197] (Section 3.3.3). OZone is capable of modelling local fire growth and spread, predicting the onset of flashover, and switching from a two-zone to a single-zone model to represent full compartment burning [407]. However, OZone has limited validation studies available [407] and is not as widely used as other zone models, so was not selected for the present analysis.

B-Risk is a risk-based zone model that supports input of random parameters through several defined distributions and allows Monte Carlo-based analysis. During testing for the present analysis, the B-RISK software encountered multiple unspecified errors that caused the termination of the sequence of runs. In addition, B-RISK was unable to process more than 32,767 iterations within a single set of simulation runs due to a data overflow problem related to the limitations of the Visual Basic Int16 data type. Since more than 32,767 simulations were expected to be necessary to achieve convergence, B-Risk was not selected for use in the present analysis.

The Consolidated Model of Fire and Smoke Transport (CFAST) is a zone model developed and maintained by the National Institute of Standards and Technology (NIST, or previously NBS). The NBS developed the set of model building codes upon which many of the requirements of the 1941 NBC were based (Sections 2.1.3.3 and 2.1.4). Their model, CFAST, has been in development since 1990 [405] and is one of the most

widely used zone fire models. It is based on an earlier model called FAST, which was originally developed in the late 1980s [408]. CFAST is actively maintained with all source code publicly available for review and comment, allowing broad assessment and technical feedback. Further, its development follows the guidance provided in ASTM E1355, “Standard Guide for Evaluating the Predictive Capabilities of Deterministic Fire Models” [409]. The current version, CFAST 7.7.4, was released on January 20, 2023 [405, 410-412]. The verification and validation of CFAST is extensive and addresses a wide range of model applications and outcomes. This includes key factors relevant to the present analysis, such as the prediction of the onset of flashover [411]. Therefore, given its robust validation and applicability to this study, CFAST was selected for use in the present analysis.

CFAST input files are structured into namelist groups that characterize parameters related to fire growth and spread within a compartment. These include compartment characteristics such as dimensions and material properties, opening characteristics such as size and height in a wall, and fire characteristics such as heat release rate and location. An example input file is included as Appendix H.

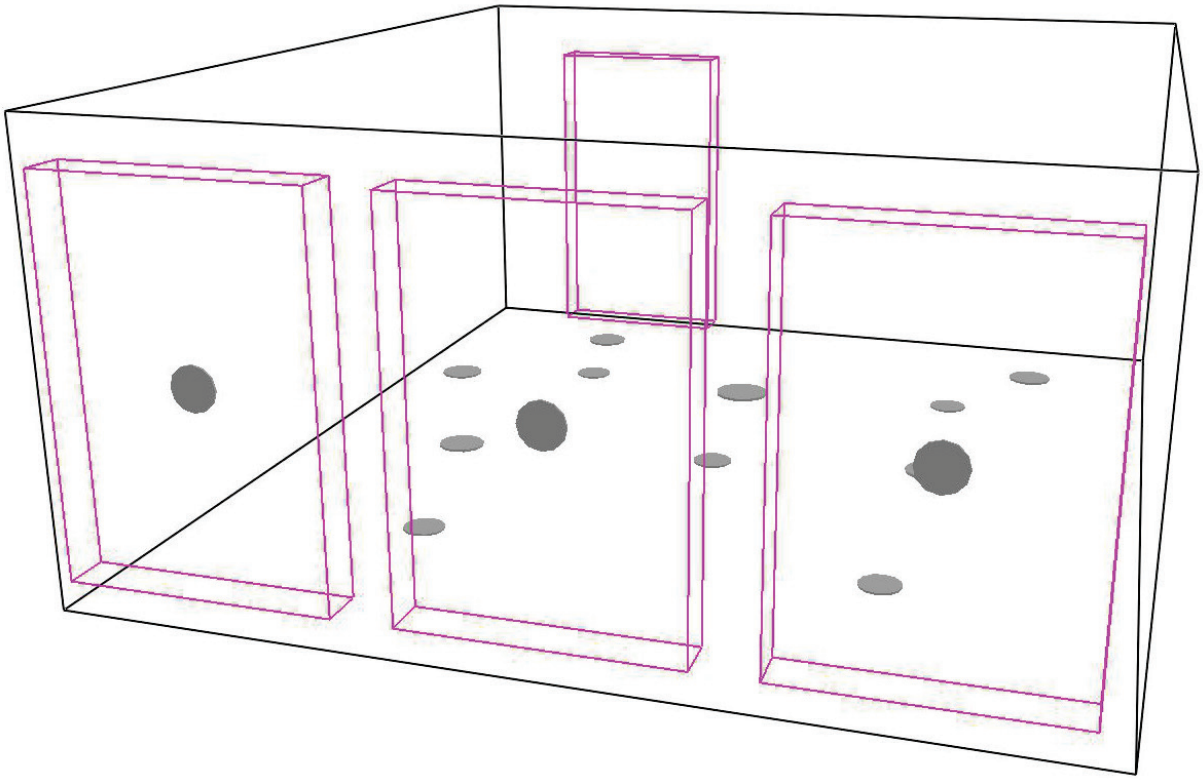


Figure 7-36: Three window scenario

CFAST model scenarios can be visualized graphically using Smokeview [413], a counterpart fire model visualization software also developed by NIST. This can be done to verify model setup and configuration, as well as for output during and after the simulation is run. An example visualization of the setup for one of the analyzed CFAST models is included in Figure 7-36. The compartment boundaries are outlined in black. The door in the back wall is outlined in pink (pink represents a boundary vent). Three windows on the front wall are also outlined in pink, with a grey circle at their center indicating the temperature device

used to indicate glass breakage. Floor level heat flux sensors are shown as grey circles on the floor of the compartment, and furniture heat flux sensors are similarly shown as grey circles positioned above floor level at the approximate centre and upper surface level for each furniture item as located in this particular scenario. The furniture items themselves are not visualized here.

CFAST input files are read and processed by a single executable file, which generates a log file, a status file, a visualization file, and multiple CSV-based output data files. Model run times range from seconds to minutes, depending on the time step required to ensure convergence of the governing ordinary differential equations.

As discussed above for Phase 1, the CFAST analysis will be used to assess fire development within the Canadian living rooms, from ignition and established burning through fire growth and development up to the onset of flashover. At this point, the Phase 2 analysis shifts from the use of CFAST to a model that couples the analysis of full compartment burning with exterior flame venting, which is then supplemented with a custom radiant heat transfer analysis. The results from this analysis are then compared to heat transfer results from more basic regulatory models, including the NBC. The Phase 2 analysis is discussed below.

7.4.2 Phase 2: Radiant Heat Flux Analysis

The next step in the analysis is to assess the radiant heat transfer from the compartment by comparing results from calculations based on fundamental approaches, informed by testing and an updated understanding of the principles governing external venting flames, with those from calculations based on the NBC methodology, as well as more current regulatory methodologies used in the development of spatial separation requirements in other international jurisdictions. These include methodologies currently incorporated in regulations in the US (NFPA 80A), the UK (ADB V2 BR187), and New Zealand (NZ C/VM2). This comparison is carried out through the development of representative models of emissive plane configurations and the associated radiant heat transfer calculations. The key factor underlying the spatial separation requirements is the critical distance at which the incident heat flux from a burning building to an adjacent building exceeds a defined threshold. Determining this critical distance is key to evaluating and comparing these models.

The regulatory approaches assume that flashover has occurred and that the compartment is fully involved in fire. They then prescribe an emissive power for the openings in the compartment face based on a defined and prescribed hazard level. The emissive source is then represented as a simplified plane, either being the entire compartment face or a rectangle that encloses the openings. The resulting heat flux at a given distance, particularly at the critical distance, depends only on the configuration and dimensions of the compartment face and its openings. In contrast, the fundamental approaches more realistically represent the geometry and temperature of an externally venting flame based on a broader range of fire compartment variables, such as fuel load and ventilation, than those of the regulatory approaches. The models that represent these approaches and are used in the present analysis are discussed below.

In the NBC model (NBC 2020 model), the emissive source is modelled as a vertical plane encompassing the entire area of one exterior face of a building or a fire compartment containing unprotected openings. This plane is offset by 1.8288 m (6 ft) from the actual location of the building face to account for the projected flame front, as shown in Figure 7-37. The plane is then approximated as a grey radiator emissive source, with effective emissive power determined by the hazard level of the occupancy (178 kW/m² for low hazard or 356 kW/m² high hazard) and percentage of unprotected openings within the plane. The critical distance is defined as the distance to the point at which the incident heat flux from the source plane reaches 12.5 kW/m². The relationship between the source plane and the point of interest is calculated using a single configuration factor equation.

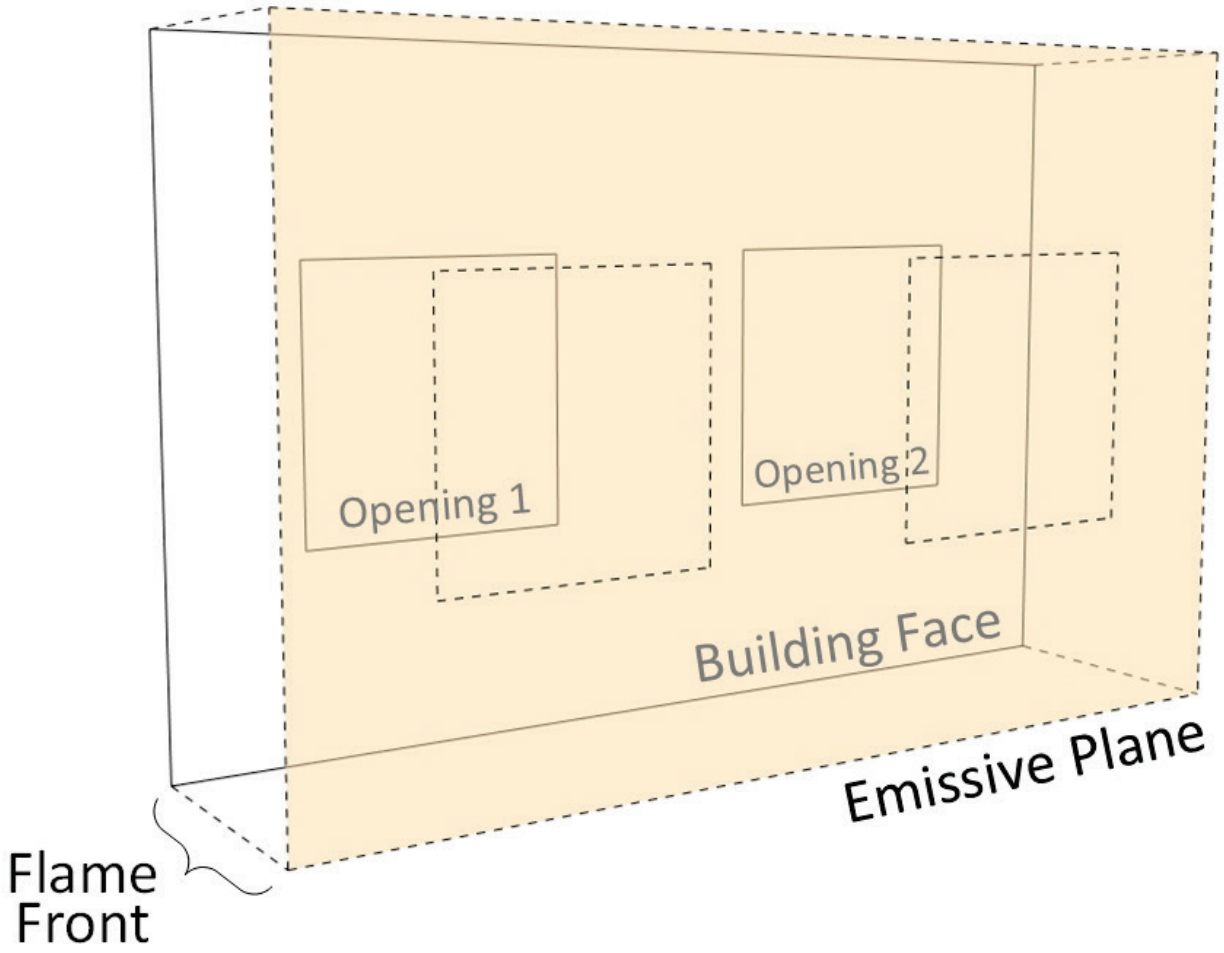


Figure 7-37: Isometric view of emissive power vertical plane for the NBC and NFPA 80A

The first regulatory model considered for comparison is based on the methodology defined in NFPA 80A (NFPA 80A model), originally published in 1925 [248], then significantly updated in 1967 [414]. At that time a table of separation distances between buildings was introduced. These distances are presented as a function of building height (in stories), building width, three levels of exposure severity, and percentage of openings in the exposing wall. The table values were derived from the methodology in [213], which was itself based on the results of the St. Lawrence burns [414], and calculated with assistance from staff at the

Division of Building Research of the National Research Council of Canada [415]. The emissive source in the NFPA 80A model is similar to the NBC 2020 model, though the source plane is offset by 1.524 m (5 ft) from the exterior face to represent the projected flame front, 0.3 m (1 ft) less than the flame front used in the NBC. The rationale for this difference is not documented. As in the NBC model, the emissive plane is represented as a grey radiator, shown in Figure 7-37. However, unlike the NBC 2020 model, the emissive power of the NFPA 80A plane is assigned based on the fire load, as specified in Table 7-17. While the emissive power levels for the moderate and severe hazard classifications in the NFPA 80A model correspond to the low and high hazard levels in the NBC 2020 model, the associated fire loads do not align with those underlying the respective NBC occupancy classifications [108].

Table 7-17: NFPA 80A exposing plane emissive power

Hazard Level	**Fire Load [kg/m² (lb/ft²)]**	**Emissive Power (kW/m²)**
Light	0-34 (0-7)	89.3
Moderate	35-73 (8-15)	178.6
Severe	≥ 74 (≥ 16)	357.1

Also similar to the NBC model, the critical distance is defined as the point at which the incident heat flux from the source plane reaches 12.5 kW/m², and the relationship between the source plane and the point of interest is calculated using a single configuration factor equation. The calculation methodology and detailed calculations of the NFPA 80A spatial separation tables are included in Appendix E.

Spatial separation requirements in the UK are detailed in [416]. This provides two simple methods to determine the maximum percentage of unprotected openings in an external wall, with a more precise calculation method described in BR187 [417]. The methodology described in BR187 defines the second comparative regulatory model (ADB V2, BR187 model). BR187 is substantially based on an approach developed by Margaret Law [381, 382], providing direct methods to calculate acceptable boundary distances by considering factors such as fire load, compartment design, and unprotected openings in an external wall. The results of the calculations are provided in 10 tables, where boundary distances are provided based on enclosing rectangle height, enclosing rectangle width, and the unprotected percentage of openings within the enclosing rectangle, as illustrated in Figure 7-38. The emissive source in this model differs from the NBC 2020 model as it is defined using an enclosing rectangle (or rectangles) (Section 7.2.5.1). While still a grey radiator approximation, the enclosed rectangle provides a result that is more precise than when the entire building or fire compartment face is used as the emissive plane. Also, in contrast to the NBC 2020 model, the ADB V2, BR187 model does not include a flame front factor. Further, the emissive power is based on fire load, as in the NFPA 80A model, though with differing values as specified in Table 7-17. The emissive power associated with the moderate hazard level in the ADB V2, BR187 model corresponds to that specified for the low hazard level in the NBC 2020 model. The emissive power for low hazard in the ADB V2, BR187 model, though, is approximately half that of the low hazard level in the NBC 2020 model.

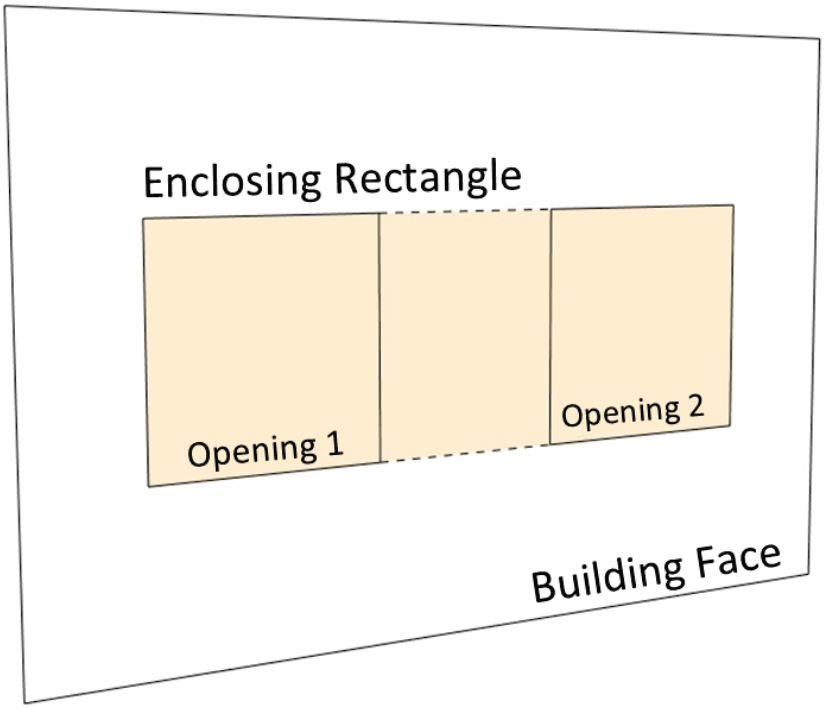


Figure 7-38: Isometric view of emissive power vertical plane for the UK and NZ regulations

Table 7-18: BR187 critical configuration factors

Hazard Level	Fire Load [kg/m² (lb/ft²)]	Emissive Power (kW/m²)
Low	< 25 (< 5)	83.7
Moderate	≥ 25 (≥ 5)	167.4

The critical distance is again determined at the point where the incident heat flux from the source plane reaches 12.5 kW/m², and the relationship between the source enclosing rectangle plane and the point of interest is calculated using a single configuration factor equation. The calculation methodology and detailed calculations of the BR187 spatial separation tables are included in Appendix D.

The third comparative regulatory model follows the methodology defined in the current edition of C/VM2 for the New Zealand Building Code [206]. This includes tables of maximum percentage of unprotected openings (NZ C/VM2 tables) as a function of minimum distance to the relevant boundary, height of enclosing rectangle, width of enclosing rectangle, and fire Load Energy Density (FLED) in MJ/m². The NZ C/VM2 methodology is very similar to that of BR187 with the exception of the specified fire loads and the threshold value used for incident heat flux at the critical distance. Unlike the models above, emissive power in the NZ C/VM2 model is assigned based on energy density fire loads, as specified in Table 7-19 and Table 7-20. These fire loads are not directly comparable to the weight-based fire loads without a common heat of combustion. If the heat of combustion of 24 MJ/kg underlying the NBC occupancy

classifications is used, the energy density based fire loads are as follows: 400 MJ/m² ≈ 16.7 kg/m² and 800 MJ/m² ≈ 33.3 kg/m².

Table 7-19: NZ C/VM2 critical configuration factors, unsprinklered

Hazard Level	Fire Load Energy Density (MJ/m²)	Radiant Emissive Power (kW/m²)
Low	≤ 400 MJ/m²	83
Moderate	400 MJ/m² to ≤ 800 MJ/m²	103
High	FLED > 800 MJ/m²	144

Table 7-20: NZ C/VM2 critical configuration factors, sprinklered

Hazard Level	Fire Load Energy Density (MJ/m²)	Radiant Emissive Power (kW/m²)
Low	≤ 400 MJ/m²	58
Moderate	400 MJ/m² to ≤ 800 MJ/m²	72
High	FLED > 800 MJ/m²	101

Also, unlike any of the models above, two threshold performance criteria in the NZ C/VM2 model are defined at fixed distances from the relevant boundary. The defined thresholds are 30 kW/m² at the relevant boundary and 16 kW/m² at 1 m beyond the relevant boundary. The calculation methodology and detailed calculations of the C/VM2 spatial separation tables are included in Appendix F.

Fundamental models for flame extension do exist and are used here to compare the results of the regulatory approaches, particularly the NBC 2020 model. This approach is more realistic than the grey radiator planes and enclosing rectangles that form the bases of the regulatory models, since flame extension from window openings and associated characteristics, such as temperature and emissivity, are represented by “external venting flame (EVF)” [403, 418] models.

Several external venting flame models [419] have been developed following introduction of the concept in 1960 [420]. One notable approach by Law [421] characterizes the shape and temperature of flame extending from an opening as a function of rate of burning (R) and opening dimensions (h and w). This methodology defines the fundamental model (Law EVF model) used in this analysis. The expressions that characterize the approach are detailed in Appendix I related to compartment parameters, and Appendix J related to notional flame parameters. The output of the Law EVF model includes a notional flame extension shape, illustrated in Figure 7-39 as the yellow shaded area to the left of the figures, extending up the wall above the opening. The opening (compartment) temperature is determined as a function of the compartment ventilation factor, fuel load, and rate of burning. The flame temperature is determined as a function of distance along the flame centreline (fl in Figure 7-39), and flame emissivity as a function of flame thickness (ff).

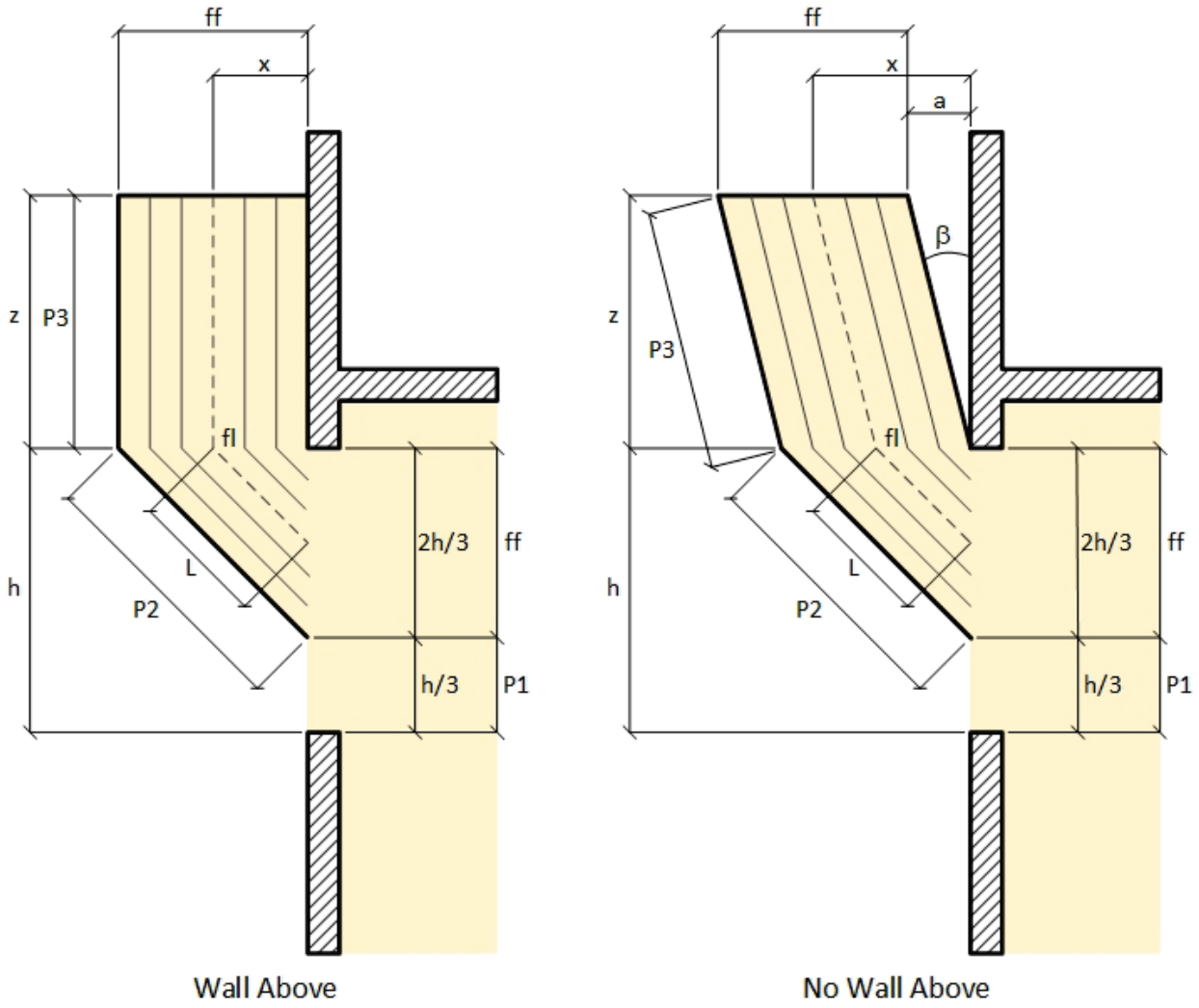


Figure 7-39: Elevation view of Law notional flame extension from an opening

The incident heat flux at any distance for flames extending from the compartment window openings (EVF model) is modelled as a function of the emissive power of the flame and configuration factors associated with the notional flame shape predicted by Law's EVF model. Since temperature varies with flame length, and emissive power depends on flame temperature, the emissive power also changes as a function of flame length. To simplify this variation and address the change in emissive power along the flame length, the front of the Law notional flame shape is subdivided into smaller planes, as shown in Figure 7-40. The orange planes (1a and 1b) represent the lower third of the opening. The dark yellow planes (2a to 2d) represent the angular portion of the flame extending from the top two-thirds of the opening. The yellow planes (3a to 3h) represent the vertical portion of the flame height. The emissive power is calculated for each plane and then combined to represent the total emissive power for the entire extended flame.

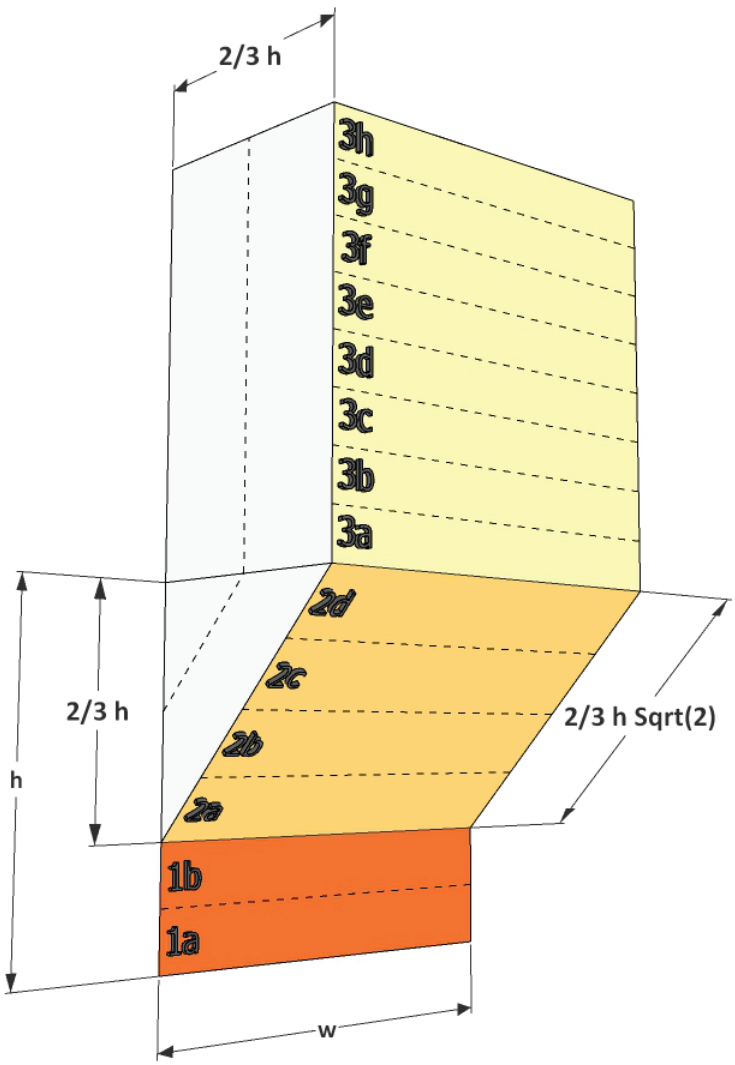


Figure 7-40: Isometric view of vertically divided Law notional flame extension from an opening

Law's EVF correlations have been used in the development of the prescriptive methodology in the Eurocode 1, which accounts for opening (compartment) temperature, externally venting flame dimensions and temperature, and associated convective and radiative heat fluxes [321]. The model has also been validated against full scale testing and other numerical methods, such as CFD analyses [403, 418, 421-423]. Comparisons indicate that this model accurately represents, and in some cases overpredicts, real fire characteristics in terms of external fire geometry and temperature.

Therefore, this model is used, per the simplified version illustrated in Figure 7-41, to generate a realistic representation of the emissive power of flame extending from each opening in the wall of the model compartment. This enables comparison with the regulatory models toward further evaluation of the technical validity of the NBC 2020 methodology.

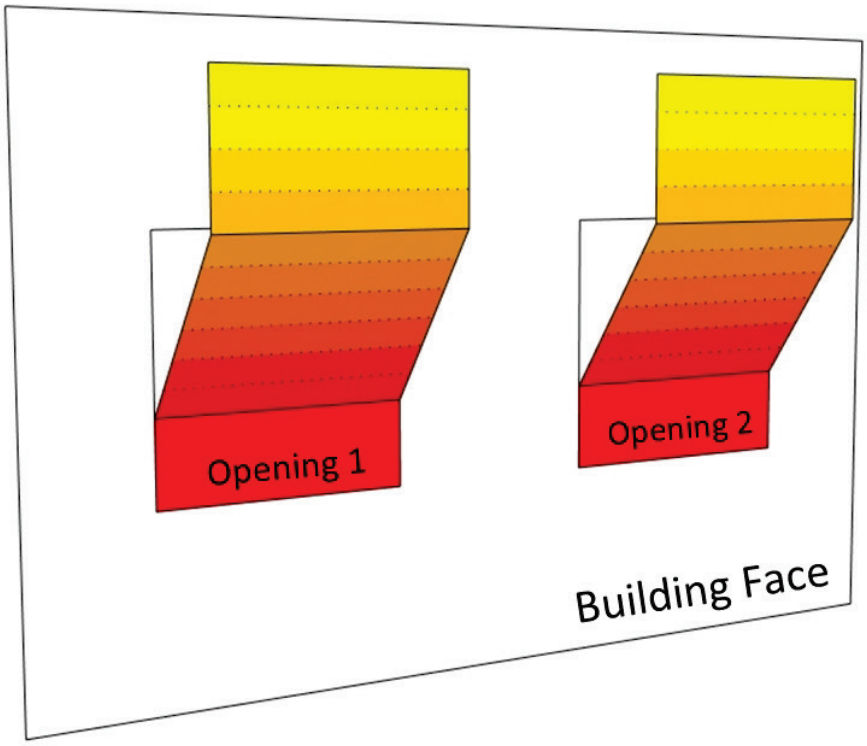
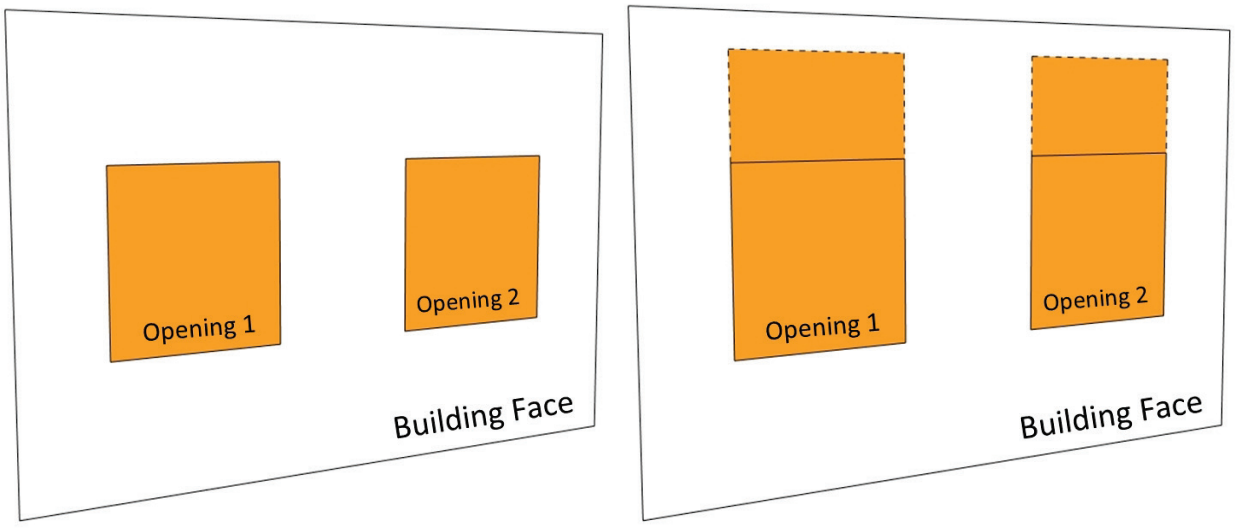


Figure 7-41: Isometric view of emissive power source planes for the Law EVF model



(a) (b)

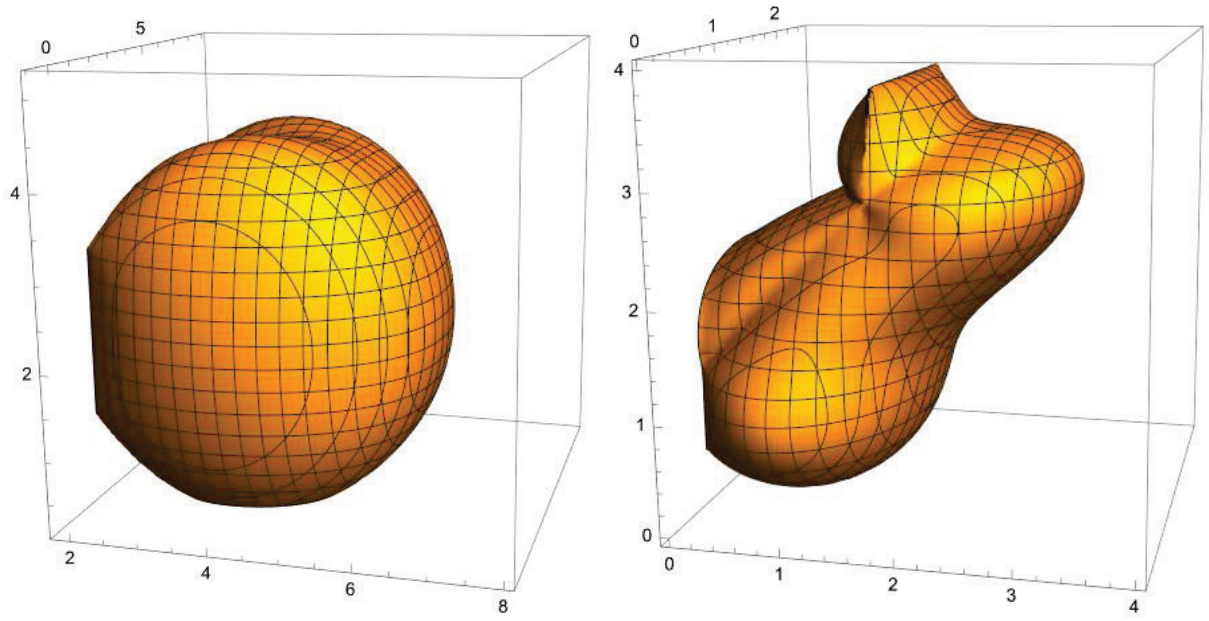
Figure 7-42: Isometric view of emissive power vertical planes for the (a) ADV1, and (b) ADV2 models

Hybrid “advanced” models have also been developed here for comparison with both the regulatory and EVF models. The intent was to develop models that combine elements of the regulatory and Law EVF models, to provide a new simplified, yet more accurate model, suitable for regulatory implementation. For this, the emissive power from each individual opening in the exposing compartment face is calculated, rather than relying on the grey radiator approximation used in the regulatory models. The first advanced

model (ADV1), illustrated in Figure 7-42(a), then uses the configuration factor representing the actual size and configuration of the openings in the compartment face to determine critical distance. The second advanced model (ADV2), illustrated in Figure 7-42(b), calculates the required separation distance based on the width of the actual openings combined with the flame height calculated using the Law EVF model. Emissive power in both models is based on compartment opening temperatures, which are determined using the Law EVF correlations detailed in Appendix J.

With the regulatory and more advanced models defined above, the next step is a means to calculate the configuration factor from each emissive source to a point of interest. While compilations of configuration factors exist [374], none were suitable for the present analysis. Thus, a more appropriate configuration factor was derived to relate radiant emission from a forward tilted plane to a vertical point located away from the plane, as detailed in Appendix K. Variations of this configuration factor plane can be used to represent the single plane regulatory emitter (i.e., angle = 0°) and the more complex and multi-plane Law notional flame shape geometry.

From this, it is necessary to extract the key variable of interest for the spatial separation, which is the critical distance from the building face. Since distance is an independent variable in the complex configuration factor equation, and in the absence of an analytical solution, numerical methods are used to calculate the critical distance corresponding to a given critical incident heat flux, or the critical configuration factor. For this, the Contour Plot function in Mathematica [424], was used to examine the shape of the isosurface representing the critical heat flux value for single instances of the regulatory, advanced, and EVF model emissive surfaces. Examples of the isosurfaces for the advanced and EVF models are shown in Figure 7-43(a) and (b), respectively.



(a) (b)

Figure 7-43: Isosurfaces representing (a) the advanced emissive openings (2 openings) and (b) EVF emissive shape

The results indicate a spheroidal shape for the advanced emissive opening planes, and a rounded shape that follows the profile of the flame shape planes of the EVF model. Due to its planar configuration, the regulatory model is expected to produce a similar profile to the advanced models. Both shapes exhibit a maximum x-dimension point on the isosurface that represents the critical distance. Therefore, a two-part numerical method is required to approximate the value at this point:

1. **Optimization Method:** Given an x value and initial y, z (seed) coordinates, this method converges to y, z coordinates that maximize the configuration factor for the given x value.
2. **Root-Finding Method:** Given an initial x (seed) value and the (y, z) coordinates from the optimization method, this method converges to an x value that corresponds with the critical configuration factor (critical heat flux).

Several methods exist for numerical optimization and root-finding so the combination of methods and sequence of steps that would yield optimal convergence to the maximum distance on the critical configuration factor (critical heat flux) isosurface were examined using sample data and Python scripts.

The first, the Newton-Raphson (NR Method), is primarily used for root-finding but can also be applied as an optimization method by locating the roots of the derivative of the function as follows:

$$\mathrm{x}_{n+1} = \mathrm{x}_n - [\nabla^2 f(x_n)]^{-1} \nabla f(x_n) \qquad \text{Equation 7-20}$$

Where:

x_{n+1} = Solution vector at the next step
x_n = Solution vector
$\nabla f(x_n)$ = Gradient vector of the function
$[\nabla^2 f(x_n)]^{-1}$ = Inverse of the Hessian matrix

This method is sensitive to the proximity of the selected seed value(s) to the root value(s) and the steepness of the function. If the seed value is far from the root, the NR method may fail to converge. However, when a suitable seed value is selected, the NR Method exhibits quadratic convergence (p = 2).

The second, the gradient descent method (GD Method), is primarily an optimization technique but can also be applied as a root-finding method, expressed as follows:

$$\mathrm{x}_{n+1} = \mathrm{x}_n - \alpha \cdot \nabla f(x_n) \qquad \text{Equation 7-21}$$

Where:

α = Dampening factor

The GD Method is less sensitive to the selection of a proximal seed value compared to the NR Method, but tends to converge more slowly, exhibiting near linear convergence. The actual order of convergence of the GD Method depends on the dampening factor (α).

The third, the Levenberg-Marquardt method (LM Method), combines the Gauss-Newton method (similar to the NR Method) and the gradient descent method. This combination achieves a balance

between the efficiency of the NR Method and the stability of the GD Method, depending on the dampening factor. The LM Method is expressed as follows:

$$\mathrm{x}_{n+1} = \mathrm{x}_n - [\mathcal{J}^T \cdot \mathcal{J} + \lambda \cdot I]^{-1} \mathcal{J}^T f(x_n) \qquad \text{Equation 7-22}$$

Where:

- $\mathcal{J}$ = Jacobian matrix of the configuration factor function
- λ = Dampening factor
- I = Identity matrix

The dampening factor can be static or updated at each iteration based on the convergence improvement in the previous steps. If convergence degrades, the dampening factor is increased to reduce the likelihood of divergence, making the method behave more like the GD Method. Conversely, If convergence improves, the dampening factor is decreased to allow larger updates and potentially faster convergence, resembling the NR Method.

The final method involves modifications of the LM Method to allow dynamic updating of the dampening factor. The Levenberg-Marquardt-Fletcher-Adam method [425, 426] (LMFA Method) improves convergence by using incremental and adaptive adjustments of the dampening factor, enhancing the method's capability to optimize more effectively and reduce the risk of convergence to local minima (or maxima in this case).

Based on the analysis of root-finding and optimization methods, the following algorithm was developed to optimize the probability of convergence to the maximum critical distance on the critical configuration factor isosurface:

1. **Seed Value Identification:** A critical distance (x) seed value is determined for each scenario using a GD Method root-finding analysis of a set of (y, z) coordinates derived from grid values spanning the exposing compartment face. The maximum x value and the corresponding y and z values are then recorded as the seed values input into the next step.
2. **Sequential Use of Methods:** The seed values determined using the first step are used as a starting point whereby the following methods are applied sequentially, exiting the sequence upon confirmation of successful convergence:
    a. NR Method
    b. LM Method
    c. GD Method
    d. LMFA Method

The output of the optimization and root-finding analysis is a set of (x, y, z) coordinates for a given scenario, where x denotes the critical distance that corresponds to the critical heat flux for that scenario.

7.4.3 Analysis Methods and Inputs (Uncertainty)

A stochastic approach is used here in analyzing radiant exposure (critical distances) from fires in living rooms to account for the uncertainty and variability of parameters that might be found in different Canadian living room configurations and contents at a broader societal level. Given the complex nature of fire dynamics and the numerous parameters associated with fire development and spread, a Monte Carlo based approach is used to examine the variability, and thus potential uncertainty, of critical distances across a wide range of living room fire scenarios.

Monte Carlo analysis is a computational technique used to approximate the results of complex, multi-dimensional processes. It involves sampling from distributions of input parameters and evaluating outcomes based on the samples. The accuracy of Monte Carlo approximations is governed by the law of large numbers, which shows that a larger number of samples provides a better representation of the true characteristics of the input parameters. The number of samples can be optimized based on the desired confidence interval, margin of error, and the standard deviation of the parameter space. However, for the demonstrative analysis in this thesis, a large number of samples (100,000) is examined and assumed to be representative of the underlying parameters.

One of the key advantages of the Monte Carlo method is its ability to approximate high-dimensional processes that lack an analytical solution. This method has been successfully applied to complex fire safety phenomena, including radiant heat transfer [427, 428], the onset of flashover [429, 430], safe egress times [431, 432], and structural sufficiency [433]. In the present analysis, Monte Carlo techniques, similar to those employed by Bruns [429, 430], are used to estimate the probability of flashover based on results of the CFAST model (Phase 1). These are used to identify a subset of simulations for characterizing and comparatively analyzing the uncertainty in values of critical distances based on the regulatory models as well as the more physically representative advanced and Law EVF models (Phase 2). The analysis therefore involved a four-step process, including two sets of Monte Carlo analysis.

The first step involves performing a Monte Carlo analysis of early fire growth up to the onset of flashover and the transition to full compartment involvement, using CFAST to account for uncertainty in input parameters that could influence this transition. These fire conditions are precursors to hazardous flame extension from a compartment opening. The onset of flashover can be predicted using the modelled outcomes of key input variables, which may be deterministic or random, either discrete or continuous.

The deterministic parameters include simulation time and wall, ceiling, floor, and window materials as defined in Table 7-21 and following.

Table 7-21: Deterministic (fixed) parameters

Parameter	**Value**
Simulation Time (s)	6000
Wall and Ceiling Material	Gypsum
Floor Material	Fir

Parameter	Value
Window Material	Glass

A single standard sized door is included in the back wall of each model compartment scenario to limit under-ventilated conditions that could otherwise impede established burning.

The discrete and continuous parameters include compartment and window opening characteristics, as defined in Table 7-22 to Table 7-24. Compartment characteristics include size, aspect ratio, and fuel load. The front wall of the compartment includes one to three window openings of varying size. For simplicity, these window openings have an aspect ratio proportional to the front wall in which they are located and are centered vertically.

Table 7-22: Discrete

Random Parameter	Values	Weighting Factor	Source
Living Room Height (m)	2.1, 2.4, 2.7, 3.0	0.1, 0.5, 0.3, 0.1	2020 NBC [21]
Number of Windows	1 to 3	None	None

Table 7-23: Uniform distribution

Random Parameter	Range	Source
Compartment Aspect Ratio	0.6 to 1.0	None
Percentage Window Opening Area (%)	0.0 to 100.0	None

Table 7-24: Truncated normal distribution

Random Parameter	Alpha	Beta	Mean	SD	Source
Compartment Area (m^2)	6.1	33.2	17.6	4.3	Modified [261]
Fuel Load (MJ/m^2)	106.0	897.0	412.0	127.0	

A combination of deterministic values, distributions, and an algorithm were used to select and place the furniture items within each CFAST model compartment. The data sources and distributions for the furniture items are listed in Appendix L. The furniture algorithm is detailed as follows:

1. Selection of furniture items:
    a. Based on a weighting factor.
    b. Selection continues until the total fuel load of the furniture items is approximately equal to the fuel load of the specific scenario (Table 7-24).
    c. Some furniture items can be repeated.

2. Furniture item location:
    a. Randomly located in the compartment.
    b. At least 0.5 m from a wall.
    c. At least 1 m from other furniture items.
3. Furniture item heat release rate:
    a. Peak heat release rate selected from a distribution.
    b. Assume triangular heat release rate history with a base width derived as a function of the peak heat release rate (Item a) and the energy of the item (weight and heat of combustion).
4. Furniture item ignition is based on the condition of a heat flux sensor as described below.

An "initial fire event" is then prescribed as an input parameter to define an immediate fire growth condition to a peak heat release rate, since the analysis assumes that ignition has occurred and the fire has become established. Subsequent fire development and spread in the model is governed by ignition of the furniture items randomly located in the fire compartment, as described above, with their ignition calculated based on heat transfer to each item from the fire. A single heat flux sensor is located at the top centre of each furniture item to record incident heat flux. When the measured heat flux reaches 12.5 kW/m², that item ignites and the prescribed heat release rate of that item is added to the fire.

As the fire continues to grow, the glass in window openings is defined to break when the surface temperature reaches 300 °C. This results in the complete opening of the window with consequent addition of air into the simulated compartment.

For each model scenario, where the input is a distribution as detailed in the tables above, the sampling of an input parameter from each distribution is defined as:

$$X \sim \mathrm{P}(X) \qquad \text{Equation 7-23}$$

Where:

X = A random variable

$\mathrm{P}(X)$ = The probability distribution function (PDF) or probability mass function (PMF) of the random variable X

This can be further expressed on a sample basis as follows:

$$x_i^{(j)} \sim \mathrm{P}(x_i) \qquad \text{Equation 7-24}$$

Where:

$x_i^{(j)}$ = The *j*th sample of the *i*th input parameter

$\mathrm{P}(x_i)$ = The probability distribution of the *i*th input parameter

With the distribution of input parameters specified, values can be sampled as final input into the Monte Carlo analysis. For this, Latin hypercube sampling (LHS) is used to improve the convergence of Monte Carlo analysis by ensuring a more uniform sampling of the entire parameter space. Unlike simple random

sampling, which can result in clustering of samples in certain regions, LHS aims to achieve a more evenly distributed sampling of the parameter space. In this analysis, Latin hypercube sampling is implemented as follows:

1. **Define the Parameter Space:** Identify the distribution of each parameter to be sampled (see Table 7-21 to Table 7-24).
2. **Compartmentalize Each Parameter Space:** Divide the range of each parameter into N equally probable intervals or compartments. The number of compartments is the same for all parameters, where N is the total number of samples to be drawn.
3. **Randomize Samples:** Randomly generate one sample within each compartment, ensuring that every compartment of the parameter space is represented exactly once.
4. **Create a Matrix of Samples:** Generate a matrix where each column represents a parameter and each row represents a sample. Shuffle the values in each parameter column to ensure randomness while maintaining stratification.
5. **Analysis Input:** Conduct the scenario analysis using the samples from each row of the matrix as inputs.

These samples serve as inputs to the CFAST model resulting in a set of key random variables to be analyzed relative to the potential for the onset of flashover. This is stochastically expressed as follows:

$$Y = f(X_1, X_2, \dots, X_n) \qquad \text{Equation 7-25}$$

Where:

Y = A random variable that characterizes the onset of flashover

f = A function (CFAST model) that predicts the outcome of random variables associated with fire compartment development

X = Input parameter

The results of three model output parameters (random variables – Y) are assessed to predict the onset of flashover, since at present there are no definitive models for this phenomenon. The parameters considered here are the upper layer temperature (ULT), floor radiant heat flux (FHF), and ignition of all furniture items (FII). All are tracked and compared to generally established thresholds from the literature as [434-436], including an upper layer gas temperature that exceeds 600 °C, heat flux at the floor that exceeds 20 kW/m² (measured by five heat flux sensors located at floor level corresponding to the number five dice pattern), and ignition of all compartment combustibles (furniture items). Current understanding of these criteria has been established under a relatively narrow set of conditions, such as limited compartment size and configuration [434-436]. Therefore, while these criteria are considered appropriate for the present analysis given the relatively narrow set of conditions associated with Canadian living rooms, they may not adequately represent the onset of flashover in all scenarios and should be adjusted accordingly for technical reconciliation analyses of other situations. Further, the criteria are considered both individually and collectively as indicators of the onset of flashover in current engineering analyses. In this work, the value of each is examined in isolation to set a conservative indicator of flashover. At the same time, the times required to reach each flashover criterion and the corresponding fire heat release

rates are also evaluated in combination. Accordingly, the transient heat release rate history for each ignited furniture item, as well as the total for the compartment are recorded to facilitate additional analysis, as understanding may evolve in the future.

With the criteria defining the onset of flashover established, the second step of the analysis then involves using the Heaviside step function, expressed below, to filter the results of the Step 1 Monte Carlo analysis to identify those scenarios that are considered to have transitioned to flashover based on this criteria.

$$H(Y-y)=\begin{cases}0, & Y-y<0\\ 1, & Y-y\geq 0\end{cases} \qquad \text{Equation 7-26}$$

Where:

$H(\cdot)$ = Heaviside step function

y = A threshold criteria indicative of the onset of flashover

The end of this step marks the initiation of full compartment fire involvement and the transition from using CFAST to applying the radiant heat flux models, representing the third step in the analysis. This step involves applying the radiant heat exposure analysis (Section 7.4.2) to the scenarios that remain after the Heaviside filtering conducted in Step 2, using the emitter geometry, emissive power, and incident heat flux thresholds defined in Table 7-25.

Table 7-25: Summary of model emitter geometry, emissive power, and incident heat flux threshold

Model	**Emitter Configuration**	**Emissive Power (kW/m²)**	**Incident Heat Flux Threshold (kW/m²)**
2020 NBC	Compartment face single plane	178.6	12.5
NFPA 80A	Compartment face single plane	89.3	12.5
ADB V2, BR187	Enclosing rectangle	84.0	12.5
NZ C/VM2	Enclosing rectangle	84.0	30 at relevant boundary 16 at 1 m from relevant boundary
Law EVF	Complex flame geometry	Based on gradient flame temperature as a function of flame length	12.5
ADV 1	Each Opening	Based on Law EVF opening temperature	12.5
ADV 2	Each opening + Law EVF flame height	Based on Law EVF opening temperature	12.5

For the regulatory models, as discussed above, the emissive power is prescribed based on the hazard defined in the respective regulatory approach. As a result, the heat flux calculated at a given distance depends only on the size and percentage of window openings in the compartment face, and not on other factors such as compartment fuel load. On the other hand, the emissive power in the Law EVF, ADV1, and ADV2 models is calculated based on the compartment fire temperature, temperature at the openings, and flame temperature. These variables are all based on configuration of the openings (height and width), compartment dimensions, and fuel load as detailed in Appendix I.

These values and configurations, along with the compartment characteristics from each filtered CFAST scenario resulting from step 2, serve as inputs to each of the radiant heat transfer models through a second Monte Carlo analysis, expressed as:

$$Z = g\big(H(Y - y)\big) \qquad \text{Equation 7-27}$$

Where:

Z = Random variable of interest (critical exposure distance)

$g(\cdot)$ = A function that predicts the outcome of random variables associated with exposure analysis

Step 4 of the analysis then involves a comparison of the results from the regulatory, the advanced, and the Law EVF models using the following metrics:

- **Interval Coverage:** Examination of overlap between the regulatory model predictions and the advanced model, and Law EVF model predictions.
- **Difference:** The difference between the regulatory model critical distance predictions and the advanced model, and Law EVF model critical distance predictions for each scenario.

In addition to the comparative approach outlined above, a global sensitivity analysis is performed to assess the impact of input parameters on the random variable outcomes following each Monte Carlo analysis step. The sensitivity of the output variables to the input variables is evaluated using a linear regression-based analysis, similar to Bruns [429]. While the relationship between input and output variables may not always be linear, a linear regression sensitivity analysis can still provide meaningful insights [429].

7.4.4 Analysis Sequence and Results

The first phase of analysis utilizes CFAST to predict fire growth and development within a living room. The second phase analyzes flame extension from openings to evaluate the maximum distance at which a critical radiant heat exposure is reached. The Monte Carlo based approach requires significant input, the computation of numerous scenarios, and the analysis of voluminous output data. To streamline this process, a Python-based framework has been developed to manage the analysis phases, from input parameter development to output data post-processing. The Python code is structured as follows:

- **Generate Model Parameters:** CFAST and exposure analysis input parameters are generated using Latin hypercube sampling from characteristic distributions and other descriptive data (DATA.xlsx: Appendix L). These values are written to a comma separated values file (PARAMETERS.csv).
- **Generate CFAST Files:** A specific number of CFAST input files are generated based on the model input parameters and descriptive data files (PARAMETERS.csv and DATA.xlsx). The CFAST input files are then written to a specified folder.
- **Run CFAST Files:** The CFAST input files are run using the CFAST executable file. The CFAST output files are written to the same folder as the input files.
- **Process CFAST Output:** Upon completion of running all of the CFAST files, each output file is analyzed and key data is compiled and written to a comma separated output file (OUTPUT.csv).
- **Run Exposure Analysis:** The exposure analysis is conducted using a custom Python script that evaluates the regulatory, advanced, and Law EVF models. The results are written to a comma separated output file (EXPOSURE_OUT.csv).
- **Results Analysis:** The results of the exposure analysis are processed using a custom Python script to prepare visualizations of the results using Seaborn and Matplotlib libraries for Python.

Multiprocessing is used to optimize the run time for the 100,000 model scenarios. The results from the analysis are discussed in the following sections.

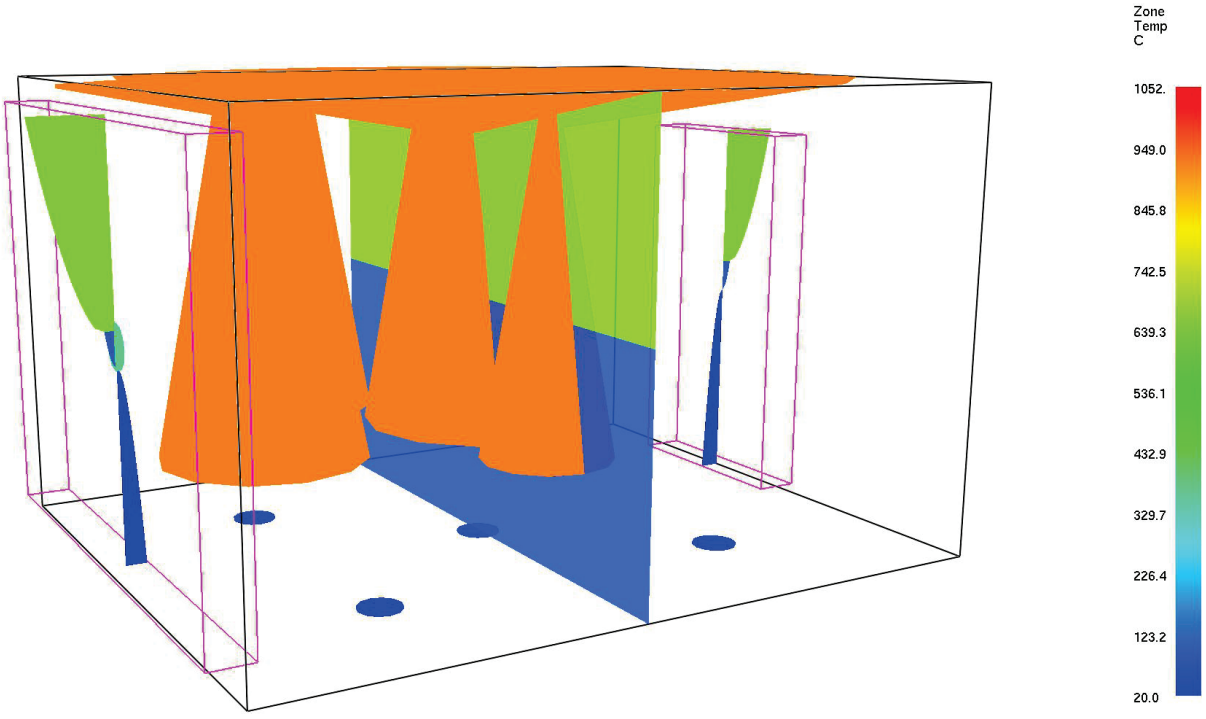


Figure 7-44: CFAST example result showing fire plumes, upper layer temperature, and opening air flow

7.4.4.1 Zone Modelling Results - Flashover

Each of the 100,000 CFAST model runs produces a Smokeview visualization file, as shown in Figure 7-44. The fire plumes are shown in orange, including flame extension along the ceiling. The upper layer is

represented in green on the plane at the center of the compartment, while the lower layer is shown in blue. The door and single window of the compartment are shown in the open position (closed windows and doors have an 'X' on the plane). The velocity profile is shown perpendicular to the centre of each opening and is green for fire gas flow out of the compartment, and blue for air flow into the compartment. According to the legend to the right of the compartment, the green colouration corresponds to temperatures exceeding 600°C, one of the indicators of the onset of flashover. These visualization files are also time-based, showing the transient development of the plume, the upper layer, and the velocity profile of the openings. Most importantly, they provide context through which to interpret the modelled fire development within each compartment.

The three criteria defined as indicating the onset of flashover were an upper layer gas temperature exceeding 600 °C, a floor level heat flux greater than 20 kW/m², and ignition of all furniture items. The probability distribution and cumulative distribution plots of the upper layer temperature are shown in Figure 7-45, across all scenarios modelled. The distribution is multimodal, with peaks at approximately 450 °C and 570 °C. The specific reason for these distinct peaks has not been investigated in this analysis. However, it is hypothesized that they may be indicative of the spread of fire from the initial furniture item to adjacent items. The 600 °C upper layer temperature threshold is marked as a vertical black line on the plots. Using the Heaviside step function, the CFAST results are filtered yielding a probability of flashover of 0.23.

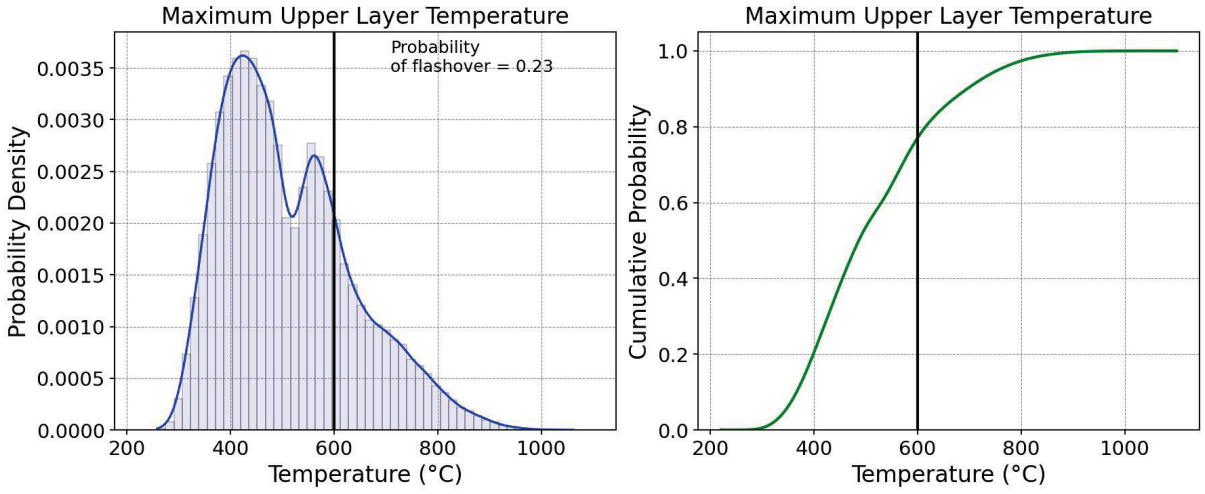


Figure 7-45: The maximum upper layer temperature PDF and CDF

The probability distribution and cumulative distribution plots of the maximum floor level incident heat flux are shown in Figure 7-46. The 20 kW/m² threshold is shown by a vertical black line on the plots. The CFAST results are filtered using the Heaviside step function, indicating a probability of flashover of 0.27.

The results of the third flashover criterion of ignition of all furniture items within the compartment are shown on the binomial probability plot in Figure 7-47. These results indicate a 0.25 probability of flashover based on this criterion.

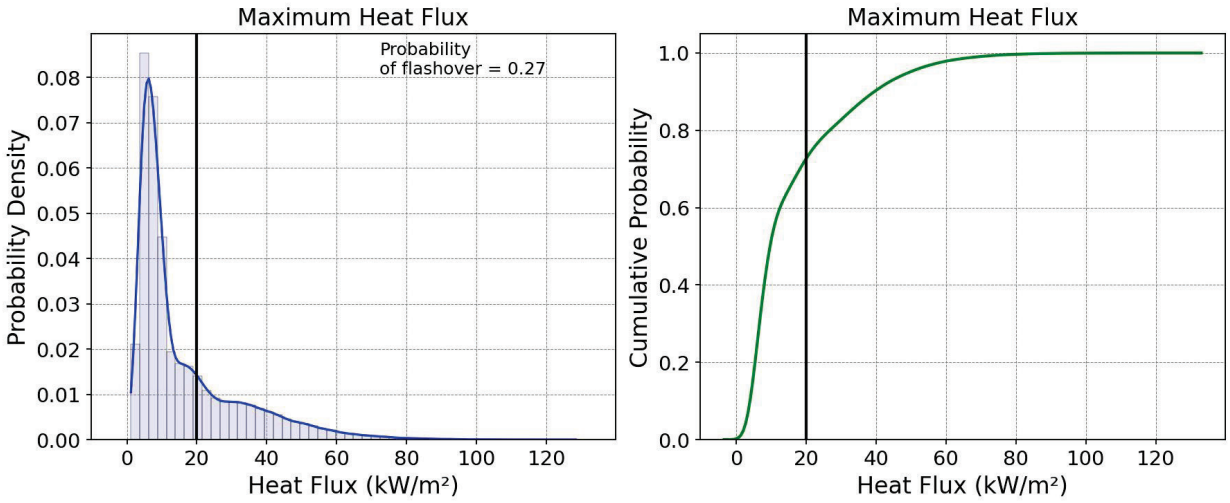


Figure 7-46: The maximum floor heat flux PDF and CDF

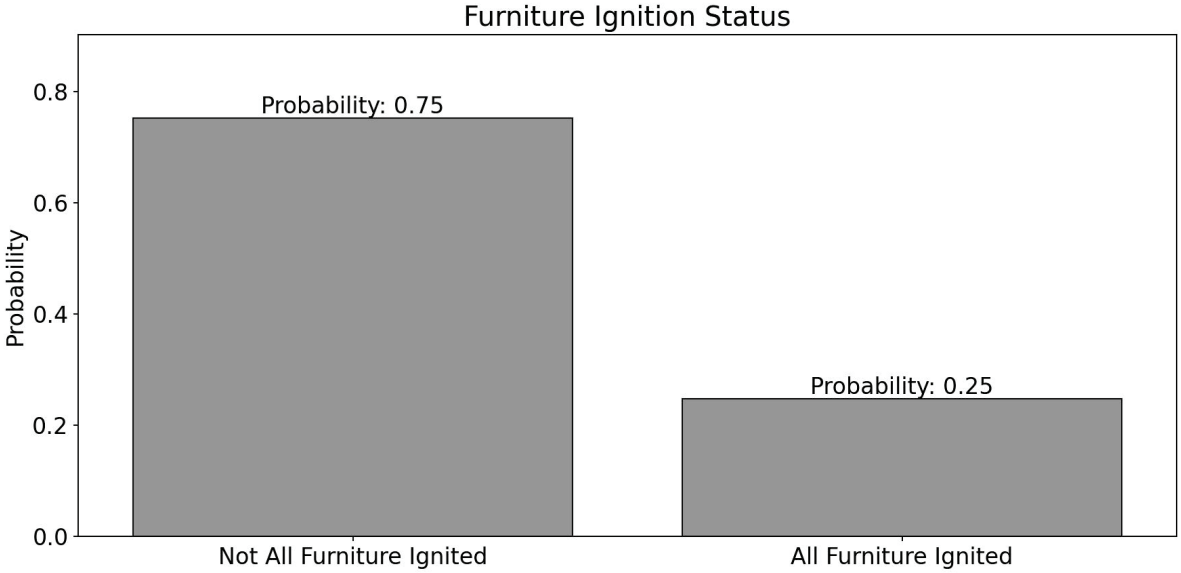


Figure 7-47: Binomial probability plot of the onset of flashover as a function of ignited furniture items

The combined and normalized upper layer temperature and floor incident heat flux PDF and CDF plots are shown in Figure 7-48. The floor heat flux distribution shows a strong peak toward lower values of heat flux in comparison to the upper layer temperature distribution, which is weighted towards higher values. The CDF plot also shows a steep rise in the floor incident heat flux compared to the upper layer temperature. These results align with the model layout in which there are a limited number of point measurements of floor heat flux, while the corresponding upper-layer temperature represents an average across the entire upper layer. Point measurements will reflect spatial variations in heat flux due to their potential proximity to fire sources within the compartment. As such, these values provide context for evaluating the representativeness of point measurements relative to compartment-scale distributions, and support the use of these approaches to characterize thermal exposure conditions across different spatial domains.

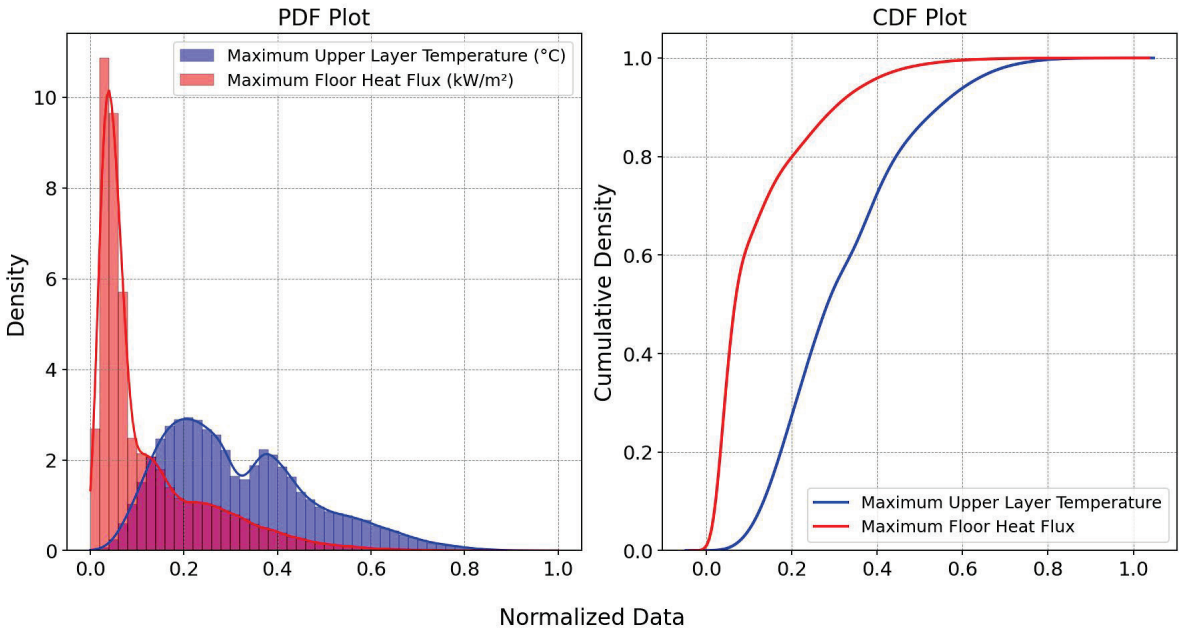


Figure 7-48: Combined upper layer temperature and floor incident heat flux PDF and CDF plots

The squared standardized regression coefficients (β^2) for the selected flashover criteria for the five main compartment parameters are shown in Table 7-26. These coefficients quantify the sensitivity of the onset of flashover based on each criterion and corresponding input parameters. Values are ranked by their order of influence, with higher β² values representing a greater impact on predicted transition to flashover.

Table 7-26: Squared standardized regression coefficients (β^2) for flashover criteria

Parameter	**Upper Layer Temperature, β^2**	**Floor Incident Heat Flux, β^2**	**All Furniture Ignited, β^2**
Fire load (MJ/m²)	1.5356 (1)	1.1219 (1)	1.1896 (1)
Compartment floor area (m²)	0.8589 (2)	0.5494 (2)	0.6281 (2)
Ventilation Factor, $A\sqrt{H}$ (m$^{2.5}$)	0.0668 (3)	0.0003 (5)	0.0001 (5)
Compartment Aspect Ratio	0.0004 (4)	0.0004 (4)	0.0022 (4)
Percentage opening area (%)	0.0001 (5)	0.0207 (3)	0.0213 (3)

The fire load parameter has the highest influence on the propensity for flashover, as indicated by all three flashover criteria, with a squared standardized regression coefficient nearly twice that of the next-ranked parameter, compartment floor area. Ventilation ranks third based on assessment via the upper layer temperature criterion, but the ranking differs for the other criteria, where percentage opening area ranks third, although with squared standardized regression coefficients less than one-third that for ventilation under the upper layer temperature criterion. Overall, the results identify fire load and compartment floor area as the primary determinants of the onset of flashover.

Scatterplots in Figure 7-49 to Figure 7-51 show the regression line for each dataset, further highlighting the influence of input parameters on flashover as determined by the defined criteria. The positive slope of the regression line in the fuel load plots indicates that an increase in fire load per unit floor area corresponds to an increase in upper layer temperature. In contrast, the negative slope in the floor area plots suggests that larger compartments result in lower upper layer temperatures, likely due to increased heat dissipation into a larger space, particularly under the assumptions inherent in the zone model used. The upper layer temperature regression line for the percentage opening area plot is nearly flat, indicating a limited correlation between these parameters. However, the regression lines for the other two flashover indicator plots show a slight upward slope, suggesting weaker but still positive correlations.

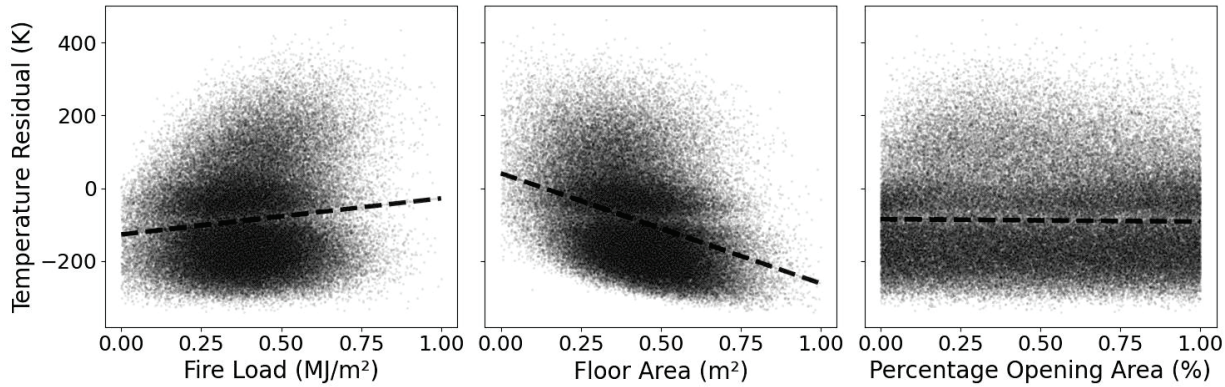


Figure 7-49: Scatter plots of temperature residual versus normalized input parameters

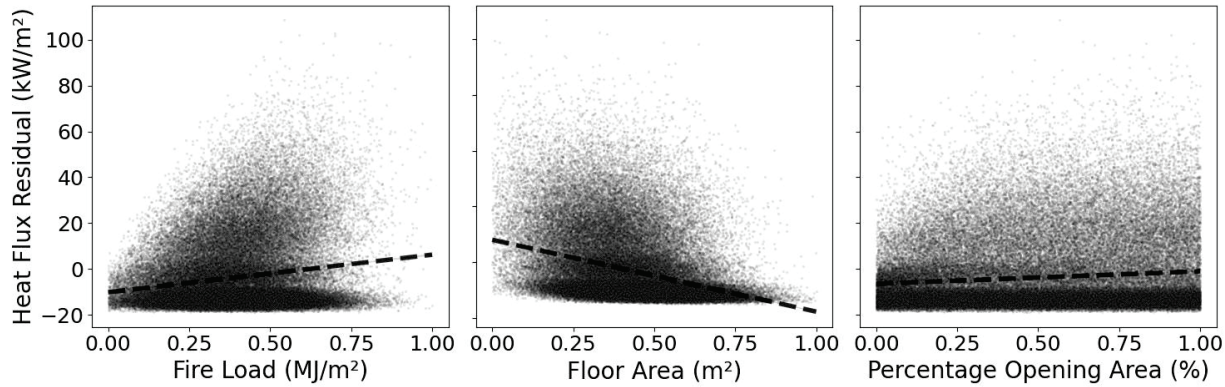


Figure 7-50: Scatter plots of heat flux residual versus normalized input parameters

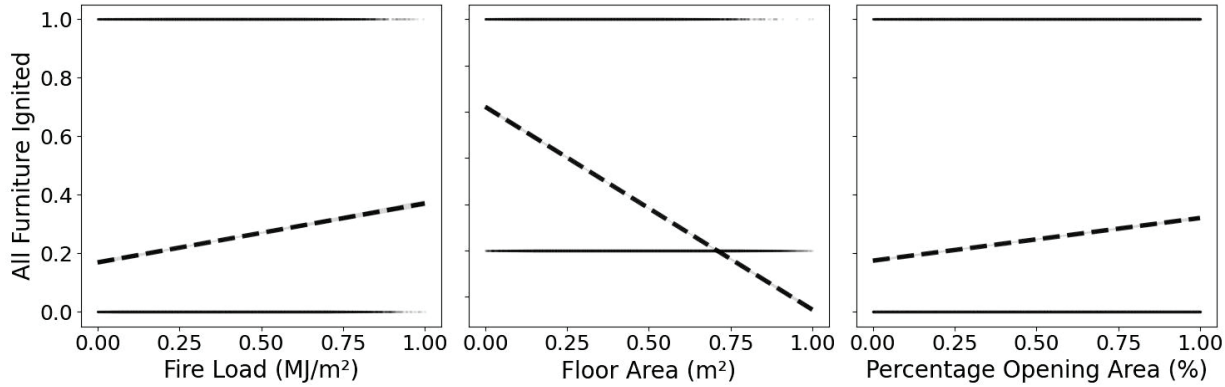


Figure 7-51: Scatter plots of furniture item ignition versus normalized input parameters

The sensitivity analysis indicates that fire load has the most significant impact on the probability of flashover. These findings are important in a regulatory context, as they identify key parameters that most significantly affect risk characterization. The influence of fire load on the probability of flashover highlights the significance of this parameter in occupancy classification. This is the key risk characteristic identified almost 100 years ago and has been used since then as a key means to characterize fire severity in the development of fire safety requirements.

Combined PDF and CDF plots are shown in Figure 7-52 for the heat release rate of the fire at the predicted time for the onset of flashover for the three defined flashover criteria. The heat release rate distributions for the floor level incident heat flux and all furniture ignited criteria are multimodal, likely an artifact of the ignition of secondary furniture items. In contrast, the heat release rate for the upper layer temperature is concentrated around 1500 kW, likely related to the averaged nature of the upper layer temperature as discussed above.

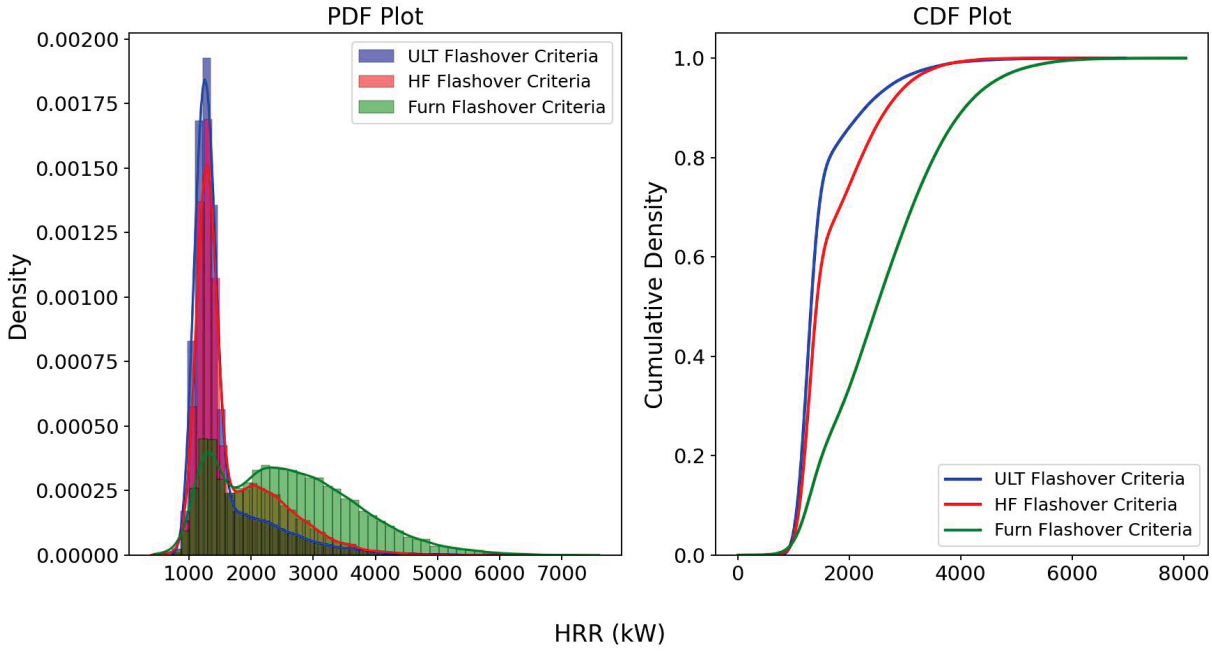


Figure 7-52: Combined upper layer temperature, floor incident heat flux and furniture ignite PDF and CDF plots versus heat release rate at flashover

The prediction of flashover based on the “all furniture ignited” criterion exhibits a more dispersed distribution, with a broad concentration around 2500 kW. The CDF plot shows that flashover based on the upper layer temperature and floor incident heat flux criteria occurs at heat release rates above approximately 800 kW and below 4000 kW. In comparison, the “all furniture ignited” criterion shows a similar lower bound heat release rate, but a higher bound heat release rate of approximately 6000 kW. These findings highlight the variability in fire heat release rate that might be associated with different flashover criteria, emphasizing the need to consider more specific criteria when evaluating fire growth and flashover potential.

Combined PDF and CDF plots are shown in Figure 7-53 for the time of onset of flashover. The time distributions for the upper layer temperature and floor incident heat flux criteria exhibit peaks between 400 to 500 seconds. In comparison, the “all furniture ignited” criterion shows a peak between 500 to 600 seconds, indicating a slight delay in the predicted onset of flashover based on this criterion. The CDF plot indicates that the majority of flashover events occur within approximately 800 to 1100 seconds after ignition. The corresponding peak around 500 seconds (8 minutes 20 seconds) and the fact that the majority of flashover events occur before 800 seconds (13 minutes and 20 seconds) highlight the importance of early fire department intervention. It is important to note that these times do not account for the incipient burning phase or all the possible complexities in different fire situations, as the fire scenarios were initiated using an already established burning furniture item and simplified zone model formulation.

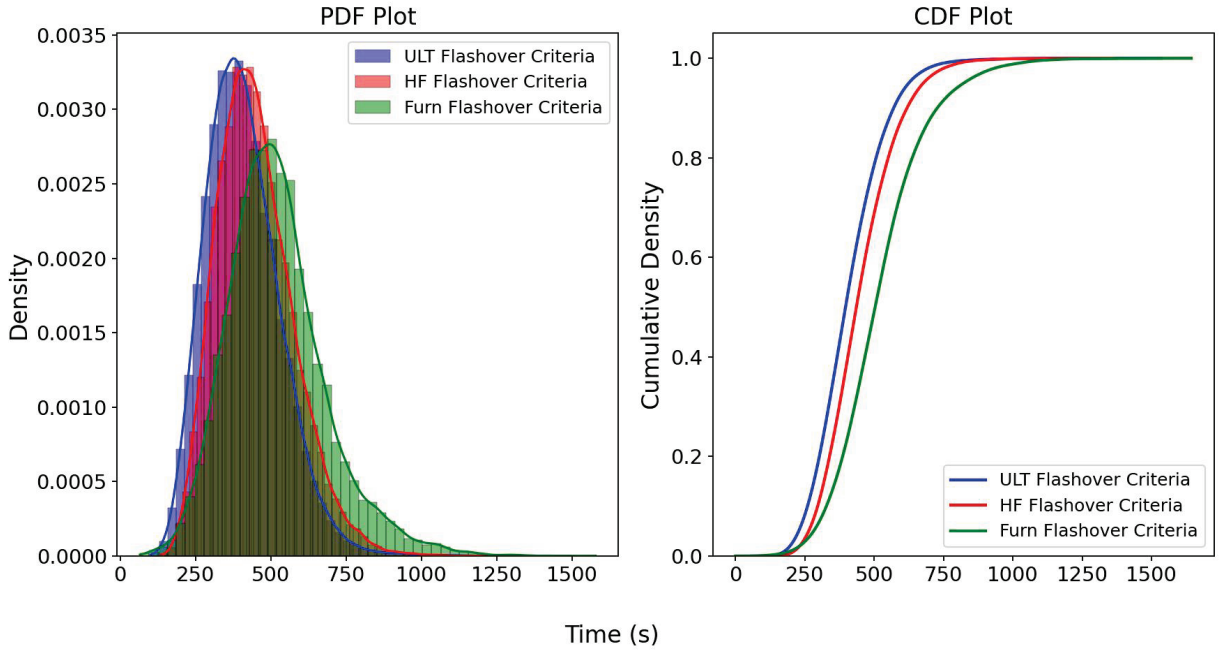


Figure 7-53: Combined upper layer temperature, floor incident heat flux, and furniture ignite PDF and CDF plots versus time of flashover

Table 7-27 summarizes the results of the fire size and times to onset of flashover obtained from the simulations based on the three criteria. Among these, the floor incident heat flux criterion is selected as the overriding indicator due to its slightly higher probability of predicting flashover compared to the other two criteria. Use of this criterion outlines the wide range of flashover heat release rates and times, ensuring that a wider range of fire scenarios are accounted for in the exposure analysis assessment carried out in Phase 2 of the analysis.

Table 7-27: Summary of flashover results

Output	Upper layer temperature ≥ 600 °C	Floor incident heat flux ≥ 20 kW/m²	All furniture items ignited
Probability of flashover	0.23	0.27	0.25
Peak flashover HRR (kW)	1500	1500	2500
Flashover HRR range (kW)	800 to 4000	800 to 4000	800 to 6000
Flashover time (s)	500 to 600	500 to 600	800 to 1100
Most influential input parameter	Fire Load	Fire Load	Fire Load

7.4.4.2 Exposure Analysis Results

The exposure analysis utilizes results from the zone modelling analysis, filtered using the Heaviside step function based on the criterion that the floor incident heat flux was above the threshold value of 20 kW/m². This filtering process identified 26,669 of the original 100,000 scenarios simulated, in which the onset of flashover and subsequent full compartment fire involvement are predicted. These scenarios are further analyzed to determine the corresponding values of critical distances obtained using the regulatory, advanced, and Law EVF model scenarios.

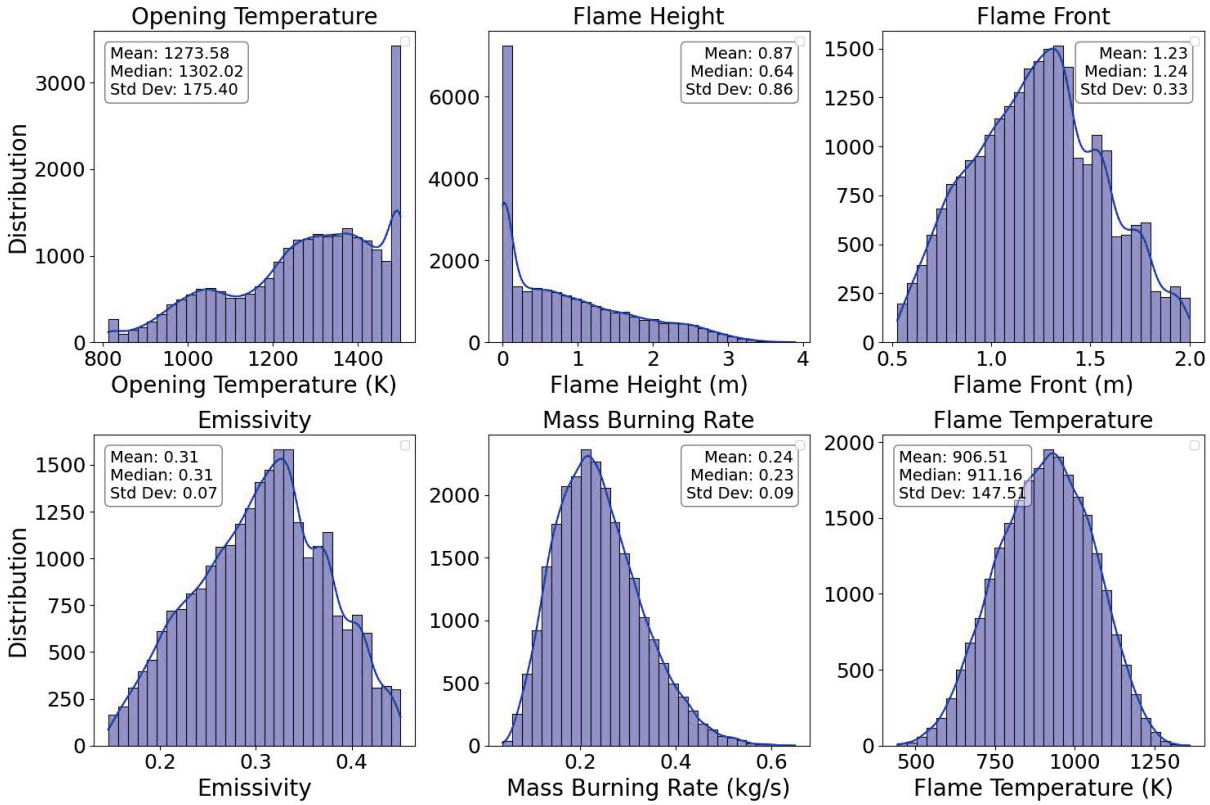


Figure 7-54: Output random variable distributions

The histograms included in Figure 7-54 show the distributions of random variables most important in determining critical incident heat flux distances and for characterizing the emissive power for the Law EVF model. Data included are the opening temperature, flame height, flame front, emissivity, mass burning rate, and flame temperature from the filtered scenarios. Basic descriptive statistics for each variable are also included in the plots.

The distribution of window opening temperature is multimodal, with significant frequency of values near 1100 K and 1350 K. A pronounced peak also aligns with 1500 K, the default maximum opening temperature considered in the Law EVF model. The distribution of flame height, measured above the top of the opening, is dominated by a peak at zero, corresponding with the fact that larger openings had no flame extension. The remainder of the distribution is characterized by a long tail toward highest values, with the majority of flame heights below 1 m but then extending up to a maximum of 4 m. The distribution of flame front length is approximately triangular, peaking at a value of around 1.25 m, with most values ranging between 0.7 m and 1.8 m. The distribution of flame emissivity for the flame extending from the opening is also approximately triangular, peaking at a value of around 0.35, with most ranging between 0.2 and 0.4. The distribution of mass burning rate (kg/s) is approximately normal but slightly skewed toward higher values, with most values ranging from 0.1 kg/s to 0.4 kg/s with a peak near 0.25 kg/s. The distribution of flame temperature is approximately normal, with values lower than those for the window opening temperatures, and peaking around 950 K, with the majority of values between 600 K and 1200 K. The similarity in these distributions is expected given the emissivity is calculated as a function of the flame front length in the Law EVF model. These distributions provide a comprehensive basis for characterizing the emissive behaviour of the living room fires under consideration here and the influence of that behaviour on critical incident heat flux distances.

The squared standardized regression coefficients (β^2) for these same output variables as a function of key input parameters were determined through the exposure analysis. Based on the rankings, the most influential input parameters include the ventilation factor, percentage opening area, fire load, compartment floor area, and compartment aspect ratio, with β^2 values as listed in Table 7-28.

Table 7-28: Squared standardized regression coefficients (β^2) for the exposure fire output parameters

Parameter	**Opening Temp., β^2**	**Flame Height, β^2**	**Flame Front, β^2**	**Emissivity, β^2**	**Burning Rate, β^2**	**Fire Temp., β^2**
Ventilation Factor, $A\sqrt{H}$ ($m^{2.5}$)	1.4130 (1)	0.5886 (1)	1.2242 (1)	1.1747 (1)	0.0762 (3)	0.0948 (3)
Percentage opening area (%)	0.5645 (2)	0.2874 (2)	0.4619 (2)	0.4589 (2)	0.0124 (4)	0.0358 (4)
Fire load (MJ/m^2)	0.0604 (3)	0.2034 (3)	0.0059 (3)	0.0056 (3)	0.4321 (2)	0.5431 (1)
Compartment floor area (m^2)	0.0063 (4)	0.0434 (4)	0.0042 (4)	0.0044 (4)	0.4660 (1)	0.1001 (2)
Compartment Aspect Ratio	0.0017 (5)	0.0062 (5)	0.0000 (5)	0.0000 (5)	0.0000 (5)	0.0018 (5)

The random variables representing conditions within the compartment include burning rate and fire temperature. These have influence rankings that are of similar order of magnitude. Floor area and fire

load are the most influential parameters on burning rate, with fire load being the most influential parameter on fire temperature. This is consistent with the previous observation that these parameters were also most influential to the onset of flashover. Ventilation factor and percentage openings area follow as the next most influential parameters for both burning rate and fire temperature.

For exterior flame conditions such as opening temperature, flame height, flame front, and emissivity, the influence rankings of input parameters are consistent. Ventilation factor and the percentage of window openings significantly influence these variables, whereas fire load and compartment floor area have much less impact. This result is again as expected, given the reliance on ventilation and opening size in the Law EVF model. Among all parameters, the compartment aspect ratio has the least influence on the random variables studied.

The scatterplots in Figure 7-55 and Figure 7-56 show the relationships between burning rate, fire temperature, and key input parameters. The regression line for the fire load shows the clear trend in the present predictions toward increasing burning rate and fire temperature with higher fire load, as would physically be expected. A similar trend is shown for floor area, though its effect on fire temperature is less pronounced. The regression line representing the percentage of window openings indicates a slight increase in the burning rate with an increase in the percentage of window openings. However, an increased percentage of openings tends to decrease fire temperature, likely due to increased ventilation.

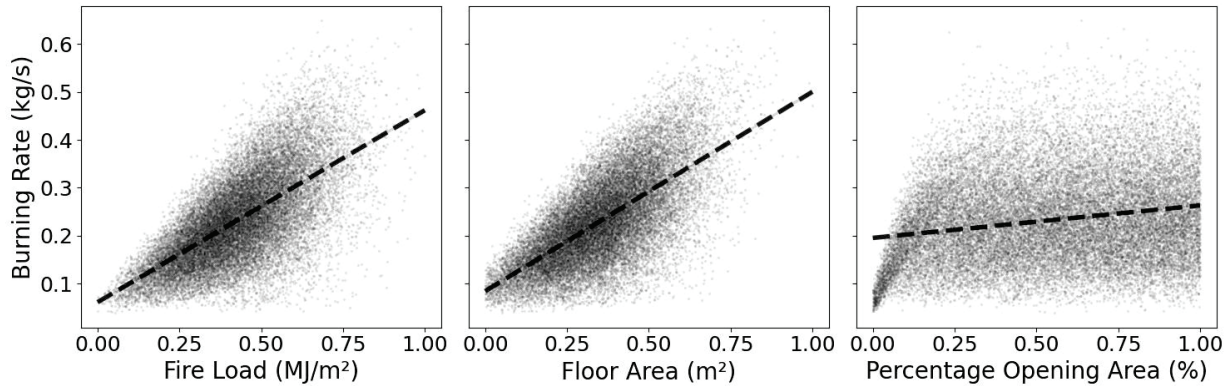


Figure 7-55: Scatter plots of burning rate versus normalized input parameters

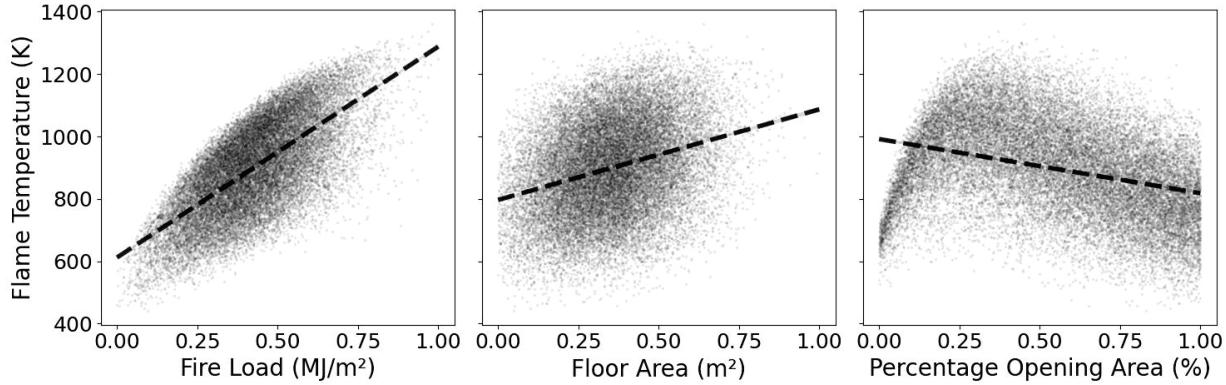


Figure 7-56: Scatter plots of fire temperature versus normalized input parameters

The scatterplots in Figure 7-57 to Figure 7-60 show the linear regression lines for opening temperature, flame height, flame front, and emissivity. The regression line for fire load shows an increase in opening temperature and flame height with higher fire load, with a smaller increasing trend for flame front and emissivity. The regression line for floor area indicates a slight increase in opening temperature, flame front, and emissivity, with a slightly larger increase in flame height with increasing floor area. The regression line for the percentage opening area shows a decrease in opening temperature and flame height, accompanied by an increase in flame front and emissivity as the percentage of opening area increases, consistent with the Law EVF model.

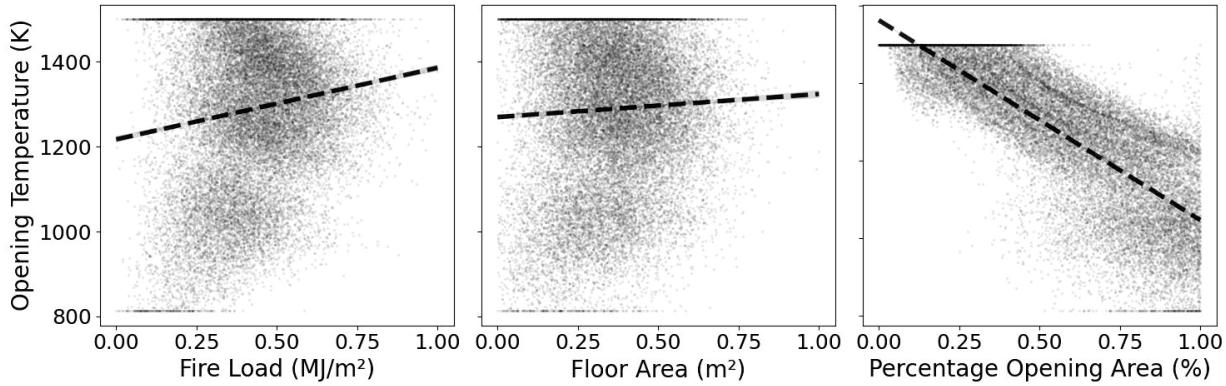


Figure 7-57: Scatter plots of opening temperature versus normalized input parameters

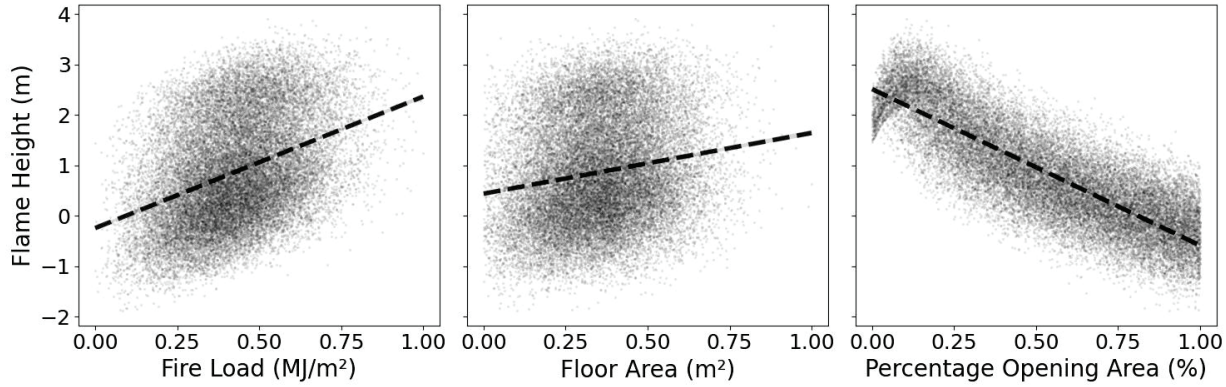


Figure 7-58: Scatter plots of flame height versus normalized input parameters

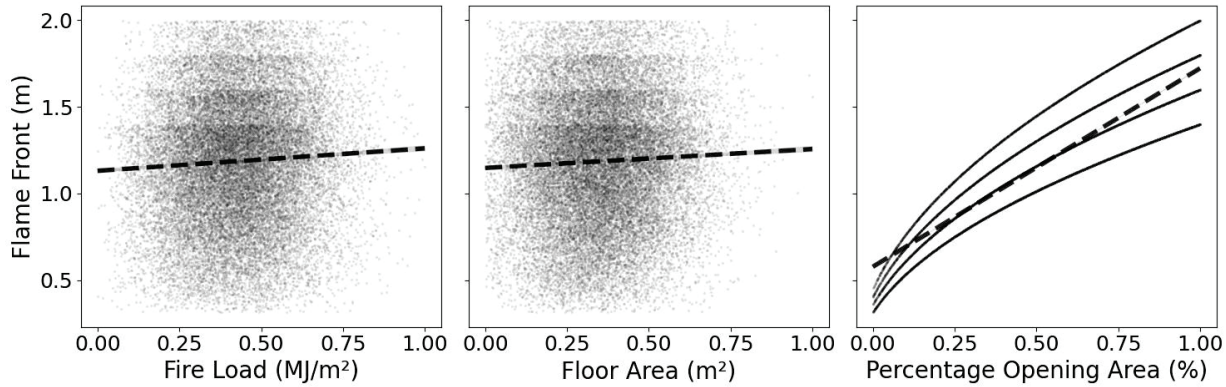


Figure 7-59: Scatter plots of flame front versus normalized input parameters

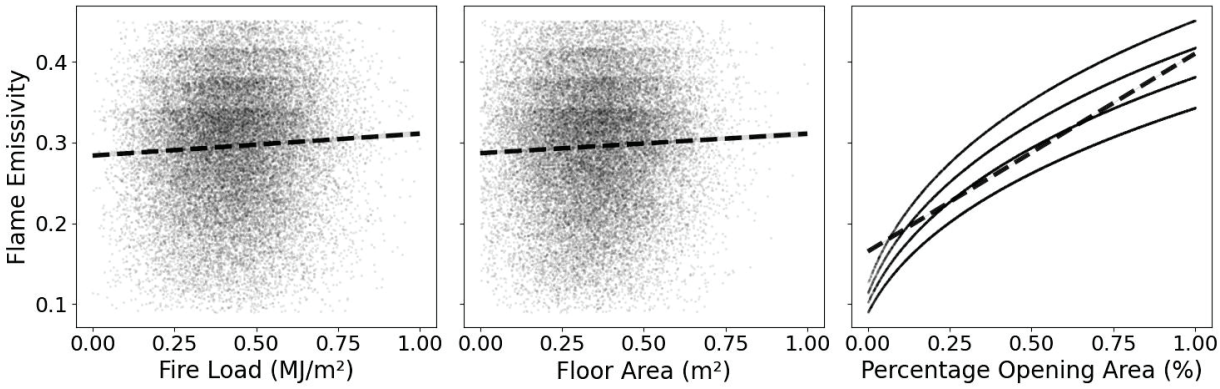


Figure 7-60: Scatter plots of emissivity versus normalized input parameters

The histogram in Figure 7-61 illustrates the distribution of critical distances (m) predicted using the Law EVF model. The distribution appears approximately normal, with values ranging from 1 m to 5 m, with a peak at approximately 3.5 m. The mean critical distance is 3.24 m, with most values falling between 2.5 m and 4 m. The data shows a slight skew toward lower critical distances but remains relatively symmetrical around the mean.

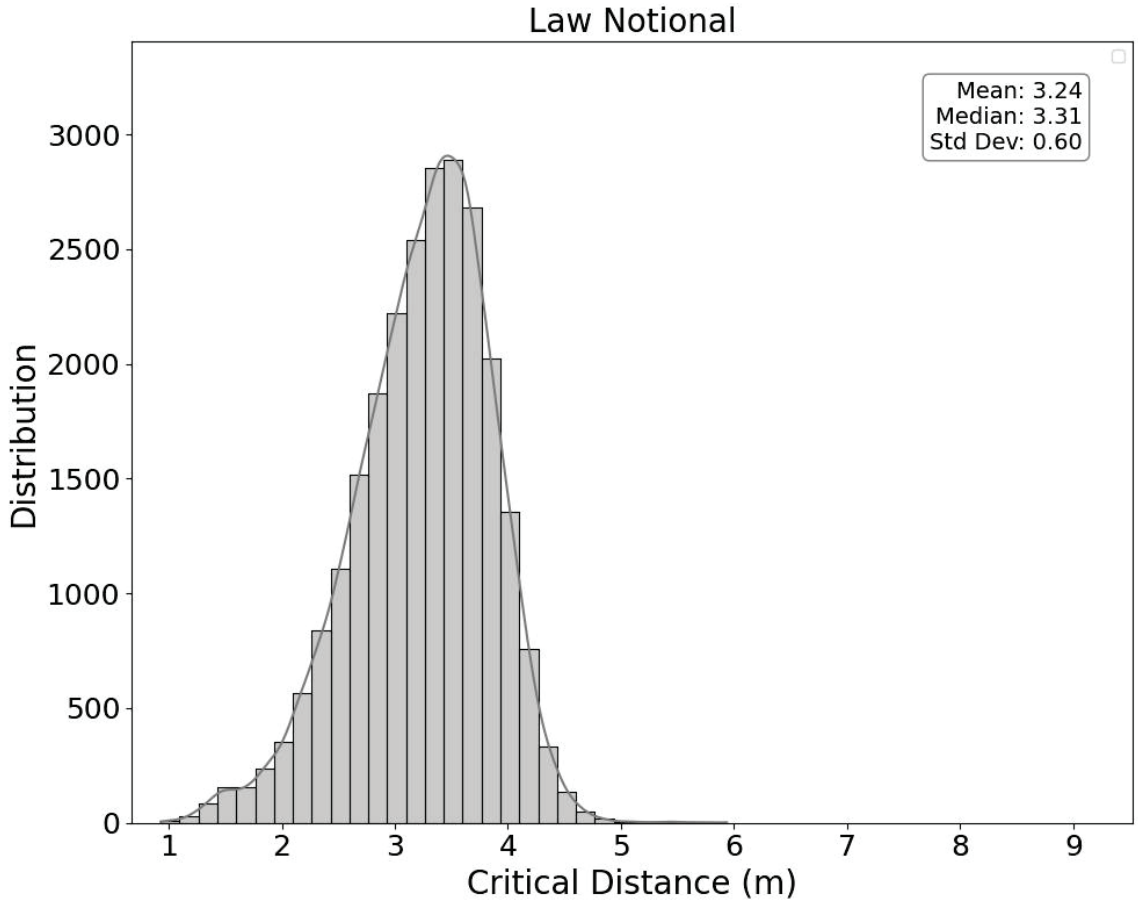


Figure 7-61: Law Normal PDF

Similar distributions are shown in Figure 7-62 for the critical distances predicted by the regulatory and advanced models. To facilitate comparison, these results are shown on a common distribution density

range and critical distance range, that also aligns with the plot axes ranges in Figure 7-61. These distributions are approximately normal, with the regulatory model results almost triangular. The regulatory model predictions, including the 2020 NBC, NFPA 80A, ADB V2 BR187, and NZ C/VM2, have a similar shape that is slightly skewed to the lower critical distance, with the exception of the NZ C/VM2 model, which is nearly symmetrical.

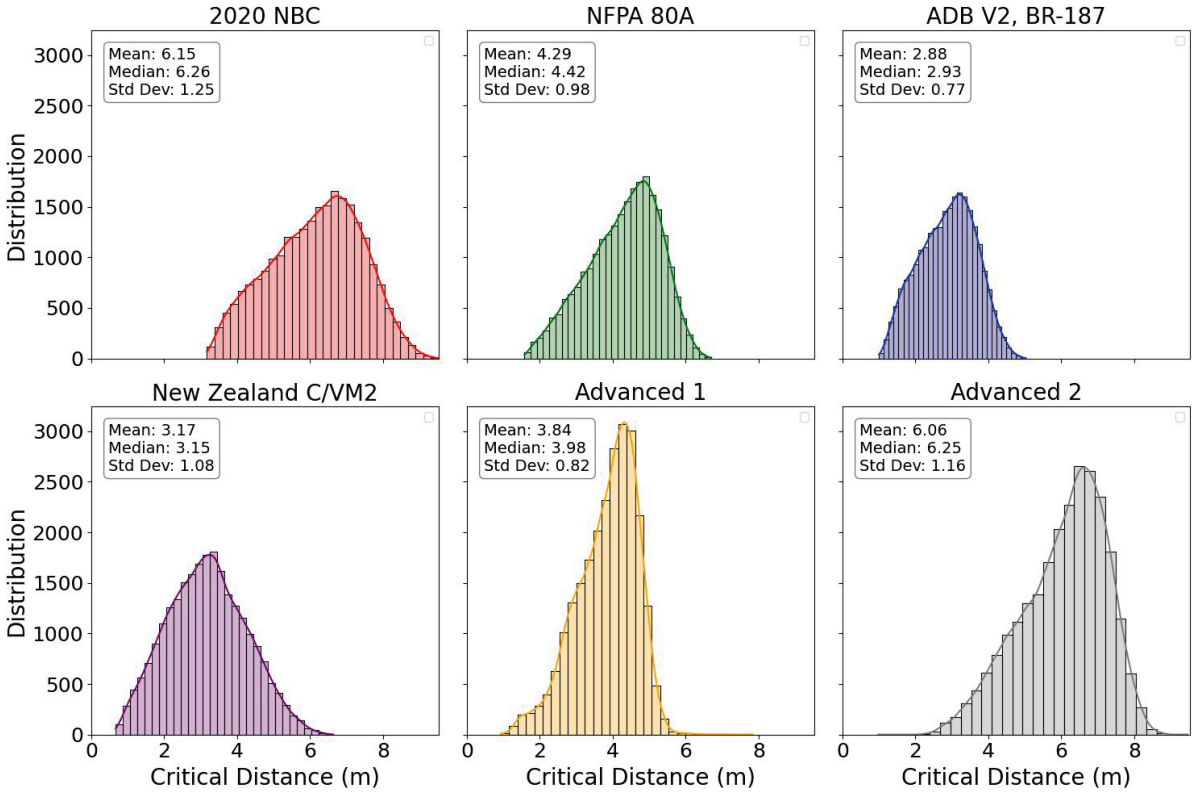


Figure 7-62: Critical distance regulatory and advanced distributions

The advanced model predictions are also slightly skewed to the lower values of critical distance, but they have a narrower range compared to the other regulatory models. Among the regulatory models, the 2020 NBC model predictions have the widest range, spanning from 1 m to approximately 9 m. The ADB V2 BR187 model predictions have the narrowest range, between 1 m and 5 m. The NFPA 80A and NZ C/VM2 models have similar ranges, extending from approximately 1 m to 6 m. The broader range of values in the NBC 2020 model likely relates to the significantly higher emissive power for this model and the flame front factor.

The distribution boundary of the Law EVF model predictions (Figure 7-61) is superimposed over the regulatory and advanced model predictions (Figure 7-62) as shown in the combination histogram/kernel density plots in Figure 7-63. To facilitate comparison, these results are also shown on a common distribution density range and critical distance range. The kernel density plots use a Gaussian kernel to provide a continuous estimate of the histogram data. The 2020 NBC and ADV2 distributions show the most significant variation from the Law EVF model, with their peaks occurring at greater critical distances. The

NFPA 80A and ADV1 distributions have broader bases than the Law EVF distribution and predict greater critical distances. The NZ C/VM2 distribution has a broader base than that of the Law EVF model, with approximately equal under- and over-predictions of the critical distance compared to the Law EVF model. The ADB V2 BR187 distribution has a similar base to the Law EVF model but tends to under-predict critical distance values in comparison to the Law EVF model predictions.

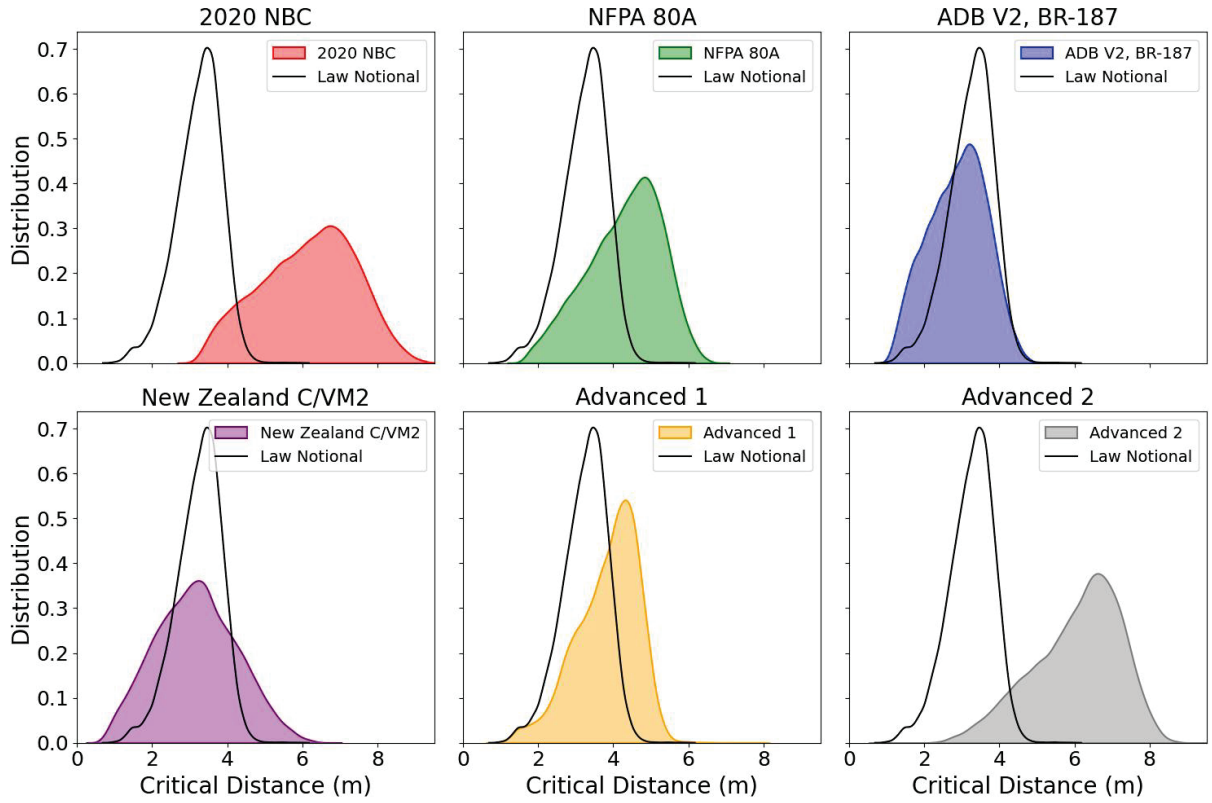


Figure 7-63: Critical distance regulatory and advanced distributions compared to the Law Notional distribution

Figure 7-64 includes a set of contour plots showing the relationship between the percentage of openings (%) and critical distance (m), to align with how the NBC 2020 spatial separation requirements are presented. The black contour lines on each plot represent the Law EVF results, while the coloured contour shapes represent the regulatory or advanced model results, using the same order and colour as shown in Figure 7-63. The contours show a decrease in data point density as the critical distance increases. The regulatory model results have the same general contour shape, indicating an increase in critical distance with increased percentage of openings, broadening toward the top right of the plot. In contrast, the Law EVF and advanced model results show critical distances increasing up to approximately 60% openings, above which they remain relatively unchanged. The Law EVF and Advanced model contour shapes are similar, although the ADV1 model results show an increased upper bound of critical distance that is approximately 1 m greater, and the ADV2 model results are approximately 4 m greater, than the Law EVF results.

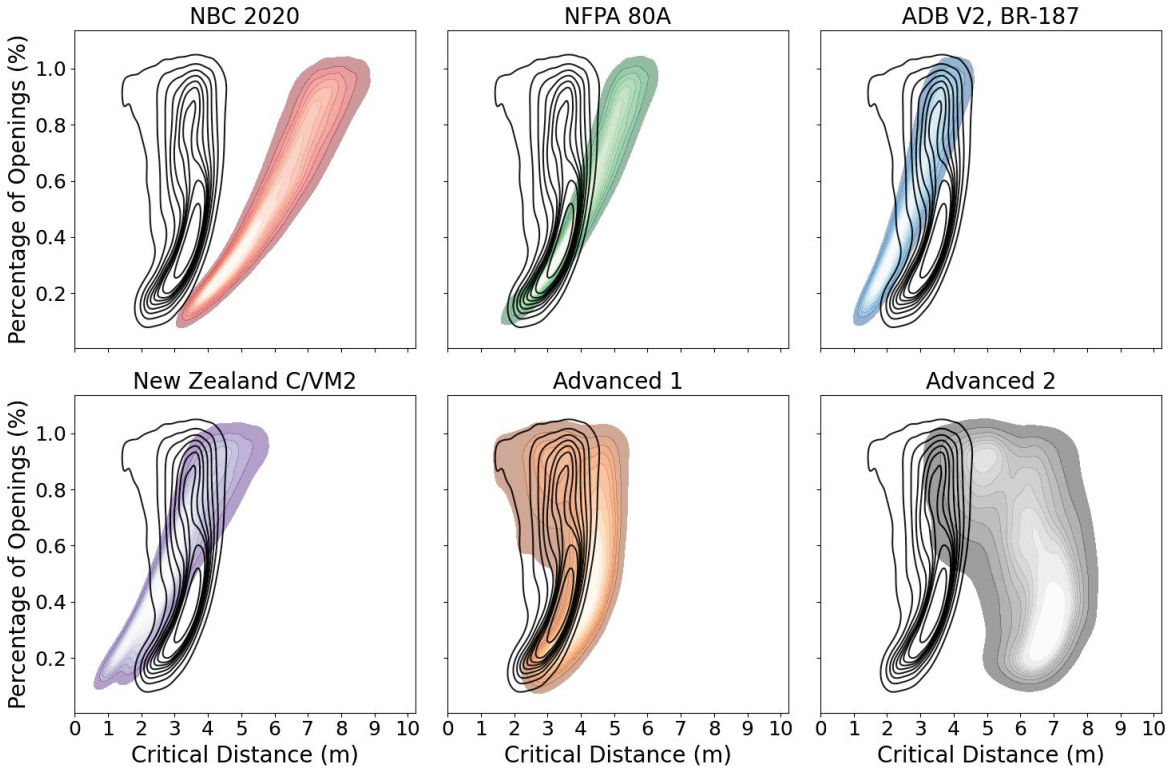


Figure 7-64: Law Notional versus regulatory and advanced model critical distance comparisons

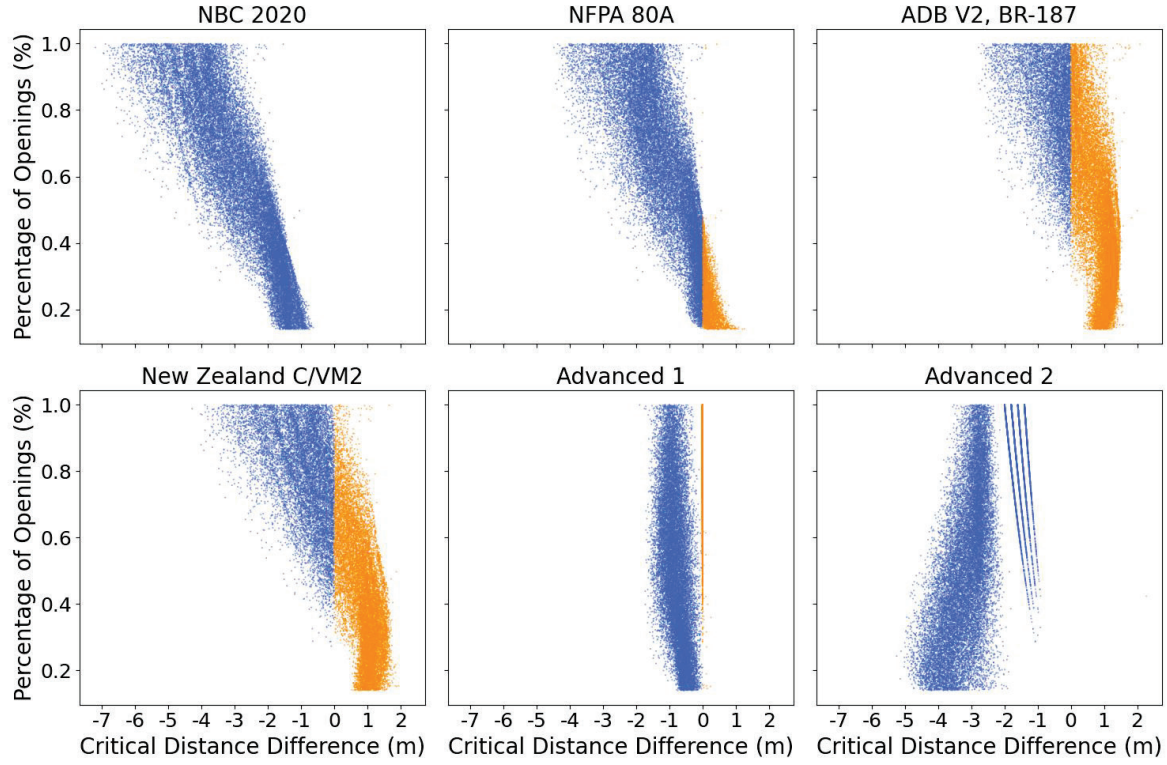


Figure 7-65: Critical distance differences from the LN model

The set of scatter plots in Figure 7-65 illustrate the difference in critical distances between the regulatory/advanced models and the Law EVF model for each corresponding set of results. Data points for the regulatory or advanced models that over-predict the critical distance relative to the Law EVF model are coloured blue, while data points that under-predict are coloured orange. Both the contour plots and these results show that the NBC 2020, ADV1, and ADV2 models largely overpredict critical distances compared to the Law EVF model. The NFPA 80A, ADB V2 BR187, and NZ C/VM2 models underpredict the critical distances at lower percentage of openings in comparison to the Law EVF model. Among these, the ADB V2 BR187 and NZ C/VM2 models show the greatest difference, which is likely due to the combination of their lower emissive heat fluxes and lack of flame front factor.

The squared standardized regression coefficients (β^2) for the exposure analysis critical distance are included in Table 7-29, as a function of the key input parameters of ventilation factor, percentage opening area, fire load, compartment floor area, and compartment aspect ratio for the Law EVF, ADV1, 2020 NBC, and, ADB V2 BR187 models. The coefficients for the Advanced 2 model closely resemble those of the Law EVF and Advanced 1 models, while the other regulatory models show similarities to the 2020 NBC and ADB V2 BR187 models. Due to these similarities, the Advanced 2 and other regulatory models are not included in Table 7-29.

Table 7-29: Squared standardized regression coefficients (β^2) for the critical distances

Parameter	**Law EVF, β^2**	**ADV1, β^2**	**2020 NBC, β^2**	**ADB V2 BR187, β^2**
Compartment floor area (m^2)	0.1625 (1)	0.1362 (1)	0.0607 (3)	0.0977 (3)
Fire load (MJ/m^2)	0.1187 (2)	0.0703 (2)	0.0032 (4)	0.0049 (4)
Ventilation Factor, $A\sqrt{H}$ ($m^{2.5}$)	0.0695 (3)	0.0176 (3)	0.6927 (1)	1.0207 (1)
Percentage opening area (%)	0.0325 (4)	0.0129 (4)	0.2875 (2)	0.4023 (2)
Compartment Aspect Ratio	0.0002 (5)	0.0008 (5)	0.0026 (5)	0.0045 (5)

The critical distances predicted by the Law EVF and ADV1 models are both shown to be most influenced by the compartment floor area and fuel load. In contrast, the 2020 NBC and ADB V2 BR187 predicted values of critical distance are most influenced by values of the ventilation factor and percentage opening area. Across all models, the compartment aspect ratio has the least influence on critical distance. As discussed earlier, these results are expected.

The scatterplots in Figure 7-66 and Figure 7-67 show the linear regression lines for the 2020 NBC and ADB V2 BR187 model predicted critical distances. The regression line for the fire load is nearly flat, which is not surprising since the emissive power for the regulatory models does not depend on fire load, or at least for the range of fire loads analyzed in this case study. In contrast, the regression line for floor area shows an increasing trend of critical distances with increasing floor area, which indirectly relates to an increased exposing wall area. The regression line for percentage of opening area shows a strong positive

correlation, indicating the critical distance increases as the percentage opening area increases. This trend is more pronounced for the 2020 NBC model compared to the ADB V2 BR187 model. These findings align with the parameters that are fundamental to the spatial separation requirements of the respective codes.

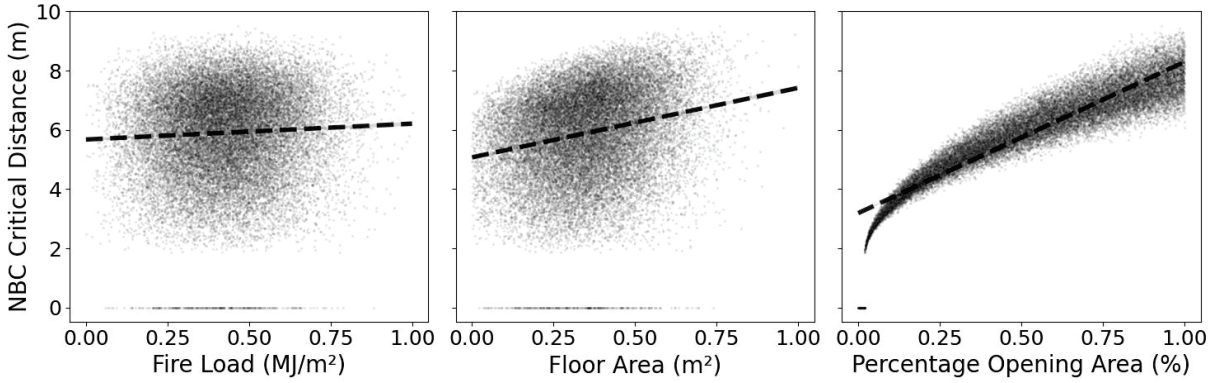


Figure 7-66: Scatter plots of the NBC critical distance versus normalized input parameters

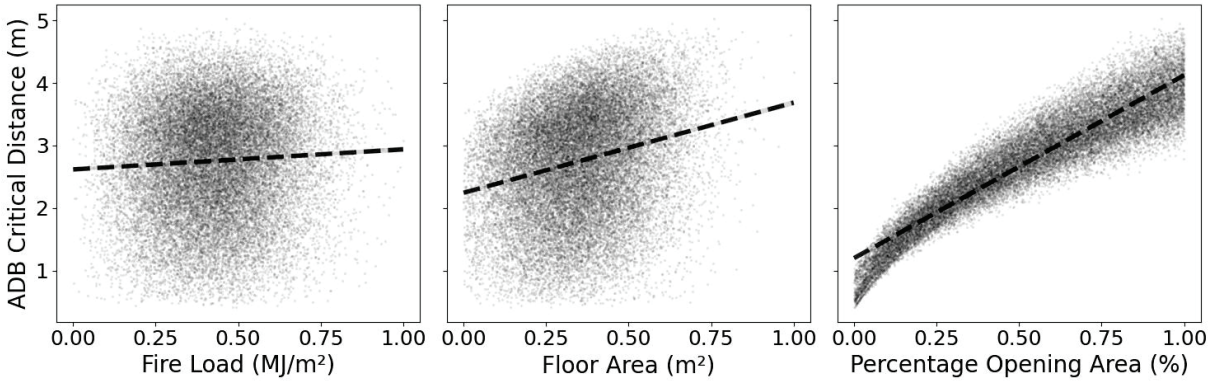


Figure 7-67: Scatter plots of the ADB V2, BR187 critical distance versus normalized input parameters

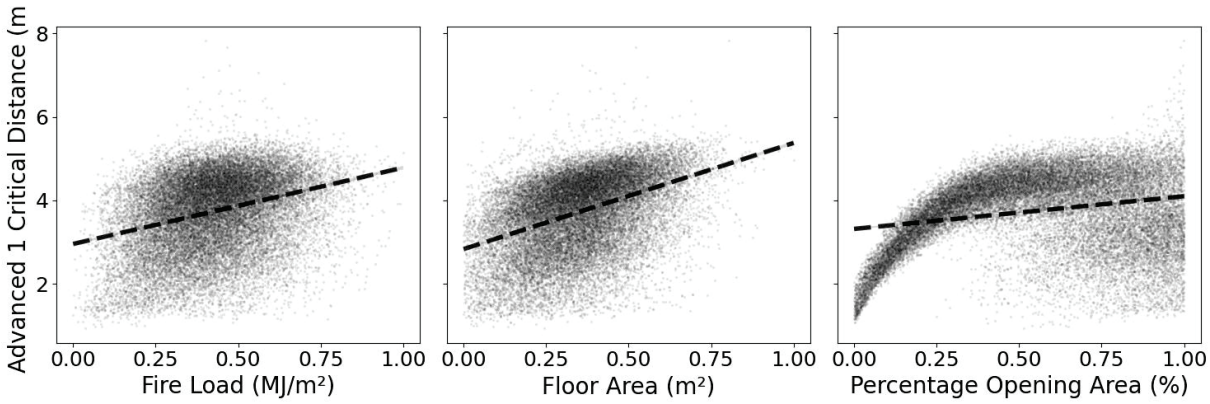


Figure 7-68: Scatter plots of the Advanced 1 critical distance versus normalized input parameters

The scatterplots in Figure 7-68 and Figure 7-69 show the linear regression line for the ADV1 and Law EVF models. The regression lines indicate that the fire load has a stronger influence on predicted critical distance for these models as compared to the regulatory models, with the critical distance increasing with increasing fire load. The floor area regression lines for the Law EVF and ADV1 models show similar trends

to the regulatory models, with an increase in critical distance as the floor area increases. The regression lines for percentage opening area also shows a positive correlation, though this parameter is less influential for the ADV1 and Law EVF models compared to the regulatory models.

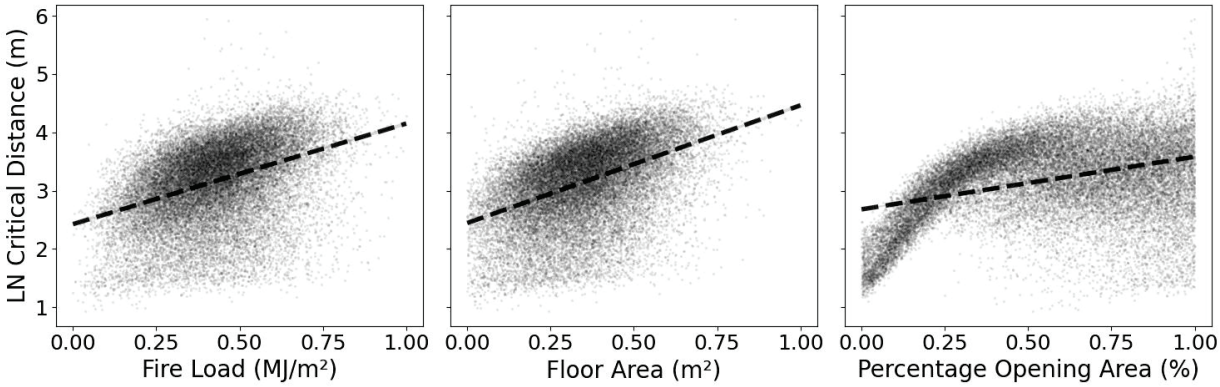


Figure 7-69: Scatter plots of Law notional critical distance versus normalized input parameters

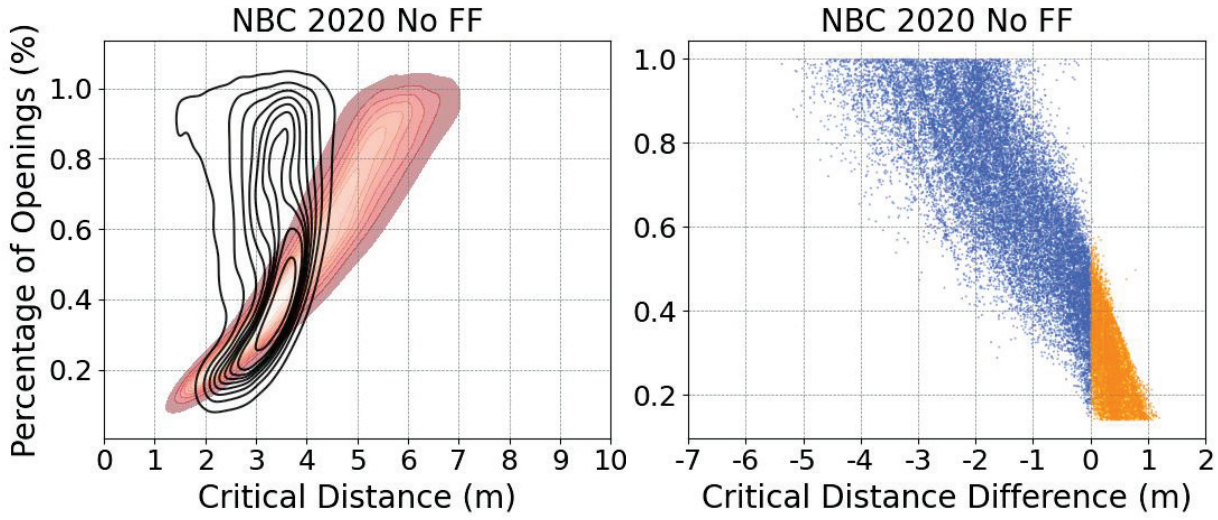
The sensitivity analyses indicate that floor area and fire load have a greater influence on critical distance predictions in the Law EVF and ADV1 models compared to the regulatory models. In contrast, the percentage opening area has a more significant influence on the critical distance in the regulatory models. Therefore, similar to the key parameters influencing the prediction of the onset of flashover, when models based on the most current literature are used in determining critical distance, it can be shown that fire load and floor area are the most critical parameters for characterizing risk relative to radiant heat exposure in determining values for critical distances from a building. Incorporation of the greater influence of these variables into characterization of the fire hazard could inform changes to the NBC 2020 spatial separation requirements.

7.4.5 Summary

Technical reconsideration of the flame front factor applied to the 2020 NBC spatial separation requirements suggested that this factor may result in overly conservative estimates of critical distance and was potentially unnecessary in providing an acceptable level of safety. This conclusion is supported by the quantitative generic risk assessment in which the existing calculation method is compared to newer models developed based on extended research and improved scientific foundation. The comparison shows that critical distances estimated using the 2020 NBC methodology are generally greater than those predicted by the Law EVF model and also generally exceed those calculated using other regulatory models that evolved differently over time. The factors determined to influence critical distance predictions from models such as the Law EVF model align more closely with those factors which relate to realistic fire conditions than those for the regulatory models. Thus, the findings from the more comprehensive technical reconciliation phase of the proposed new framework further support the need to reconsider the application of the flame front factor in the 2020 NBC requirements.

Additional analysis of critical distances predicted using the 2020 NBC methodology, but without the flame front factor, is shown in Figure 7-70. Comparison of these modified predictions to the Law EVF model show that they slightly underpredict critical distances at percentages of openings below 40 percent, followed by a gradually increasing overprediction of critical distance up to 100 percent opening. The underprediction at lower percentages of openings could potentially be addressed by applying the enclosing rectangle method used in the UK and New Zealand, and as was recommended in the earlier phase of technical reconciliation in Section 7.3.3.

The generic risk assessment has therefore demonstrated that the addition of a flame front factor is unnecessary in predicting the critical distance required between adjacent buildings to reduce the risk of fire spread due to radiant heat exposure, assuming the results apply more broadly to compartments beyond Canadian living rooms and that the enclosing rectangle concept is used for close separation distances.



(a) (b)

Figure 7-70: Contour and scatter plots of the critical distance as a function of the percentage of openings for the 2020 NBC model with no flame front factor

An interesting finding from this more comprehensive technical reconciliation analysis is the similarity between the results of the Law EVF and the ADV1 model. The final distributions of predicted critical distance are very similar, but with a skew to the higher values for the ADV1 data (Figure 7-63). This indicates that the ADV1 model provides a slightly more conservative prediction than the Law EVF model, as shown in the percentage of openings versus critical distance comparisons (Figure 7-64 and Figure 7-65). While the ADV1 model uses the same opening temperature as the Law EVF model, it uses a simpler planar geometric configuration in calculation of critical distance as compared to the multiplane and angled configuration used in the much more complex Law EVF model. Given advances in computational capabilities since the original development of the spatial separation requirements in Canada and elsewhere, the ADV1 method could be adopted for estimation of required spatial separation in more complex design scenarios and could also be simplified into a tabular format for easier and more

prescriptive regulatory application to replace the existing outdated spatial separation tables. Providing both methods in the NBC as parallel performance/prescriptive compliance paths increases design flexibility, while maintaining a common and consistent technical base common to these methods.

7.5 Modified IRCC Framework Integration

The historical basis of the spatial separation requirements, in combination with technical reconciliation, can be used to populate the modified IRCC hierarchy. A comprehensive detailing of this information is beyond the scope of this thesis, which is limited to demonstrating the efficacy of the framework for building code analysis and modification outlined in Chapter 4. The following provides an example of the incorporation of new information to populate levels 4 and 5 of the modified IRCC hierarchy for office buildings. Information for Levels 1 to 3 has already been incorporated in the objective-based framework of the 2020 NBC [21].

7.5.1 Regulatory Development Paradigm

The historical analysis of the spatial separation requirements has quantitatively characterized the risk of exposure from fire through the key elements of the regulatory risk paradigm as follows:

1) **Hazard:** The hazard is characterized as:
    a. Full compartment involvement, where flames extend through unprotected openings in the compartment's exterior.
    b. The radiant emissive power of the fire source is concentrated in the area of unprotected openings. Testing has established values of 178 kW/m² for low-hazard occupancies and 356 kW/m² for high-hazard occupancies.
2) **Exposed:** The exposed is characterized as follows:
    a. The impact of the hazard on the exposed was developed to align with the most common building material having the lowest ignition heat flux at the time of development of the spatial separation requirements (1960s and earlier), which is wood.
    b. To address potential external ignition sources, such as sparks or direct flame contact, the piloted ignition threshold of wood (12.5 kW/m²) was identified as the performance criterion for solution development.
3) **Relationship:** The relationship between the hazard and the exposed is characterized as follows:
    a. The relationship between the hazard and the exposed surface is quantified through critical configuration factors, defined as the ratio of the critical incident heat flux to the source radiant emissive power.
    b. For low-hazard occupancies, the critical configuration factor is 0.07, while for high-hazard occupancies, it is 0.035.
    c. The relationship between the hazard and exposed is expressed as a function of the configuration factor of the source plane at a distance, based on a simplified configuration

factor equation through use of a grey radiator approximation. This approach applies an emissivity correction based on the proportion of openings relative to the total exterior wall area.

d. The allowable percentage of unprotected openings in the exterior wall of a compartment is determined by the ratio of the critical configuration factor to the configuration factor of the exposing plane.

These factors are then aligned in the context of the regulatory risk paradigm, with the modified IRCC hierarchy.

7.5.2 Level 4: Performance or Risk Groups

The spatial separation requirements categorize buildings into two primary risk groups based on fire load and occupancy type. These groups are defined as follows:

1. **Low Hazard Occupancies:** Those with a low fire load of 50 kg/m² (10 lb/ft²), as was detailed in Table 6-2 of Section 6.3.2, including assembly (Group A), detention/treatment/care (Group B), residential (Group C), business (Group D), and low hazard industrial (Group F, Division 3).
2. **High Hazard Occupancies:** Those with a medium to high fire load of 100 kg/m² (20 lb/ft²) or more, including mercantile (Group E), medium and high hazard industrial (Group F, Divisions 1 and 2).

To mitigate fire risks associated with these groups, the spatial separation requirements limit the percentage of unprotected openings in the exterior wall of a fire compartment or limit the distance to a property line or centre of a street. The performance/risk criteria implicit to the building size and construction specifications are detailed in the following section.

7.5.3 Level 5: Performance or Risk Criteria

The quantitative acceptance criteria implicit in the spatial separation requirements is the pilot ignition of wood, which is considered to be 12.5 kW/m².

7.6 Conclusion and Recommendations

This case study demonstrates the practical application of the new framework to identify the historical basis of the spatial separation requirements followed by a more in-depth technical reconciliation of the factors underlying the present requirements in the NBC. The historical information was utilized to populate Levels 4 and 5 of the modified IRCC Framework, either in an unmodified form or in combination with technical reconciliation of certain aspects of the requirements. Populating Levels 1 through 5 of the modified IRCC Framework then allows for the reconsideration of the existing prescriptive requirements (Level 6A) and the development of parallel performance requirements (Level 6B). Even the preliminary assessment within this case study suggests that certain aspects of the spatial separation requirements may warrant

reconsideration, particularly given subsequent testing, advances in knowledge, and improvements in analytical methods since the original development of these requirements. These would include the following:

1. Updates to the spatial separation tables to remedy numerical errors.
2. Reconsideration of the effectiveness of the grey radiator approximation and consideration for the alternative application of the enclosing rectangle concept.
3. Reconsideration of the fire department arrival time for low hazard occupancies.
4. Evaluation of whether the application of the flame front factor is technically appropriate given advances since the time of its incorporation in the NBC.

Additional analyses, building on the generic risk assessment approach outlined in this thesis, could provide a broader cross-section of results that further support reconsideration of the grey radiator approximation, more precise opening analysis (enclosing rectangle), and modification or removal of the flame front factor.

Chapter 8
Conclusions

The prescriptive and legacy-based nature of the fire and life safety requirements in the NBC has limited the use of modern materials and construction methods that facilitate greater flexibility in design, a necessity that is becoming increasingly important to address evolving and potentially detrimental environmental risks. The shift to a performance-based framework has been recognized as a solution to these challenges. However, this transition has been limited by a lack of calculation methods and quantitative performance criteria linked to the existing, primarily prescriptive requirements. This stems from the long history of development of these requirements, for which performance has been demonstrated more through the test of time than through a fundamental understanding of how fire safety strategies influence the relationship between fire hazards and the exposed people or property.

The present research addresses this challenge through the development of a comprehensive risk-structured framework consisting of three sub-frameworks connected through a regulatory risk paradigm. This framework integrates an analysis of the historical basis of the fire and life safety requirements (sub-framework 1) with a method to technically reconcile that basis with more current fire science and fire engineering principles (sub-framework 2), along with a means for aligning the resulting information into a risk-structured performance-based hierarchy that connects high level objectives and detailed regulatory solutions through shared risk metrics and verification methods (sub-framework 3).

The efficacy of this framework was demonstrated through three case studies, each focusing on distinct aspects of how the sub-frameworks could be applied to assess the existing fire and life safety requirements in the NBC. These case studies examined occupant load factors and exit width requirements, building size limits and types of construction, and spatial separation requirements. The detailed historical analysis undertaken within these case studies identified the rationale underlying the associated requirements, including the quantitative performance criteria determined to be important to address the longstanding issues of misinterpretation and ambiguity in the application of fire safety requirements. This information will enable designers, building officials, and code development organizations to apply and adapt these requirements in a more consistent and technically sound manner.

The case study examining office occupant load factors identified that this factor is based on passive ventilation limits established for office buildings in the late nineteenth and early twentieth centuries, confirmed through statistical analyses of office building populations from the early 1900s. The same case study identified that the minimum exit width factor originated from the width of a file of persons in motion based on military experience from over two hundred years ago. These factors are incorporated into the existing code provisions to represent characteristics of those who may be exposed to fire, and are therefore key to understanding the development and application of regulatory solutions that facilitate

egress from buildings. With an understanding of their basis, these factors can be applied either directly across varying design contexts, or appropriately adapted for alternative designs.

Similarly, the case study on building size limits and types of construction established that the height limit for combustible buildings is primarily based on the assumption that such buildings, due to their combustible nature, could become fully involved in fire. A typical Canadian fire service was presumed capable of controlling such fires from the exterior to prevent spread to adjacent buildings. This understanding provides a basis for considering increased building heights for combustible construction through alternative or enhanced strategies that achieve an equivalent level of performance, which is fire containment to the building of origin.

In addition to discovering the rationale underlying the requirements in each case study, the historical analysis also identified errors, outdated assumptions, mischaracterizations of fire risk, and shifted baselines of performance. These findings underscore the limitations of the non-technical test of time approach to regulatory development. The present research addressed these issues through technical reconciliation of the fire and life safety requirements within the context of the regulatory risk paradigm, incorporating more current fire science and fire engineering concepts. For example, in terms of changing characteristics, it was established that passive ventilation is no longer a controlling factor for office occupant load densities, a finding supported by more current statistical analyses suggesting a lower occupant density. Similarly, outdated assumptions of anthropometrics underlying the existing exit width factor were found not to represent modern characteristics that require a greater width for exiting.

The impact of changing characteristics was more pronounced in the case study addressing building size limits and types of construction. These included fire-resistance and containment in light of a reduction in total fire load and configuration of that load (i.e., contents vs. wall and ceiling lining), based on more recent statistical surveys, advances in fire service capabilities compared to those of the late 1800s, to which the maximum combustible building size is currently linked, and advances in methods to protect combustible construction materials from participation in fire. Reconsideration of these solutions, in combination with advancements in fire compartmentation and sprinkler protection, all within the context of the fire safety concepts tree, allowed for a more holistic assessment of their combined performance. This, in turn, allowed for further assessment of the individual contributions of each of these fire safety strategies to the overall combined performance of the set of strategies. It was found that if a building is equipped with a sprinkler system, that the type of construction is not a significant factor impacting unacceptable fire growth and spread, and therefore may no longer be an effective regulatory solution to limit such outcomes. This finding is particularly significant given recent efforts to promote embodied carbon in construction by encouraging greater use of wood in larger and taller buildings, which is currently limited by the existing prescriptive requirements.

Historical analysis of the spatial separation case study found significant limitations in the current requirements, largely due to their reliance on the limited set of results from the St. Lawrence burn tests. These included calculation errors in the table values, increased fire risk associated with the grey radiator approximation, presumed fire department arrival time based on the results of a single test burn, and the

addition of a flame front factor despite artificially high emissive power already accounting for flame front effects. Each of these was examined, through technical reconciliation, in a more current context with detailed analyses suggesting corrections to the table values, adoption of the enclosing rectangle concept instead of the grey radiator approximation, and an increase in the assumed fire department arrival time.

The addition of the flame front factor was re-examined through risk-based methods to address uncertainty in regulatory solution development and verify effectiveness at a broader societal level. This factor was found to be excessive when compared to regulatory approaches taken in other international jurisdictions that utilize more current test data and methodologies, and when compared with results from a more fundamental fire science-based approach to characterize external venting flames from an opening. This finding is particularly important given efforts toward improving building energy efficiency, which through exterior wall upgrades often require increased exterior wall thicknesses that reduce distances to property boundaries. Elimination of the flame front factor would facilitate such changes without increasing the risk of fire spread.

The final step of the proposed framework involved aligning the information established through the historical analysis, and updated through technical reconciliation for each case study with the modified IRCC hierarchy. This included organization of the newly identified information through the regulatory risk paradigm, to align with the risk-structure of the modified hierarchy. The office occupant load and exit width factors were identified as risk characteristics rather than complete regulatory solutions. Therefore, the information from this case study was mapped to the performance/risk group level (i.e., Level 4) of the modified hierarchy. Since these characteristics impact the development of solutions for occupant egress, the information can be used in the future to identify performance/risk criteria (Level 5) and to develop, maintain, or modify parallel prescriptive (Level 6A) performance-based (Level 6B) solutions.

The building size limits and types of construction case study provided information aligning with all levels of the modified hierarchy. Several performance/risk groups were identified, including occupancy type quantified through fire load surveys, building size, provision of a sprinkler system, and fire service capability. The criteria of acceptable performance (Level 5) for noncombustible buildings was identified to be limiting fire from spreading from one storey to another, or alternatively, containment to the storey of origin. For combustible buildings, this criteria was identified to be limiting fire from spreading to a neighbouring building, or alternatively, containment to the building of origin. This information is critical to support alternative solutions and the development of a parallel performance based path (Level 6b) to the existing prescriptive path (Level 6a).

The information identified in the spatial separation case study similarly aligned with all levels of the modified IRCC hierarchy. Two performance/risk groups were identified, namely low and high hazard occupancies, modified based on the presence of a sprinkler system. Specific criteria were identified, including source emissive power values (Level 4) for each hazard level as well as a critical incident heat flux of 12.5 kW/m² (Level 5). Similar to the other case studies, this information can be used to develop a parallel performance based path (Level 6b) to the existing prescriptive path (Level 6a). Furthermore, the

specific method of verification, the configuration factor equation and its associated assumptions and simplifications such as the grey radiator approximation, was explicitly identified (Level 7).

Through the identification and organization of the key elements of fire risk underlying the fire and life safety requirements, including rationale and quantified performance criteria, the modified hierarchy serves as the foundation for a new performance-based framework for the NBC, and as a repository for archiving key information to support future regulatory changes and advancements. This structured framework directly addresses longstanding challenges such as generational amnesia, status-quo bias, the regulatory ratchet effect, and shifting baselines of acceptable performance, all of which have limited understanding of the basis for the fire and life safety requirements and the subsequent development of alternative and innovative designs. As demonstrated through the case studies, the proposed new framework addresses the limitations rooted in the current prescriptive-based fire safety design practices by introducing a risk-structured, performance-based hierarchy for the NBC. This provides fire safety engineers with the foundation to more holistically address fire risk in the built environment, while at the same time providing flexibility in design. This is a necessary step for the evolution and maturation of the fire engineering discipline in Canada.

The results of this study are relevant to various stakeholders. Through use of the novel framework:

- Fire safety engineers will be provided with tools to better understand and apply the regulatory requirements applicable to their projects, thereby optimizing their designs toward scientifically founded, performance-based solutions.
- Building code development organizations can better support regulatory reform through requirements that, while acknowledging the historical roots, are based on fire science and fire safety engineering principles, toward enhanced clarity, consistency, and adaptability of these requirements in the NBC.
- Designers and building officials will benefit from greater consistency in enforcement and reduced ambiguity, achieved through clarity of intent and measurable performance. This clarity also supports the development and acceptance of innovative materials and construction methods.

The conclusions of this research are based on applying the proposed framework to a subset of important fire and life safety requirements of the NBC, and may not directly apply in jurisdictions with different regulatory systems or to other parts of the NBC unrelated to fire and life safety.

In conclusion, through historical analysis to identify the basis of the fire and life safety requirements, technical reconciliation of those requirements using modern fire science and fire engineering principles, and alignment of the resulting information with a risk-structured performance-based hierarchy, this research facilitates the transition of the NBC from its current objective-based framework to a fully performance-based framework.

8.1 Contributions

This research contributes the first structured framework for transitioning the NBC from objective-based to performance-based for fire safety. It provides a systematic approach to address the challenges that have previously limited such a transition in Canada. The specific contributions of this research are detailed below:

- Comparative method: This research contributes a critical analysis that challenges the reliability of the comparative method to establish acceptable performance for the fire and life safety requirements in the NBC. This analysis demonstrates, through case study evidence, the current limitations of this approach in providing a consistent or even acceptable level of risk that is implicit in the current acceptable solution requirements of the NBC.
- Social limitations: This research contributes a new understanding of how the interconnection of the 'test of time,' generational amnesia, status-quo bias, and shifting baselines of performance have limited the acceptance of performance-based solutions as alternatives to the acceptable solutions of the NBC.
- Novel framework: This research contributes a novel framework to effectively transition the NBC from its current primarily prescriptive-based framework to a performance-based framework and thereby support increased sustainability, sensitivity and economically effective designs. Contributions associated with the elements of the novel framework include:
    - Regulatory Risk Paradigm: The regulatory risk paradigm contributes a new adapted traditional risk assessment approach to identify and characterize the risk elements implicit in existing NBC fire safety requirements, enabling their translation into more explicit risk metrics and informing the development of future performance criteria.
    - Historical Sub-framework: The historical sub-framework contributes a new systematic method that traces the evolution of fire safety requirements to identify the original risk factors and assumptions underlying their development. This is a methodology that did not previously exist, greatly enhancing understanding of the inherent background incorporated into regulatory requirements, highlighting technical limitations, and identifying key performance metrics.
    - Technical Reconciliation Sub-framework: The technical reconciliation sub-framework contributes a new method to systematically identify and technically resolve non-technical inconsistencies or outdated information that underlies the fire safety requirements that are presently in the NBC. This analysis should only be undertaken by those who have requisite knowledge and competence in the relevant technical matters.
    - The Modified IRCC Hierarchy Sub-framework: The population of the modified IRCC Hierarchy with information developed through the historical and technical reconciliation sub-frameworks, in alignment with the regulatory risk paradigm, provides

a direct link between broad societal goals and detailed regulatory solutions through shared risk metrics and verification methods and through this structured information, limits the future impact of the identified limiting social conditions.

- Historical analysis case study contributions: By establishing the historical basis of the office occupant load factor, the exit width factors, building size requirements, and spatial separation requirements, this research fills a knowledge gap and contributes new understanding of the original risk elements and performance assumptions implicit in these requirements. This knowledge can be used to support reduced ambiguity, consistent enforcement, clarity of intent, and facilitate the development of performance-based approaches. Specific contributions include:
    - Knowledge that the office occupant load factor is based on passive ventilation limits in office buildings in the late 1800s and early 1900s, confirmed by statistical analyses of these occupancies in the early 1900s.
    - Knowledge that the unit exit width factor is based on the width of the "average man" in the 1800s, with origins in army troop formations of the late 1700s.
    - Knowledge that the building size limits and construction type requirements are based on ultimate fire size within the capability of a responding fire service from the late 1800s to early 1900s to control.
    - Knowledge that the fire-resistance requirements for larger buildings are correlated with occupancy risk characteristics, such as fire load and occupant capability, and are construction type specific due to material limits in the 1940s.
    - Knowledge of the specific connection between the spatial separation requirements and the results of the St. Lawrence burn tests.
- Technical reconciliation case study contributions: Through case study analysis, this research demonstrates and contributes systematic approaches for analytically updating fire safety requirements using current fire science and fire safety engineering principles, specifically addressing occupant load factors, exit width factors, building size limits, and spatial separation requirements. Specific contributions include:
    - Demonstration that the original passive ventilation basis and statistical representation of the office occupant load factor is no longer valid, and this factor should be updated in the NBC based on modern statistics.
    - Demonstration that the basis for the exit width factor is no longer valid and should be increased in the NBC to represent more current demographics and associated anthropometrics.
    - Demonstration that the combustible fire load, used to characterize fire hazard, has evolved over time, and that even though the content (furniture) load has increased from

legacy to modern times, the total quantity of combustible materials has decreased, primarily due to a significant reduction in combustible room lining materials. Further, demonstration that even with the changes in the configuration of the fire load from legacy to modern times, fire intensity has remained relatively constant.

- Demonstration that the basis of the existing fire-resistance requirements of the NBC is no longer technically relevant and that, beyond just a fire load quantity-based fire severity metric, the basis should also consider configuration of fire load and ventilation, as well as fire intensity as it relates to the onset of flashover. This provides greater understanding of the impact of fire load configuration on both the severity and intensity of fire, which should be used to improve and update the current fire containment requirements of the NBC.
- Demonstration that limiting building size and type of construction, based on fire service capability from the early 1900s, is no longer valid and these limits should be updated to represent modern fire service capability.
- Demonstration that noncombustible construction as a primary solution to limit fire growth and spread in larger and taller buildings may no longer be statistically significant given increased requirements for sprinklers and fire compartmentation. This technical reconciliation provides an understanding of the impact of combined solutions that are intended to limit fire growth and spread, and reconsideration of the importance attributed to the solution of noncombustible construction currently in the NBC, allowing the potential for greater use of combustible materials to achieve energy efficiency goals without increasing fire risk.
- Identification and correction of errors in spatial separation tables that will be incorporated into the next edition of the NBC. This provides greater consistency between the equations on which the tables are based and the table values, facilitating performance-based approaches that use the equations as an alternative to the table values.
- Demonstration that the fire department response time should be based on consideration of the fire test results associated with both the high hazard and low hazard spatial separation classifications, rather than just the value associated with the high hazard classification. Modifying this response time, with appropriate justification, allows greater design flexibility for buildings and neighbourhoods beyond the current 10-minute fire service intervention limit without compromising fire safety.
- Demonstration that the use of the grey radiator approximation results in a range of incident heat flux values that straddle the current value intended as an acceptable level of heat flux, supporting Bjelland's findings, but in a Canadian context, that the performance associated with acceptable solutions does not necessarily provide a single consistent level of safety. To address this inconsistency, implementation of an enclosing

rectangle concept is recommended, as has been done in other jurisdictions such as the UK and New Zealand. Use of the enclosing rectangle approach will address the identified limits of the current grey radiator approximation used in the NBC and provide levels of acceptable performance that align more closely with the original intent of the requirements to limit the spread of fire between buildings.

- Demonstration that the flame front factor incorporated in the calculation of the current spatial separation table values is unnecessary, being redundant to existing emissive power characterization. Based on comparison with Margaret Law's exterior flame venting model, it was shown that acceptable performance can be achieved without this factor. This is further supported by comparison with calculations from other jurisdictions (UK, New Zealand) that do not include a flame front factor. Removal of this factor enables greater design flexibility in facilitating the energy retrofit of existing building exterior walls without increasing the risk of fire spread between buildings.
- Development of a simplified computational method for calculating critical distances that produces results comparable to Margaret Law's exterior flame venting model while requiring significantly less complex configuration factor calculations. This method enables practical application to complex design scenarios and provides a foundation for developing new more scientifically representative spatial separation table values.
- Demonstration of the feasibility of using advanced Monte Carlo approaches with CFAST modelling and linear regression-based sensitivity analysis to better predict the onset of flashover, building on and extending Bruns' research. Within limitations of the models employed, this allows a broader understanding of the uncertainty associated with the prediction of the onset of flashover.
- Development of computational methods that overcome convergence limitations in critical distance calculations. This approach enables more reliable spatial separation analysis for performance-based building design.

8.2 Further Research

While the proposed framework establishes a solid basis for regulatory reform of the fire and life safety requirements in Canada, further research is necessary to refine and expand its application. The case studies presented in this thesis did not address all fire and life safety requirements in Part 3 of the NBC. A more comprehensive analysis of all Part 3 requirements, within the context of the proposed framework, could reveal their interdependencies and support the development of a more holistic and integrated regulatory structure. Further, while this thesis focused on fire and life safety, the efficacy of the proposed framework could be further assessed through its application to other subject-matter in the NBC, and even to selected aspects, or the entirety, of building codes in other jurisdictions.

The historical analysis of the building size limits and type of construction requirements of the NBC found that combustible building size limits were originally established on the assumption that such buildings would become fully involved in fire, and that fire spread to adjacent buildings could be reasonably limited based on the capabilities of a fire service from the early 1900s. The outdated nature of this basis information presents opportunities for further research. One such opportunity concerns the validity of the assumption that a building constructed of combustible materials will become fully involved in fire, which is questionable given the increased degree of fire compartmentation incorporated into the NBC fire and life safety requirements since that time. In addition, the capabilities of a modern fire service to limit fire spread from combustible buildings to adjacent buildings could also be examined further, particularly given uncertainty regarding the extent to which fire outcomes are influenced by the type of construction in light of sprinklers.

The spatial separation case study examined the application of the generic risk assessment approach to the technical reconciliation of the existing solution underlying these requirements, providing support for eliminating the flame front factor without compromising safety. However, this analysis was conducted only in the context of residential living rooms, and should be expanded to analyze key factors associated with all occupancies in order to justify elimination of the flame front factor in the NBC.

The risk-based spatial separation analysis provided a comprehensive evaluation of uncertainties over a broader societal scale than the more traditional approach to regulatory development governed by a limited set of fire incidents and the test of time. Application of the risk-based analysis to other NBC requirements could similarly address uncertainties on a broader scale to better align regulatory requirements with the portfolio of designs and buildings they are intended to address.

The proposed framework can serve as a basis for further regulatory reform, as recommended in several performance-based methods and approaches that have been proposed over the last 20 to 30 years [196-200, 202]. In particular, further research is needed to confirm whether the framework presented in this thesis provides a structured means to quantify the technical risk basis necessary to support decision-making within the broader legal and regulatory environment of a socio-technical system [198], thereby contributing to the advancement of a performance-based NBC.

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Appendices

Appendix A
Spatial Separation Interpolation Equations

Interpolation

Interpolate the permitted percentage of unprotected openings if the area of the exposing building face does not match the table values:

$$UPO = UPO_1\left(\frac{A_2 - A}{A_2 - A_1}\right) + UPO_2\left(\frac{A - A_1}{A_2 - A_1}\right) \qquad \text{Equation A-1}$$

Interpolate the permitted percentage of unprotected openings if the limiting distance does not match the table values:

$$UPO = UPO_1\left(\frac{LD_2 - LD}{LD_2 - LD_1}\right) + UPO_2\left(\frac{LD - LD_1}{LD_2 - LD_1}\right) \qquad \text{Equation A-2}$$

Interpolate the permitted percentage of unprotected openings if the area of the exposing building face and the limiting distance do not match the table values:

$$\begin{aligned} UPO = {} & \left(\frac{LD - LD_1}{LD_2 - LD_1}\right)\left[UPO_{12}\left(\frac{A_2 - A}{A_2 - A_1}\right) + UPO_{22}\left(\frac{A - A_1}{A_2 - A_1}\right)\right] \\ & + \left(\frac{LD_2 - LD}{LD_2 - LD_1}\right)\left[UPO_{11}\left(\frac{A_2 - A}{A_2 - A_1}\right) + UPO_{21}\left(\frac{A - A_1}{A_2 - A_1}\right)\right] \end{aligned} \qquad \text{Equation A-3}$$

The following interpolation can be used to determine the limiting distance where the actual percentage of unprotected openings is known and does not match a table value:

$$\begin{aligned} LD = {} & \left[LD_1 + (LD_2 - LD_1)\left(\frac{UPO - UPO_{11}}{UPO_{21} - UPO_{11}}\right)\right] \\ & + \left\{\left[LD_1 + (LD_2 - LD_1)\left(\frac{UPO - UPO_{11}}{UPO_{21} - UPO_{11}}\right)\right]\right. \\ & \left. - \left[LD_1 + (LD_2 - LD_1)\left(\frac{UPO - UPO_{11}}{UPO_{21} - UPO_{11}}\right)\right]\right\}\left(\frac{A - A_1}{A_2 - A_1}\right) \end{aligned} \qquad \text{Equation A-4}$$

Based on the table lookup example above for an exposing building face area of 18 m², a ratio of 4:1 and a limiting distance of 3 m, the permitted percentage of unprotected openings based on interpolation is as shown in Figure A-1.

Exposing Building Face		Area of *Unprotected Opening* for gr											
Max.	Ratio												*Limit*
Area, m²	(L/H or H/L)	0	1.2	1.5	2	2.5	3	4	5	6	7	8	9
10	Less than 3:1	0	8	10	18	29	46	91	100				
	3:1 to 10:1	0	8	12	21	33	50	96	100				
	over 10:1	0	11	18	32	48	68	100					
A1	Less than 3:1	0	7	9	14	22	UPO1	63	100				
15	3:1 to 10:1	0	8	10	17	25	37	67	100				
	over 10:1	0	10	15	26	39	53	87	100				
	Less than 3:1	0	7	9	12	18	26	49	81	100			
20	3:1 to 10:1	0	8	10	15	21	30	53	85	100			
A2	over 10:1	0	9	14	23	33	UPO2	72	100				
	Less than 3:1	0	7	8	11	16	23	41	66	98	100		
25	3:1 to 10:1	0	8	9	13	19	26	45	70	100			
	over 10:1	0	9	13	21	30	39	62	90	100			

Figure A-1: Exposing building face interpolation example

The interpolated permitted percentage of unprotected openings (UPO) is as follows:

$$UPO = 37\left(\frac{20-18}{20-15}\right) + 30\left(\frac{18-15}{20-15}\right) = 32.8\% \qquad \text{Equation A-5}$$

The resulting 32.8% of unprotected openings is 2.8% greater than based on the table and conservative rounding of the input values.

Appendix B
St. Lawrence Building No. 5 Configuration Factor Calculation

Building No. 5: Configuration Factor Calculations

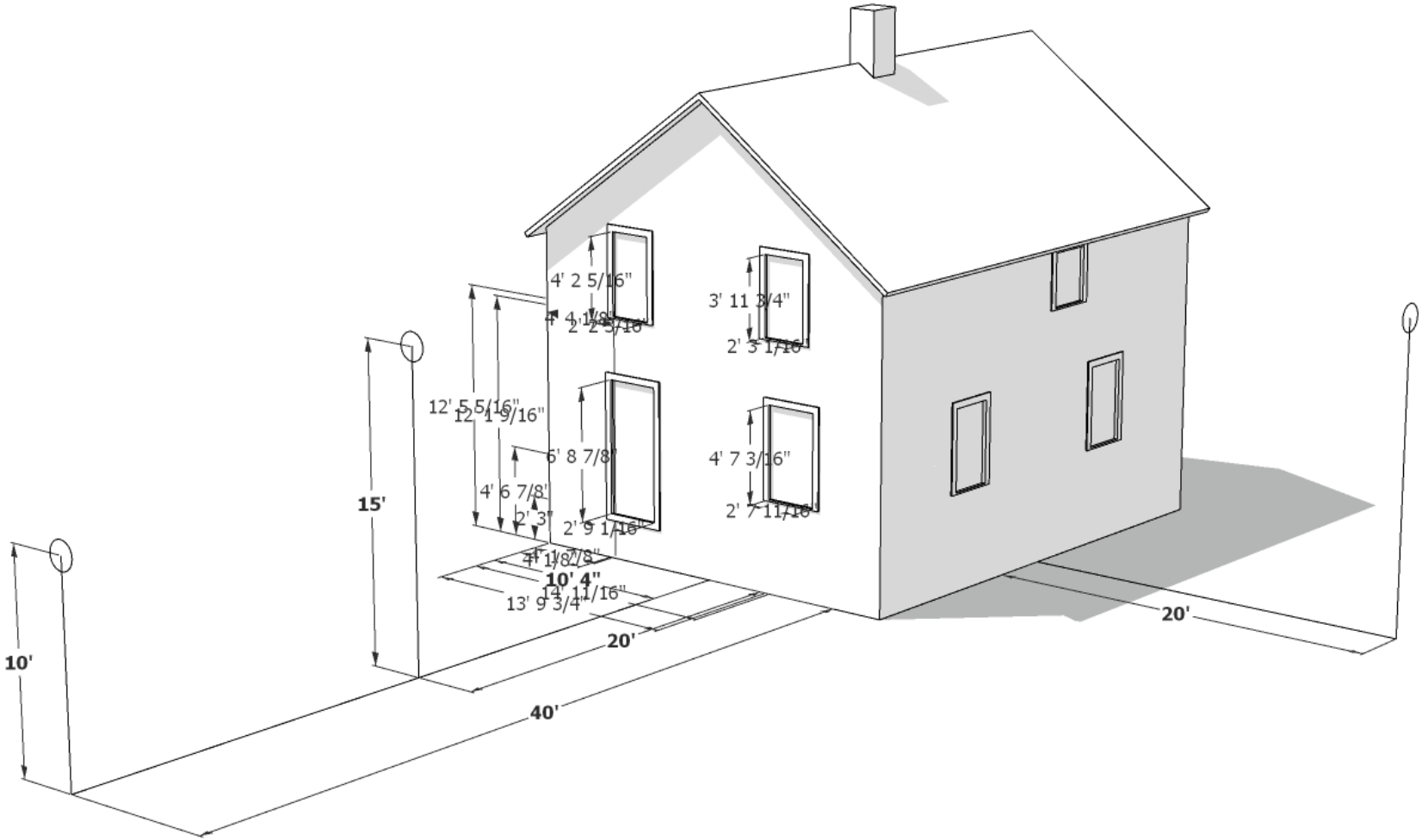


Figure B-1: SketchUp 2023 model of Building No. 5

Sensor Data

Q	0	Angle
xp	10.3	Horizontal Distance (ft)
zp	15	Vertical Distance (ft)
D (R1)	20	Distance from the Wall (ft)
D (R4)	40	Distance from the Wall (ft)

Table B-1: Exposing Opening Data

Number	Component	x_1 (ft)	x_2 (ft)	Width	z_1 (ft)	z_2 (ft)	Height	Area (ft^2)	PHI (20 ft)	PHI (40 ft)
1	Door	4.156	6.911	2.755	2.250	8.990	6.740	2.255	0.0091	0.0032
2	Lower Window	14.057	16.698	2.641	4.500	9.083	4.583	1.462	0.0063	0.0021
3	Upper Left Window	4.344	6.526	2.182	12.130	16.323	4.193	1.263	0.0064	0.0018
4	Upper Right Window	13.813	16.068	2.255	12.443	16.422	3.979	1.268	0.0064	0.0017
								Configuration Factor	0.0282	0.0089

Appendix C
NBC Spatial Separation Calculation Methodology

Inputs:

$E = \begin{cases} 178\ kW/m^2, & \text{Groups A, B, C, D and F3} \\ 356\ kW/m^2, & \text{Groups E, F1 and F2} \end{cases}$

$I_c = 12.5\ kW/m^2$

$\phi_c = \begin{cases} 0.070, & \text{Groups A, B, C, D and F3} \\ 0.035, & \text{Groups E, F1 and F2} \end{cases}$

h = exposing building face height (m)

w = exposing building face width (m)

LD = Limiting distance (m)

ff = Flame front (1.8288 m)

Step 1: Calculate the distance (d) based on Equation 7-11

$$d = 2 \cdot LD - ff$$

Step 2: Calculate the ratio (S) of the exposing building face based on Equation 7-9

$$\mathrm{S} = \max\left[\frac{h}{w}, \frac{w}{h}\right]$$

Step 3: Calculate the normalize area (T) of the exposing building face based on Equation 7-8

$$\mathrm{T} = \frac{A}{d^2} = \frac{h \cdot w}{d^2}$$

Step 4: Calculate the configuration factor (ϕ) based on Equation 7-7

$$\phi = \frac{2}{\pi}\left[\sqrt{\frac{\frac{T}{S}}{\frac{T}{S}+4}}\tan^{-1}\left(\sqrt{\frac{T \cdot S}{\frac{T}{S}+4}}\right) + \sqrt{\frac{T \cdot S}{T \cdot S+4}}\tan^{-1}\left(\sqrt{\frac{\frac{T}{S}}{T \cdot S+4}}\right)\right]$$

Step 5: Calculate the percentage of unprotected openings ($\%\mathbf{UPO}$) based on Equation 7-12, rounded to the nearest percent

$$\%\mathrm{UPO} = 100 \cdot \left(\frac{\phi_c}{\phi}\right)$$

Example:

ϕ_c = 0.070

h = 2.1213 m

w = 8.4853 m

LD = 3 m

ff = 1.8288 m

S = 4

T = 2

ϕ = 0.2022

%UPO = 34.6%

Appendix D
BR187 Spatial Separation Calculation Methodology

Inputs:

$$E = \begin{cases} 84\ kW/m^2, & \text{residential, office and assembly uses} \\ 167\ kW/m^2, & \text{other} \end{cases}$$

$$I_c = 12.5\ kW/m^2$$

$$\phi_c = \begin{cases} 0.150, & \text{residential, office and assembly uses} \\ 0.075, & \text{other} \end{cases}$$

h = enclosing rectangle height (m)

w = enclosing rectangle width (m)

BD = Boundary distance (m)

Step 1: Calculate the distance (d)

$$d = 2 \cdot BD$$

Step 2: Calculate the ratio (S) of the enclosing rectangle based on Equation 7-9

$$\mathrm{S} = \max\left[\frac{h}{w}, \frac{w}{h}\right]$$

Step 3: Calculate the normalize area (T) of the enclosing rectangle based on Equation 7-8

$$\mathrm{T} = \frac{A}{d^2} = \frac{h \cdot w}{d^2}$$

Step 4: The percentage of unprotected openings ($\%\mathrm{UPO}$) based on Equation 7-12, is expressed as follows

$$\%\mathrm{UPO} = 100 \cdot \left(\frac{\phi_{crit}}{\phi}\right)$$

Solving for ϕ yields the following:

$$\phi = 100 \cdot \left(\frac{\phi_{crit}}{\%\mathrm{UPO}}\right)$$

Step 5: ϕ is then substituted into the configuration factor equation (Equation 7-7) as follows:

$$\phi = \frac{2}{\pi}\left[\sqrt{\frac{\frac{T}{S}}{\frac{T}{S}+4}}\tan^{-1}\left(\sqrt{\frac{T \cdot S}{\frac{T}{S}+4}}\right) + \sqrt{\frac{T \cdot S}{T \cdot S+4}}\tan^{-1}\left(\sqrt{\frac{\frac{T}{S}}{T \cdot S+4}}\right)\right]$$

$$100 \cdot \left(\frac{\phi_c}{\%\mathrm{UPO}}\right) = \frac{2}{\pi}\left[\sqrt{\frac{\frac{T}{S}}{\frac{T}{S}+4}}\tan^{-1}\left(\sqrt{\frac{T \cdot S}{\frac{T}{S}+4}}\right) + \sqrt{\frac{T \cdot S}{T \cdot S+4}}\tan^{-1}\left(\sqrt{\frac{\frac{T}{S}}{T \cdot S+4}}\right)\right]$$

This equation is then solved for distance (d). This can be done using any numerical solver.

The tables were calculated and compared to those in BR187 as shown below. The calculated values are in the tables on the left, the actual values are in the tables at the centre, and the differences are shown on the right with colouring showing values that differ.

Table D-1: BR187 spatial separation calculation tables for enclosing rectangle 3 to 9

Calculated values (left)

Width of enclosing rectangle	0.075	0.150	8	Distance from relevant boundary for unprotected percentage not exceeding														
	20%		30%		40%		50%		60%		70%		80%		90%		100%	
	Minimum boundary distance (m)																	
Enclosing rectangle 3																		
3	1.0	0.5	1.5	1.0	2.0	1.0	2.0	1.5	2.0	1.5	2.5	1.5	2.5	2.0	3.0	2.0	3.0	2.0
6	1.5	0.5	2.0	1.0	2.5	1.5	3.0	1.5	3.0	2.0	3.5	2.0	3.5	2.5	4.0	2.5	4.0	3.0
9	1.5	0.5	2.5	1.0	3.0	1.5	3.5	2.0	3.5	2.5	4.0	2.5	4.5	3.0	4.5	3.0	5.0	3.5
12	1.5	0.5	2.5	1.0	3.0	1.5	3.5	2.0	4.0	2.5	4.5	3.0	5.0	3.0	5.5	3.5	5.5	3.5
15	2.0	0.5	2.5	1.5	3.5	2.0	4.0	2.0	4.5	2.5	5.0	3.0	5.5	3.5	6.0	3.5	6.0	4.0
18	2.0	0.5	2.5	1.5	3.5	2.0	4.0	2.5	4.5	2.5	5.5	3.0	6.0	3.5	6.0	4.0	6.5	4.0
21	2.0	0.5	3.0	1.5	3.5	2.0	4.5	2.5	5.0	3.0	5.5	3.0	6.0	3.5	6.5	4.0	7.0	4.5
24	2.0	0.5	3.0	1.5	3.5	2.0	4.5	2.5	5.0	3.0	6.0	3.0	6.5	3.5	7.0	4.0	7.5	4.5
27	2.0	0.5	3.0	1.5	3.5	2.0	4.5	2.5	5.5	3.0	6.0	3.5	6.5	3.5	7.0	4.0	7.5	4.5
30	2.0	0.5	3.0	1.5	4.0	2.0	4.5	2.5	5.5	3.0	6.0	3.5	7.0	4.0	7.5	4.0	8.0	4.5
40	2.0	0.5	3.0	1.5	4.0	2.0	5.0	2.5	5.5	3.0	6.5	3.5	7.0	4.0	8.0	4.5	8.5	5.0
50	2.0	0.5	3.0	1.5	4.0	2.0	5.0	2.5	6.0	3.0	6.5	3.5	7.5	4.0	8.5	4.5	9.0	5.0
60	2.0	0.5	3.0	1.5	4.0	2.0	5.0	2.5	6.0	3.0	6.5	3.5	7.5	4.0	8.5	4.5	9.5	5.0
80	2.0	0.5	3.0	1.5	4.0	2.0	5.0	2.5	6.0	3.0	7.0	3.5	8.0	4.0	8.5	4.5	9.5	5.0
100	2.0	0.5	3.0	1.5	4.0	2.0	5.0	2.5	6.0	3.0	7.0	3.5	8.0	4.0	9.0	4.5	10.0	5.0
Enclosing rectangle 6																		
3	1.5	0.5	2.0	1.0	2.5	1.5	3.0	1.5	3.0	2.0	3.5	2.0	3.5	2.5	4.0	2.5	4.0	3.0
6	2.0	1.0	3.0	1.5	3.5	2.0	4.0	2.5	4.5	3.0	5.0	3.0	5.5	3.5	5.5	4.0	6.0	4.0
9	2.5	1.0	3.5	2.0	4.5	2.5	5.0	3.0	5.5	3.5	6.0	4.0	6.5	4.5	7.0	4.5	7.0	5.0
12	3.0	1.0	4.0	2.0	5.0	3.0	5.5	3.5	6.0	4.0	7.0	4.5	7.5	5.0	8.0	5.0	8.5	5.5
15	3.0	1.5	4.5	2.5	5.5	3.0	6.0	4.0	7.0	4.5	7.5	5.0	8.0	5.5	8.5	5.5	9.0	6.0
18	3.5	1.5	4.5	2.5	5.5	3.5	6.5	4.0	7.5	4.5	8.0	5.0	9.0	5.5	9.5	6.0	10.0	6.5
21	3.5	1.5	5.0	2.5	6.0	3.5	7.0	4.0	8.0	5.0	8.5	5.5	9.5	6.0	10.0	6.5	10.5	7.0
24	3.5	1.5	5.0	2.5	6.0	3.5	7.5	4.5	8.5	5.0	9.0	5.5	10.0	6.0	10.5	7.0	11.5	7.5
27	3.5	1.5	5.0	2.5	6.5	3.5	7.5	4.5	8.5	5.0	9.5	6.0	10.5	6.5	11.0	7.0	12.0	7.5
30	3.5	1.5	5.0	2.5	6.5	3.5	8.0	4.5	9.0	5.0	10.0	6.0	11.0	6.5	11.5	7.5	12.5	8.0
40	3.5	1.5	5.5	2.5	7.0	3.5	8.5	4.5	10.0	5.5	11.0	6.5	12.0	7.0	13.0	8.0	14.0	8.5
50	3.5	1.5	5.5	2.5	7.5	3.5	9.0	4.5	10.5	5.5	11.5	6.5	13.0	7.5	14.0	8.0	15.0	9.0
60	3.5	1.5	5.5	2.5	7.5	3.5	9.0	4.5	11.0	5.5	12.0	6.5	13.5	7.5	14.5	8.5	16.0	9.0
80	3.5	1.5	6.0	2.5	7.5	3.5	9.5	4.5	11.0	6.0	13.0	6.5	14.5	7.5	16.0	8.5	17.0	9.5
100	3.5	1.5	6.0	2.5	8.0	3.5	9.5	5.0	11.5	6.0	13.5	7.0	15.0	8.0	16.5	8.5	18.0	9.5
120	3.5	1.5	6.0	2.5	8.0	3.5	10.0	5.0	11.5	6.0	13.5	7.0	15.0	8.0	17.0	9.0	18.5	10.0
140	3.5	1.5	6.0	2.5	8.0	3.5	10.0	5.0	11.5	6.0	13.5	7.0	15.5	8.0	17.0	9.0	19.0	10.0
Enclosing rectangle 9																		
3	1.5	0.5	2.5	1.0	3.0	1.5	3.5	2.0	3.5	2.5	4.0	2.5	4.5	3.0	4.5	3.0	5.0	3.5
6	2.5	1.0	3.5	2.0	4.5	2.5	5.0	3.0	5.5	3.5	6.0	4.0	6.5	4.5	7.0	4.5	7.0	5.0
9	3.5	1.5	4.5	2.5	5.5	3.5	6.0	4.0	6.5	4.5	7.5	5.0	8.0	5.5	8.5	5.5	9.0	6.0
12	3.5	1.5	5.0	3.0	6.0	3.5	7.0	4.5	7.5	5.0	8.5	5.5	9.0	6.0	9.5	6.5	10.5	7.0
15	4.0	2.0	5.5	3.0	6.5	4.0	7.5	5.0	8.5	5.5	9.5	6.0	10.0	6.5	11.0	7.0	11.5	7.5
18	4.5	2.0	6.0	3.5	7.5	4.5	8.5	5.0	9.5	6.0	10.0	6.5	11.0	7.5	12.0	8.0	12.5	8.5
21	4.5	2.0	6.5	3.5	7.5	4.5	9.0	5.5	10.0	6.5	11.0	7.0	12.0	7.5	12.5	8.5	13.5	9.0
24	4.5	2.0	6.5	3.5	8.0	4.5	9.5	6.0	10.5	6.5	11.5	7.5	12.5	8.0	13.5	9.0	14.0	9.5
27	5.0	2.0	7.0	3.5	8.5	5.0	10.0	6.0	11.0	7.0	12.0	7.5	13.0	8.5	14.0	9.0	15.0	10.0
30	5.0	2.0	7.0	3.5	9.0	5.0	10.5	6.0	11.5	7.0	12.5	8.0	14.0	9.0	15.0	9.5	15.5	10.5
40	5.0	2.0	7.5	4.0	9.5	5.0	11.5	6.5	13.0	7.5	14.5	8.5	15.5	9.5	16.5	10.5	18.0	11.5
50	5.5	2.0	8.0	4.0	10.0	5.5	12.0	7.0	14.0	8.0	15.5	9.0	17.0	10.0	18.0	11.0	19.5	12.0
60	5.5	2.0	8.0	4.0	10.5	5.5	13.0	7.0	14.5	8.0	16.5	9.5	18.0	10.5	19.5	11.5	21.0	13.0
80	5.5	2.0	8.5	4.0	11.0	5.5	13.5	7.0	16.0	8.5	18.0	10.0	19.5	11.0	21.5	12.5	23.0	13.5
100	5.5	2.0	8.5	4.0	11.5	5.5	14.0	7.0	16.5	8.5	18.5	10.0	21.0	11.5	22.5	12.5	24.5	14.0
120	5.5	2.0	8.5	4.0	11.5	5.5	14.5	7.0	17.0	8.5	19.5	10.0	21.5	11.5	23.5	13.0	26.0	14.5
140	5.5	2.0	8.5	4.0	11.5	5.5	14.5	7.0	17.0	8.5	19.5	10.0	22.0	11.5	24.5	13.0	26.5	14.5

Actual values (centre)

Width of enclosing rectangle	0.075	0.150	8	Distance from relevant boundary for unprotected percentage not exceeding														
	20%		30%		40%		50%		60%		70%		80%		90%		100%	
	Minimum boundary distance (m)																	
Enclosing rectangle 3																		
3	1.0	1.0	1.5	1.0	2.0	1.0	2.0	1.5	2.5	1.5	2.5	1.5	2.5	2.0	3.0	2.0	3.0	2.0
6	1.5	1.0	2.0	1.0	2.5	1.5	3.0	2.0	3.0	2.0	3.5	2.0	3.5	2.5	4.0	2.5	4.0	3.0
9	1.5	1.0	2.5	1.0	3.0	1.5	3.5	2.0	4.0	2.5	4.0	2.5	4.5	3.0	5.0	3.0	5.0	3.5
12	2.0	1.0	2.5	1.5	3.0	2.0	3.5	2.0	4.0	2.5	4.5	3.0	5.0	3.0	5.5	3.5	5.5	3.5
15	2.0	1.0	2.5	1.5	3.5	2.0	4.0	2.5	4.5	2.5	5.0	3.0	5.5	3.5	6.0	3.5	6.0	4.0
18	2.0	1.0	2.5	1.5	3.5	2.0	4.0	2.5	5.0	2.5	5.0	3.0	6.0	3.5	6.5	4.0	6.5	4.0
21	2.0	1.0	3.0	1.5	3.5	2.0	4.5	2.5	5.0	3.0	5.5	3.0	6.0	3.5	6.5	4.0	7.0	4.5
24	2.0	1.0	3.0	1.5	3.5	2.0	4.5	2.5	5.0	3.0	5.5	3.5	6.0	3.5	7.0	4.0	7.5	4.5
27	2.0	1.0	3.0	1.5	4.0	2.0	4.5	2.5	5.5	3.0	6.0	3.5	6.5	4.0	7.0	4.0	7.5	4.5
30	2.0	1.0	3.0	1.5	4.0	2.0	4.5	2.5	5.5	3.0	6.0	3.5	6.5	4.0	7.5	4.0	8.0	4.5
40	2.0	1.0	3.0	1.5	4.0	2.0	5.0	2.5	5.5	3.0	6.5	3.5	7.0	4.0	8.0	4.0	8.5	5.0
50	2.0	1.0	3.0	1.5	4.0	2.0	5.0	2.5	6.0	3.0	6.5	3.5	7.5	4.0	8.0	4.0	9.0	5.0
60	2.0	1.0	3.0	1.5	4.0	2.0	5.0	2.5	6.0	3.0	7.0	3.5	7.5	4.0	8.5	4.0	9.5	5.0
80	2.0	1.0	3.0	1.5	4.0	2.0	5.0	2.5	6.0	3.0	7.0	3.5	8.0	4.0	9.0	4.0	9.5	5.0
100	2.0	1.0	3.0	1.5	4.0	2.0	5.0	2.5	6.0	3.0	7.0	3.5	8.0	4.0	9.0	4.0	10.0	5.0
Enclosing rectangle 6																		
3	1.5	1.0	2.0	1.0	2.5	1.5	3.0	2.0	3.0	2.0	3.5	2.0	3.5	2.5	4.0	2.5	4.0	3.0
6	2.0	1.0	3.0	1.5	3.5	2.0	4.0	2.5	4.5	3.0	5.0	3.0	5.5	3.5	5.5	4.0	6.0	4.0
9	2.5	1.0	3.5	2.0	4.5	2.5	5.0	3.0	5.5	3.5	6.0	4.0	6.0	4.5	7.0	4.5	7.0	5.0
12	3.0	1.5	4.0	2.5	5.0	3.0	5.5	3.5	6.5	4.0	7.0	4.5	7.5	5.0	8.0	5.0	8.5	5.5
15	3.0	1.5	4.5	2.5	5.5	3.0	6.0	4.0	7.0	4.5	7.5	5.0	8.0	5.5	9.0	5.5	9.0	6.0
18	3.5	1.5	4.5	2.5	5.5	3.5	6.5	4.0	7.5	4.5	8.0	5.0	9.0	5.5	9.5	6.0	10.0	6.5
21	3.5	1.5	5.0	2.5	6.0	3.5	7.0	4.0	8.0	5.0	9.0	5.5	9.5	6.0	10.0	6.5	10.5	7.0
24	3.5	1.5	5.0	2.5	6.0	3.5	7.0	4.5	8.5	5.0	9.5	5.5	10.0	6.0	10.5	7.0	11.0	7.0
27	3.5	1.5	5.0	2.5	6.5	3.5	7.5	4.5	8.5	5.0	9.5	6.0	10.5	6.5	11.0	7.0	12.0	7.5
30	3.5	1.5	5.0	2.5	6.5	3.5	8.0	4.5	9.0	5.0	10.0	6.0	11.0	6.5	12.0	7.0	12.5	8.0
40	3.5	1.5	5.5	2.5	7.0	3.5	8.5	4.5	10.0	5.5	11.0	6.5	12.0	7.0	13.0	8.0	14.0	8.5
50	3.5	1.5	5.5	2.5	7.5	3.5	9.0	4.5	10.5	5.5	11.5	6.5	13.0	7.5	14.0	8.0	15.0	9.0
60	3.5	1.5	5.5	2.5	7.5	3.5	9.5	5.0	11.0	5.5	12.0	6.5	13.5	7.5	15.0	8.5	16.0	9.5
80	3.5	1.5	6.0	2.5	7.5	3.5	9.5	5.0	11.5	6.0	13.0	7.0	14.5	7.5	16.0	8.5	17.5	9.5
100	3.5	1.5	6.0	2.5	8.0	3.5	10.0	5.0	12.0	6.0	13.5	7.0	15.0	8.0	16.5	8.5	18.0	10.0
120	3.5	1.5	6.0	2.5	8.0	3.5	10.0	5.0	12.0	6.0	14.0	7.0	15.5	8.0	17.0	8.5	19.0	10.0
140	3.5	1.5	6.0	2.5	8.0	3.5	10.0	5.0	12.0	6.0	14.0	7.0	16.0	8.0	18.0	8.5	19.0	10.0
Enclosing rectangle 9																		
3	1.5	1.0	2.5	1.0	3.0	1.5	3.5	2.0	4.0	2.5	4.0	2.5	4.5	3.0	5.0	3.0	5.0	3.5
6	2.5	1.0	3.5	2.0	4.5	2.5	5.0	3.0	5.5	3.5	6.0	4.0	6.5	4.5	7.0	4.5	7.0	5.0
9	3.5	1.5	4.5	2.5	5.5	3.5	6.0	4.0	6.5	4.5	7.5	5.0	8.0	5.5	8.5	5.5	9.0	6.0
12	3.5	1.5	5.0	3.0	6.0	3.5	7.0	4.5	7.5	5.0	8.5	5.5	9.0	6.0	9.5	6.5	10.5	7.0
15	4.0	2.0	5.5	3.0	6.5	4.0	7.5	5.0	8.5	5.5	9.5	6.0	10.0	6.5	11.0	7.0	11.5	7.5
18	4.5	2.0	6.0	3.5	7.0	4.5	8.5	5.0	9.5	6.0	10.0	6.5	11.0	7.0	12.0	8.0	12.5	8.5
21	4.5	2.0	6.5	3.5	7.5	4.5	9.0	5.5	10.0	6.5	11.0	7.0	12.0	7.5	13.0	8.5	13.5	9.0
24	5.0	2.0	6.5	3.5	8.0	5.0	9.5	5.5	11.0	6.5	12.0	7.5	13.0	8.0	13.5	9.0	14.5	9.5
27	5.0	2.0	7.0	3.5	8.5	5.0	10.0	6.0	11.5	7.0	12.5	7.5	13.5	8.5	14.5	9.5	15.0	10.0
30	5.0	2.0	7.0	3.5	9.0	5.0	10.5	6.0	12.0	7.0	13.0	8.0	14.0	9.0	15.0	9.5	16.0	10.5
40	5.5	2.0	7.5	3.5	9.5	5.5	11.5	6.5	13.0	7.5	14.5	8.5	15.5	9.5	17.0	10.5	17.5	11.5
50	5.5	2.0	8.0	4.0	10.0	5.5	12.5	6.5	14.0	8.0	15.5	9.0	17.0	10.0	18.5	11.5	19.5	12.5
60	5.5	2.0	8.0	4.0	11.0	5.5	13.0	7.0	15.0	8.0	16.5	9.5	18.0	11.0	19.5	11.5	21.0	13.0
80	5.5	2.0	8.5	4.0	11.5	5.5	13.5	7.0	16.0	8.5	17.5	10.0	19.5	11.5	21.5	12.5	23.0	13.5
100	5.5	2.0	8.5	4.0	11.5	5.5	14.5	7.0	16.5	8.5	18.5	10.0	21.0	11.5	22.5	12.5	24.5	14.5
120	5.5	2.0	8.5	4.0	11.5	5.5	14.5	7.0	17.0	8.5	19.5	10.0	21.5	11.5	23.5	12.5	26.0	14.5
140	5.5	2.0	8.5	4.0	11.5	5.5	15.0	7.0	17.5	8.5	20.0	10.5	22.5	12.0	24.5	12.5	27.0	15.0

Differences (right)

Width of enclosing rectangle	0.075	0.150	8	Distance from relevant boundary for unprotected percentage not exceeding														
	20%		30%		40%		50%		60%		70%		80%		90%		100%	
	Minimum boundary distance (m)																	
Enclosing rectangle 3																		
3	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0
12	-0.5	-0.5	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.5	0.0	0.0	0.0	-0.5	0.0	0.0	0.0
21	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	-0.5	0.5	0.0	0.0	0.0	0.0	0.0
27	0.0	-0.5	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0
30	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
40	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
50	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0
60	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.5	0.0	0.0
80	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.5	0.0	0.0
100	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Enclosing rectangle 6																		
3	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
12	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.5
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.5	0.0	0.0
40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	-0.5
80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	-0.5	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	-0.5	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5
120	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	-0.5	0.0	0.0	0.5	-0.5	0.0
150	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	-0.5	0.0	-1.0	0.5	0.0	0.0
Enclosing rectangle 9																		
3	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0
24	-0.5	0.0	0.0	0.0	0.0	-0.5	0.0	0.5	-0.5	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	-0.5	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	-0.5	0.0	-0.5	-0.5	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	-0.5	0.0
40	-0.5	0.0	0.0	0.5	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.5	0.0
50	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	-0.5	0.0	-0.5
60	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0
80	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	-0.5	0.0	0.0	0.0	0.0
100	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5
120	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0
150	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	-0.5	-0.5	-0.5	-0.5	0.0	0.5	-0.5	-0.5

Table D-2: BR187 spatial separation calculation tables for enclosing rectangle 12 to 18

Enclosing rectangle	12																	
3	1.5	0.5	2.5	1.0	3.0	1.5	3.5	2.0	4.0	2.5	4.5	3.0	5.0	3.0	5.5	3.5	5.5	3.5
6	3.0	1.0	4.0	2.0	5.0	3.0	5.5	3.5	6.0	4.0	7.0	4.5	7.5	5.0	8.0	5.0	8.5	5.5
9	3.5	1.5	5.0	3.0	6.0	3.5	7.0	4.5	7.5	5.0	8.5	5.5	9.0	6.0	9.5	6.5	10.5	7.0
12	4.5	2.0	6.0	3.5	7.0	4.5	8.0	5.0	9.0	6.0	9.5	6.5	10.5	7.0	11.0	7.5	12.0	8.0
15	5.0	2.0	6.5	3.5	8.0	5.0	9.0	5.5	10.0	6.5	11.0	7.0	11.5	8.0	12.5	8.5	13.5	9.0
18	5.0	2.5	7.0	4.0	8.5	5.0	10.0	6.0	11.0	7.0	12.0	8.0	13.0	8.5	13.5	9.0	14.5	10.0
21	5.5	2.5	7.5	4.0	9.0	5.5	10.5	6.5	11.5	7.5	13.0	8.5	14.0	9.0	14.5	10.0	15.5	10.5
24	6.0	2.5	8.0	4.5	9.5	6.0	11.0	7.0	12.5	8.0	13.5	9.0	14.5	9.5	15.5	10.5	16.5	11.0
27	6.0	2.5	8.5	4.5	10.0	6.0	11.5	7.5	13.0	8.5	14.5	9.5	15.5	10.0	16.5	11.0	17.5	11.5
30	6.0	2.5	8.5	4.5	10.5	6.0	12.0	7.5	13.5	8.5	15.0	9.5	16.0	10.5	17.5	11.5	18.5	12.0
40	6.5	2.5	9.5	5.0	12.0	6.5	13.5	8.0	15.5	9.5	17.0	10.5	18.5	12.0	19.5	13.0	21.0	13.5
50	7.0	2.5	10.0	5.0	12.5	7.0	15.0	8.5	17.0	10.0	18.5	11.5	20.0	12.5	21.5	14.0	23.0	15.0
60	7.0	2.5	10.5	5.0	13.5	7.0	15.5	9.0	18.0	10.5	20.0	12.0	21.5	13.5	23.5	14.5	25.0	15.5
80	7.5	2.5	11.0	5.0	14.0	7.5	17.0	9.0	19.5	11.0	22.0	12.5	24.0	14.0	26.0	15.5	28.0	17.0
100	7.5	2.5	11.0	5.0	14.5	7.5	18.0	9.5	20.5	11.0	23.5	13.0	25.5	14.5	28.0	16.5	30.0	18.0
120	7.5	2.5	11.5	5.0	15.0	7.5	18.5	9.5	21.5	11.5	24.5	13.0	27.0	15.0	29.5	17.0	32.0	18.5
140	7.5	2.5	11.5	5.0	15.0	7.5	19.0	9.5	22.0	11.5	25.0	13.5	28.0	15.0	30.5	17.0	33.0	19.0

Enclosing rectangle	12																	
3	2.0	1.0	2.5	1.5	3.0	2.0	3.5	2.0	4.0	2.5	4.5	3.0	5.0	3.0	5.5	3.5	5.5	3.5
6	3.0	1.5	4.0	2.5	5.0	3.0	5.5	3.5	6.5	4.0	7.0	4.5	7.5	5.0	8.0	5.0	8.5	5.5
9	3.5	1.5	5.0	3.0	6.0	3.5	7.0	4.5	7.5	5.0	8.5	5.5	9.0	6.0	9.5	6.5	10.5	7.0
12	4.5	1.5	6.0	3.5	7.0	4.5	8.0	5.0	9.0	6.0	9.5	6.5	11.0	7.0	11.5	7.5	12.0	8.0
15	5.0	2.0	6.5	3.5	8.0	5.0	9.0	5.5	10.0	6.5	11.0	7.0	12.0	8.0	13.0	8.5	13.5	9.0
18	5.0	2.5	7.0	4.0	8.5	5.0	10.0	6.0	11.0	7.0	12.0	7.5	13.0	8.5	14.0	9.0	14.5	10.0
21	5.5	2.5	7.5	4.0	9.0	5.5	10.5	6.5	12.0	7.5	13.0	8.5	14.0	9.0	15.0	10.0	16.0	10.5
24	6.0	2.5	8.0	4.5	9.5	6.0	11.5	7.0	12.5	8.0	14.0	8.5	15.0	9.5	16.0	10.5	16.5	11.5
27	6.0	2.5	8.0	4.5	10.5	6.0	12.0	7.0	13.5	8.0	14.5	9.0	16.0	10.5	17.0	11.0	17.5	12.0
30	6.5	2.5	8.5	4.5	10.5	6.5	12.5	7.5	14.0	8.5	15.0	9.5	16.5	10.5	17.5	11.5	18.5	12.5
40	6.5	2.5	9.5	5.0	12.0	6.5	14.0	8.0	15.5	9.5	17.5	10.5	18.5	12.0	20.0	13.0	21.0	14.0
50	7.0	2.5	10.0	5.0	13.0	7.0	15.0	8.5	17.0	10.0	19.0	11.0	20.5	13.0	23.0	14.0	23.0	15.0
60	7.0	2.5	10.5	5.0	13.5	7.0	16.0	9.0	18.0	10.5	20.0	12.0	21.5	13.5	23.5	14.5	25.0	16.0
80	7.0	2.5	11.0	5.0	14.5	7.0	17.0	9.0	19.5	11.0	21.5	13.0	23.5	14.5	26.0	16.0	27.5	17.0
100	7.5	2.5	11.5	5.0	15.0	7.5	18.0	9.5	21.0	11.5	23.0	13.5	25.5	15.0	28.0	16.5	30.0	18.0
120	7.5	2.5	11.5	5.0	15.0	7.5	18.5	9.5	22.0	11.5	24.0	13.5	27.0	15.0	29.5	17.0	31.5	18.5
140	7.5	2.5	12.0	5.0	15.5	7.5	19.0	9.5	22.5	12.0	25.0	14.0	28.0	15.5	30.5	17.0	34.0	19.0

Enclosing rectangle	12																	
3	-0.5	-0.5	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	-0.5	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	-0.5	0.5	-0.5	0.0	-0.5	0.0	0.0	-0.5
27	0.0	0.0	0.5	0.0	-0.5	0.0	-0.5	0.5	-0.5	0.5	0.0	0.5	-0.5	-0.5	-0.5	0.0	0.0	-0.5
30	-0.5	0.0	0.0	0.0	0.0	-0.5	-0.5	0.0	-0.5	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	-0.5
40	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	-0.5	0.0	0.0	-0.5
50	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	-0.5	0.5	-0.5	-0.5	-1.5	0.0	0.0	0.0
60	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5
80	0.5	0.0	0.0	0.0	-0.5	0.5	0.0	0.0	0.0	0.0	0.5	-0.5	0.5	-0.5	0.0	-0.5	0.5	0.0
100	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	-0.5	-0.5	0.5	-0.5	0.0	-0.5	0.0	0.0	0.0	0.0
120	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.5	-0.5	0.0	0.0	0.0	0.0	0.5	0.0
150	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	-0.5	-0.5	0.0	-0.5	0.0	-0.5	0.0	0.0	-1.0	0.0

Enclosing rectangle	15																	
3	2.0	0.5	2.5	1.5	3.5	2.0	4.0	2.0	4.5	2.5	5.0	3.0	5.5	3.5	6.0	3.5	6.0	4.0
6	3.0	1.5	4.5	2.5	5.5	3.0	6.0	4.0	7.0	4.5	7.5	5.0	8.0	5.5	8.5	5.5	9.0	6.0
9	4.0	2.0	5.5	3.0	6.5	4.0	7.5	5.0	8.5	5.5	9.5	6.0	10.0	6.5	11.0	7.0	11.5	7.5
12	5.0	2.0	6.5	3.5	8.0	5.0	9.0	5.5	10.0	6.5	11.0	7.0	11.5	8.0	12.5	8.5	13.5	9.0
15	5.5	2.5	7.5	4.0	9.0	5.5	10.0	6.5	11.0	7.5	12.0	8.0	13.0	9.0	14.0	9.5	15.0	10.0
18	6.0	2.5	8.0	4.5	9.5	6.0	11.0	7.0	12.0	8.0	13.5	9.0	14.5	9.5	15.5	10.5	16.0	11.0
21	6.5	3.0	8.5	5.0	10.5	6.5	12.0	7.5	13.0	8.5	14.5	9.5	15.5	10.5	16.5	11.0	17.5	12.0
24	6.5	3.0	9.0	5.0	11.0	6.5	12.5	8.0	14.0	9.0	15.5	10.0	16.5	11.0	17.5	12.0	18.5	12.5
27	7.0	3.0	9.5	5.5	11.5	7.0	13.5	8.5	15.0	9.5	16.0	10.5	17.5	11.5	18.5	12.5	20.0	13.5
30	7.5	3.0	10.0	5.5	12.0	7.5	14.0	8.5	15.5	10.0	17.0	11.0	18.5	12.0	19.5	13.0	21.0	14.0
40	8.0	3.0	11.0	6.0	13.5	8.0	15.5	9.5	17.5	11.0	19.5	12.5	21.0	13.5	22.5	14.5	23.5	15.5
50	8.5	3.0	12.0	6.0	14.5	8.5	17.0	10.0	19.5	12.0	21.0	13.5	23.0	14.5	24.5	16.0	26.0	17.0
60	8.5	3.5	12.5	6.0	15.5	8.5	18.5	10.5	20.5	12.5	23.0	14.0	25.0	15.5	26.5	17.0	28.5	18.5
80	9.0	3.5	13.5	6.5	17.0	9.0	20.0	11.0	23.0	13.5	25.5	15.0	27.5	17.0	30.0	18.5	32.0	20.0
100	9.0	3.5	13.5	6.5	17.5	9.0	21.5	11.5	24.5	13.5	27.5	16.0	30.0	17.5	32.5	19.5	34.5	21.5
120	9.0	3.5	14.0	6.5	18.5	9.0	22.0	11.5	25.5	14.0	29.0	16.0	31.5	18.5	34.5	20.5	37.0	22.0
140	9.0	3.5	14.0	6.5	18.5	9.0	23.0	11.5	26.5	14.0	30.0	16.5	33.0	18.5	36.0	21.0	39.0	23.0

Enclosing rectangle	15																	
3	2.0	1.0	2.5	1.5	3.5	2.0	4.0	2.5	4.5	2.5	5.0	3.0	5.5	3.5	6.0	3.5	6.0	4.0
6	3.0	1.5	4.5	2.5	5.5	3.0	6.0	4.0	7.0	4.5	7.5	5.0	8.0	5.5	9.0	5.5	9.0	6.0
9	4.0	2.0	5.5	3.0	6.5	4.0	7.5	5.0	8.5	5.5	9.5	6.0	10.0	6.5	11.0	7.0	11.5	7.5
12	5.0	2.0	6.5	3.5	8.0	5.0	9.0	5.5	10.0	6.5	11.0	7.0	12.0	8.0	13.0	8.5	13.5	9.0
15	5.5	2.0	7.0	4.0	9.0	5.5	10.0	6.5	11.5	7.0	12.5	8.0	13.5	9.0	14.5	9.5	15.0	10.0
18	6.0	2.5	8.0	4.5	9.5	6.0	11.0	7.0	12.5	8.0	13.5	8.5	14.5	9.5	15.5	10.5	16.5	11.0
21	6.5	2.5	8.5	5.0	10.5	6.5	12.0	7.5	13.5	8.5	14.5	9.5	16.0	10.5	16.5	11.0	17.5	12.0
24	6.5	3.0	9.0	5.0	11.0	6.5	13.0	8.0	14.5	9.0	15.5	10.0	17.0	11.0	18.0	12.0	19.0	13.0
27	7.0	3.0	9.5	5.5	11.5	7.0	13.5	8.5	15.0	9.5	16.5	10.5	18.0	11.5	19.0	12.5	20.0	13.5
30	7.5	3.0	10.0	5.5	12.0	7.5	14.0	8.5	16.0	10.0	17.0	11.0	18.5	12.0	20.0	13.5	21.0	14.0
40	8.0	3.0	11.0	6.0	13.5	8.0	16.0	9.5	18.0	11.0	19.5	12.5	21.0	13.5	22.5	15.0	23.5	16.0
50	8.5	3.5	12.0	6.0	15.0	8.5	17.5	10.0	19.5	12.0	21.5	13.5	23.0	15.0	25.0	16.5	26.0	17.5
60	8.5	3.5	12.5	6.5	15.5	8.5	18.0	10.5	21.0	12.5	23.5	14.0	25.0	15.5	27.0	17.0	28.0	18.0
80	9.0	3.5	13.5	6.5	17.0	9.0	20.0	11.0	23.0	13.5	25.5	15.0	28.0	17.0	30.0	18.5	31.5	20.0
100	9.0	3.5	14.0	6.5	18.0	9.0	21.5	11.5	24.5	14.0	27.5	16.0	30.0	18.0	32.5	19.5	34.5	21.5
120	9.0	3.5	14.0	6.5	18.5	9.0	22.5	11.5	25.5	14.0	28.5	16.5	31.5	18.5	34.5	20.5	37.0	22.5
140	9.0	3.5	14.5	6.5	19.0	9.0	23.0	12.0	27.0	14.5	30.0	17.0	34.0	19.0	36.0	21.0	39.0	23.0

Enclosing rectangle	15																	
3	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0
15	0.0	0.5	0.5	0.0	0.0	0.0	0.0	0.0	-0.5	0.5	-0.5	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.5	0.0	0.0	0.0	0.0	-0.5	0.0
21	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	-0.5	-0.5
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	-0.5	-0.5	0.0	0.0
40	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.5
50	0.0	-0.5	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	-0.5	0.0	0.0	-0.5	-0.5	-0.5	0.0	-0.5
60	0.0	0.0	0.0	-0.5	0.0	0.0	0.5	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	-0.5	0.0	0.5	0.5
80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.5	0.0
100	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0
120	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.5	-0.5	0.0	0.0	0.0	0.0	0.0	-0.5
150	0.0	0.0	-0.5	0.0	-0.5	0.0	0.0	-0.5	-0.5	-0.5	0.0	-0.5	-1.0	-0.5	0.0	0.0	0.0	0.0

Enclosing rectangle	18																	
3	2.0	0.5	2.5	1.5	3.5	2.0	4.0	2.5	4.5	2.5	5.5	3.0	6.0	3.5	6.0	4.0	6.5	4.0
6	3.5	1.5	4.5	2.5	5.5	3.5	6.5	4.0	7.5	4.5	8.0	5.0	9.0	5.5	9.5	6.0	10.0	6.5
9	4.5	2.0	6.0	3.5	7.5	4.5	8.5	5.0	9.5	6.0	10.0	6.5	11.0	7.5	12.0	8.0	12.5	8.5
12	5.0	2.5	7.0	4.0	8.5	5.0	10.0	6.0	11.0	7.0	12.0	8.0	13.0	8.5	13.5	9.0	14.5	10.0
15	6.0	2.5	8.0	4.5	9.5	6.0	11.0	7.0	12.0	8.0	13.5	9.0	14.5	9.5	15.5	10.5	16.0	11.0
18	6.5	3.0	8.5	5.0	10.5	6.5	12.0	7.5	13.5	8.5	14.5	9.5	16.0	10.5	17.0	11.5	18.0	12.0
21	7.0	3.0	9.5	5.5	11.5	7.0	13.0	8.5	14.5	9.5	16.0	10.5	17.0	11.5	18.0	12.0	19.0	13.0
24	7.5	3.5	10.0	5.5	12.0	7.5	14.0	9.0	15.5	10.0	17.0	11.0	18.0	12.0	19.5	13.0	20.5	14.0
27	8.0	3.5	10.5	6.0	13.0	8.0	14.5	9.5	16.5	10.5	18.0	11.5	19.0	13.0	20.5	13.5	21.5	14.5
30	8.0	3.5	11.0	6.0	13.5	8.0	15.5	9.5	17.0	11.0	18.5	12.5	20.0	13.5	21.5	14.5	23.0	15.5
40	9.0	3.5	12.5	7.0	15.0	9.0	17.5	11.0	19.5	12.5	21.5	14.0	23.0	15.0	24.5	16.5	26.0	17.5
50	9.5	4.0	13.5	7.0	16.5	9.5	19.0	11.5	21.5	13.5	23.5	15.0	25.5	16.5	27.5	18.0	29.0	19.0
60	10.0	4.0	14.0	7.5	17.5	10.0	20.5	12.5	23.0	14.0	25.5	16.0	27.5	17.5	29.5	19.0	31.5	20.5
80	10.5	4.0	15.5	7.5	19.5	10.5	22.5	13.0	26.0	15.5	28.5	17.5	31.0	19.5	33.5	21.0	35.5	22.5
100	10.5	4.0	16.0	7.5	20.5	10.5	24.5	13.5	28.0	16.0	31.0	18.5	33.5	20.5	36.5	22.5	39.0	24.5
120	11.0	4.0	16.5	7.5	21.5	11.0	25.5	14.0	29.5	16.5	33.0	19.0	36.0	21.5	39.0	23.5	41.5	25.5
140	11.0	4.0	16.5	7.5	22.0	11.0	26.5	14.0	30.5	16.5	34.5	19.5	38.0	22.0	41.0	24.0	44.0	26.5

Enclosing rectangle	18																	
3	2.0	1.0	2.5	1.5	3.5	2.0	4.0	2.5	5.0	2.5	5.0	3.0	6.0	3.5	6.5	4.0	6.5	4.0
6	3.5	1.5	4.5	2.5	5.5	3.5	6.5	4.0	7.5	4.5	8.0	5.0	9.0	5.5	9.5	6.0	10.0	6.5
9	4.5	2.0	6.0	3.5	7.0	4.5	8.5	5.0	9.5	6.0	10.0	6.5	11.0	7.0	12.0	8.0	12.5	8.5
12	5.0	2.5	7.0	4.0	8.5	5.0	10.0	6.0	11.0	7.0	12.0	7.5	13.0	8.5	14.0	9.0	14.5	10.0
15	6.0	2.5	8.0	4.5	9.5	6.0	11.0	7.0	12.5	8.0	13.5	8.5	14.5	9.5	15.5	10.5	16.5	11.0
18	6.5	2.5	8.5	5.0	11.0	6.5	12.0	7.5	13.5	8.5	14.5	9.5	16.0	11.0	17.0	11.5	18.0	13.0
21	7.0	3.0	9.5	5.5	11.5	7.0	13.0	8.0	14.5	9.5	16.0	10.5	17.0	11.5	18.0	12.5	19.5	13.0
24	7.5	3.0	10.0	5.5	12.0	7.5	14.0	8.5	15.5	10.0	16.5	11.0	18.5	12.0	19.5	13.0	20.5	14.0
27	8.0	3.5	10.5	6.0	12.5	8.0	14.5	9.0	16.5	10.5	17.5	11.5	19.5	12.5	20.5	13.5	21.5	14.5
30	8.0	3.5	11.0	6.5	13.5	8.0	15.5	9.5	17.0	11.0	18.5	12.0	20.5	13.5	21.5	14.5	22.5	15.5
40	9.0	4.0	12.0	7.0	15.0	9.0	17.5	11.0	19.5	12.0	21.5	13.5	23.5	15.0	25.0	16.5	26.0	17.5
50	9.5	4.0	13.0	7.0	16.5	9.5	19.0	11.5	21.5	13.0	23.5	15.0	26.0	16.5	27.5	18.0	29.0	19.0
60	10.0	4.0	14.0	7.5	17.5	10.0	20.5	12.0	23.0	14.0	26.0	16.0	27.5	17.5	29.5	19.5	31.0	20.5
80	10.0	4.0	15.0	7.5	19.0	10.0	22.5	13.0	26.0	15.0	28.5	17.0	31.0	19.0	33.5	21.0	35.0	22.5
100	10.0	4.0	16.0	7.5	20.5	10.0	24.0	13.5	28.0	16.0	31.0	18.0	33.5	20.5	36.0	22.5	38.5	24.0
120	10.0	4.0	16.5	7.5	21.0	10.0	25.5	14.0	29.5	16.5	32.5	19.0	35.5	21.0	39.0	23.5	41.5	25.5
140	10.0	4.0	17.0	8.0	22.0	10.0	26.5	14.0	30.5	17.0	34.0	19.5	37.0	22.0	41.0	24.0	43.5	26.5

Enclosing rectangle	18																	
3	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.5	0.0	0.0	0.0	-0.5	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	-0.5	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.5	0.0	0.0	0.0	0.0	-0.5	0.0
18	0.0	0.5	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	-1.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	-0.5	0.0
24	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.5	0.0	-0.5	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.5	0.0	0.0	0.5	0.0	-0.5	0.5	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	-0.5	0.0	0.0	0.0	0.5	0.0
40	0.0	-0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.5	-0.5	0.0	-0.5	0.0	0.0	0.0
50	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	-0.5	0.5	0.0
80	0.5	0.0	0.5	0.0	0.5	0.5	0.0	0.0	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.0	0.5	0.0
100	0.5	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.5	0.0	0.5	0.5
120	1.0	0.0	0.0	0.0	0.5	1.0	0.0	0.0	0.0	0.0	0.5	0.0	0.5	0.5	0.0	0.0	0.0	0.0
150	1.0	0.0	-0.5	-0.5	0.0	1.0	0.0	0.0	0.0	-0.5	0.5	0.0	1.0	0.0	0.0	0.0	0.5	0.0

Appendix E
NFPA 80A Spatial Separation Calculation Methodology

Inputs:

$$E = \begin{cases} 89\ kW/m^2, & \text{Light hazard } (> 74\ \text{kg/m}^2) \\ 178\ kW/m^2, & \text{Moderate hazard } (35 - 73\ \text{kg/m}^2) \\ 356\ kW/m^2, & \text{Severe hazard } (0 - 34\ \text{kg/m}^2) \end{cases}$$

$I_c = 12.5\ kW/m^2$

$$\phi_c = \begin{cases} 0.140, & \text{Light hazard } (> 74\ \text{kg/m}^2) \\ 0.070, & \text{Moderate hazard } (35 - 73\ \text{kg/m}^2) \\ 0.035, & \text{Severe hazard } (0 - 34\ \text{kg/m}^2) \end{cases}$$

h = $\max\left[\frac{h}{w}, \frac{w}{h}\right]$ (m)

w = 1 m

ff = Flame front (1.5 m)

$\%UPO$ = Specified values in Table 4.3.7.3

Step 1: Calculate the ratio (S) of the exposing building face based on Equation 7-9

$$\mathrm{S} = \max\left[\frac{h}{w}, \frac{w}{h}\right]$$

Step 2: The normalize area (T) is expressed as follows based on Equation 7-8

$$T = \frac{A}{d^2} = \frac{h \cdot w}{d^2}$$

Step 3: The percentage of unprotected openings ($\%\mathbf{UPO}$) based on Equation 7-12, is expressed as follows

$$\%UPO = 100 \cdot \left(\frac{\phi_c}{\phi}\right)$$

Step 4: Substitute T and $\%UPO$ into the configuration factor (ϕ) equation (Equation 7-7)

$$\phi = \frac{2}{\pi}\left[\sqrt{\frac{\frac{T}{S}}{\frac{T}{S}+4}}\tan^{-1}\left(\sqrt{\frac{T\cdot S}{\frac{T}{S}+4}}\right)+\sqrt{\frac{T\cdot S}{T\cdot S+4}}\tan^{-1}\left(\sqrt{\frac{\frac{T}{S}}{T\cdot S+4}}\right)\right]$$

$$100\cdot\left(\frac{\phi_c}{\%\mathrm{UPO}}\right) = \frac{2}{\pi}\left[\sqrt{\frac{\frac{T}{S}}{\frac{T}{S}+4}}\tan^{-1}\left(\sqrt{\frac{T\cdot S}{\frac{T}{S}+4}}\right)+\sqrt{\frac{T\cdot S}{T\cdot S+4}}\tan^{-1}\left(\sqrt{\frac{\frac{T}{S}}{T\cdot S+4}}\right)\right]$$

This equation is then solved for distance (d). This can be done using any numerical solver. The result is the "Guide Number" in Table 4.3.7.3 of NFPA 80A.

The tables were calculated and compared to those in NFPA 80A as shown below. The calculated values are in the top table, the actual values are in the middle table, and the differences are shown in the lower table with the differences highlighted in green.

Table E-1: NFPA 80A spatial separation calculation tables

Calculated			1.0	1.3	1.6	2.0	2.5	3.2	4	5	6	8	10	13	16	20	25	32	40
0.14	0.07	0.035	1	1.3	1.6	2	2.5	3.2	4	5	6	8	10	13	16	20	25	32	40
20%	10%	5%	0.36	0.41	0.44	0.46	0.48	0.49	0.50	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
30%	15%	7.5%	0.60	0.67	0.73	0.79	0.84	0.88	0.90	0.92	0.93	0.94	0.94	0.95	0.95	0.95	0.95	0.95	0.95
40%	20%	10%	0.76	0.86	0.94	1.03	1.10	1.18	1.23	1.27	1.29	1.32	1.33	1.33	1.34	1.34	1.34	1.34	1.34
50%	25%	12.5%	0.90	1.02	1.12	1.22	1.32	1.43	1.51	1.58	1.62	1.67	1.69	1.70	1.71	1.71	1.71	1.71	1.71
60%	30%	15%	1.02	1.15	1.27	1.39	1.52	1.65	1.76	1.85	1.92	1.99	2.03	2.06	2.07	2.08	2.08	2.08	2.08
80%	40%	20%	1.22	1.39	1.53	1.68	1.85	2.03	2.19	2.34	2.45	2.59	2.67	2.74	2.77	2.79	2.80	2.81	2.81
100%	50%	25%	1.39	1.58	1.75	1.93	2.13	2.35	2.56	2.76	2.91	3.12	3.26	3.37	3.44	3.48	3.51	3.52	3.53
	60%	30%	1.55	1.76	1.94	2.16	2.38	2.64	2.88	3.13	3.32	3.60	3.79	3.97	4.07	4.15	4.20	4.23	4.24
	80%	40%	1.82	2.07	2.29	2.54	2.81	3.14	3.45	3.77	4.03	4.44	4.74	5.05	5.25	5.41	5.52	5.60	5.64
	100%	50%	2.05	2.34	2.59	2.88	3.19	3.57	3.94	4.32	4.65	5.17	5.56	6.00	6.30	6.57	6.77	6.92	7.01
		60%	2.26	2.58	2.85	3.18	3.53	3.95	4.37	4.81	5.19	5.81	6.30	6.85	7.25	7.63	7.94	8.19	8.34
		80%	2.63	3.00	3.32	3.70	4.12	4.63	5.13	5.68	6.15	6.93	7.57	8.33	8.92	9.51	10.04	10.52	10.85
		100%	2.96	3.37	3.74	4.17	4.64	5.22	5.80	6.42	6.97	7.90	8.67	9.61	10.36	11.15	11.90	12.62	13.16

Actual																			
0.14	0.07	0.035	1	1.3	1.6	2	2.5	3.2	4	5	6	8	10	13	16	20	25	32	40
20%	10%	5%	0.36	0.40	0.44	0.46	0.48	0.49	0.50	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
30%	15%	7.5%	0.60	0.66	0.73	0.79	0.84	0.88	0.90	0.92	0.93	0.94	0.94	0.95	0.95	0.95	0.95	0.95	0.95
40%	20%	10%	0.76	0.85	0.94	1.02	1.10	1.17	1.23	1.27	1.30	1.32	1.33	1.33	1.34	1.34	1.34	1.34	1.34
50%	25%	12.5%	0.90	1.00	1.11	1.22	1.33	1.42	1.51	1.58	1.63	1.66	1.69	1.70	1.71	1.71	1.71	1.71	1.71
60%	30%	15%	1.02	1.14	1.26	1.39	1.52	1.64	1.76	1.85	1.93	1.99	2.03	2.05	2.07	2.08	2.08	2.08	2.08
80%	40%	20%	1.22	1.37	1.52	1.68	1.85	2.02	2.18	2.34	2.48	2.59	2.67	2.73	2.77	2.79	2.80	2.81	2.81
100%	50%	25%	1.39	1.56	1.74	1.93	2.13	2.34	2.55	2.76	2.95	3.12	3.26	3.36	3.43	3.48	3.51	3.52	3.53
	60%	30%	1.55	1.73	1.94	2.15	2.38	2.63	2.88	3.13	3.37	3.60	3.79	3.95	4.07	4.15	4.20	4.22	4.24
	80%	40%	1.82	2.04	2.28	2.54	2.82	3.12	3.44	3.77	4.11	4.43	4.74	5.01	5.24	5.41	5.52	5.60	5.64
	100%	50%	2.05	2.30	2.57	2.87	3.20	3.55	3.93	4.33	4.74	5.16	5.56	5.95	6.29	6.56	6.77	6.92	7.01
		60%	2.26	2.54	2.84	3.17	3.54	3.93	4.36	4.82	5.30	5.80	6.30	6.78	7.23	7.63	7.94	8.18	8.34
		80%	2.63	2.95	3.31	3.70	4.13	4.61	5.12	5.68	6.28	6.91	7.57	8.24	8.89	9.51	10.05	10.50	10.84
		100%	2.96	3.32	3.72	4.16	4.65	5.19	5.78	6.43	7.13	7.88	8.67	9.50	10.33	11.15	11.91	12.59	13.15

Table E-2: NFPA 80A spatial separation calculated versus actual table value differences

Difference																		
0.14	0.07	0.035	1	1.3	1.6	2	2.5	3.2	4	5	6	8	10	13	16	20	25	32	40
20%	10%	5%	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30%	15%	7.5%	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40%	20%	10%	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50%	25%	12.5%	0.00	0.02	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
60%	30%	15%	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
80%	40%	20%	0.00	0.02	0.01	0.00	0.00	0.01	0.01	0.00	0.03	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
100%	50%	25%	0.00	0.02	0.01	0.00	0.00	0.01	0.01	0.00	0.04	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00
	60%	30%	0.00	0.03	0.00	0.01	0.00	0.01	0.00	0.00	0.05	0.00	0.00	0.02	0.00	0.00	0.00	0.01	0.00
	80%	40%	0.00	0.03	0.01	0.00	0.01	0.02	0.01	0.00	0.08	0.01	0.00	0.04	0.01	0.00	0.00	0.00	0.00
	100%	50%	0.00	0.04	0.02	0.01	0.01	0.02	0.01	0.01	0.09	0.01	0.00	0.05	0.01	0.01	0.00	0.00	0.00
		60%	0.00	0.04	0.01	0.01	0.01	0.02	0.01	0.01	0.11	0.01	0.00	0.07	0.02	0.00	0.00	0.01	0.00
		80%	0.00	0.05	0.01	0.00	0.01	0.02	0.01	0.00	0.13	0.02	0.00	0.09	0.03	0.00	0.01	0.02	0.01
		100%	0.00	0.05	0.02	0.01	0.01	0.03	0.02	0.01	0.16	0.02	0.00	0.11	0.03	0.00	0.01	0.03	0.01

Appendix F
New Zealand C/VM2 Spatial Separation Calculation Methodology

Inputs:

$$E = \begin{cases} 144\ kW/m^2, & \text{FLED} \leq 400\ \text{MJ/m}^2 \\ 103\ kW/m^2, & \text{FLED} > 400\ \text{MJ/m}^2 \text{ to } \leq 800\ \text{MJ/m}^2 \\ 83\ kW/m^2, & \text{FLED} > 800\ \text{MJ/m}^2 \end{cases}$$

$$I_c = \begin{cases} 30\ kW/m^2, & \text{At the relevant boundary} \\ 16\ kW/m^2, & \text{1 m beyond the relevant boundary} \end{cases}$$

$$\phi_{c,ic1} = \begin{cases} 0.208, & \text{FLED} \leq 400\ \text{MJ/m}^2 \\ 0.291, & \text{FLED} > 400\ \text{MJ/m}^2 \text{ to } \leq 800\ \text{MJ/m}^2 \\ 0.361, & \text{FLED} > 800\ \text{MJ/m}^2 \end{cases}$$

$$\phi_{c,ic2} = \begin{cases} 0.111, & \text{FLED} \leq 400\ \text{MJ/m}^2 \\ 0.155, & \text{FLED} > 400\ \text{MJ/m}^2 \text{ to } \leq 800\ \text{MJ/m}^2 \\ 0.193, & \text{FLED} > 800\ \text{MJ/m}^2 \end{cases}$$

h = enclosing rectangle height (m)

w = enclosing rectangle width (m)

RB = Distance to relevant boundary (m)

Step 1: Calculate the distances (d)

$$d_1 = 2 \cdot RB$$
$$d_2 = 2 \cdot RB + 1$$

Step 2: Calculate the ratio (S) of the exposing building face based on Equation 7-9

$$S = max\left[\frac{h}{w}, \frac{w}{h}\right]$$

Step 3: Calculate the normalize area (T) of the exposing building face based on Equation 7-8

$$T_1 = \frac{A}{d_1^2} = \frac{h \cdot w}{d_1^2}$$

$$T_2 = \frac{A}{d_2^2} = \frac{h \cdot w}{d_2^2}$$

Step 4: Calculate the configuration factor (ϕ) based on Equation 7-7

$$\phi_1 = \frac{2}{\pi}\left[\sqrt{\frac{\frac{T_1}{S}}{\frac{T_1}{S}+4}}\,tan^{-1}\left(\sqrt{\frac{T_1 \cdot S}{\frac{T_1}{S}+4}}\right) + \sqrt{\frac{T_1 \cdot S}{T_1 \cdot S+4}}\,tan^{-1}\left(\sqrt{\frac{\frac{T_1}{S}}{T_1 \cdot S+4}}\right)\right]$$

$$\phi_2 = \frac{2}{\pi}\left[\sqrt{\frac{\frac{T_2}{S}}{\frac{T_2}{S}+4}}\,tan^{-1}\left(\sqrt{\frac{T_2 \cdot S}{\frac{T_2}{S}+4}}\right) + \sqrt{\frac{T_2 \cdot S}{T_2 \cdot S+4}}\,tan^{-1}\left(\sqrt{\frac{\frac{T_2}{S}}{T_2 \cdot S+4}}\right)\right]$$

Step 5: Calculate the percentage of unprotected openings (%UPO) based on Equation 7-12, rounded to the nearest percent

$$\%\mathrm{UPO}_1 = 100 \cdot \left(\frac{\phi_{c,ic1}}{\phi_1}\right)$$

$$\%\mathrm{UPO}_2 = 100 \cdot \left(\frac{\phi_{c,ic2}}{\phi_2}\right)$$

$$\%\mathrm{UPO} = min[\%\mathrm{UPO}_1, \%\mathrm{UPO}_2]$$

Table F-1: New Zealand C/VM2 spatial separation calculated table

	B	B + 1																							
CHF (kW/m²):	30	16																							
Height (m):	8																								
Calculated	EP (kW/m²):	83							EP (kW/m²):	103							EP (kW/m²):	144							
Minimum distance to relevant boundary (m)	Maximum percentage of unprotected area in the external wall allowed																								
	FLED ≤ 400 MJ/m²								FLED > 400 MJ/m² to ≤ 800 MJ/m²								FLED > 800 MJ/m²								
	Width of enclosing rectangle (m)								Width of enclosing rectangle (m)								Width of enclosing rectangle (m)								
	2	3	4	6	8	10	15	20	2	3	4	6	8	10	15	20	2	3	4	6	8	10	15	20	30
1.0	45%	34%	29%	25%	23%	23%	22%	22%	36%	27%	23%	20%	19%	18%	18%	17%	26%	19%	17%	14%	13%	13%	13%	13%	12%
1.1	47%	35%	30%	25%	24%	23%	22%	22%	38%	28%	24%	20%	19%	18%	18%	18%	27%	20%	17%	15%	14%	13%	13%	13%	13%
1.2	49%	36%	31%	26%	24%	23%	22%	22%	40%	29%	25%	21%	19%	19%	18%	18%	28%	21%	18%	15%	14%	13%	13%	13%	13%
1.3	51%	38%	32%	26%	24%	24%	23%	22%	41%	30%	25%	21%	20%	19%	18%	18%	30%	22%	18%	15%	14%	14%	13%	13%	13%
1.4	54%	39%	33%	27%	25%	24%	23%	23%	43%	32%	26%	22%	20%	19%	19%	18%	31%	23%	19%	16%	14%	14%	13%	13%	13%
1.5	56%	41%	34%	28%	25%	24%	23%	23%	45%	33%	27%	22%	20%	20%	19%	19%	32%	23%	19%	16%	15%	14%	13%	13%	13%
2.0	68%	49%	39%	31%	28%	26%	25%	24%	55%	39%	32%	25%	23%	21%	20%	20%	39%	28%	23%	18%	16%	15%	14%	14%	14%
2.5	82%	58%	46%	36%	31%	29%	27%	26%	66%	46%	37%	29%	25%	23%	22%	21%	47%	33%	27%	20%	18%	17%	15%	15%	15%
3.0	98%	68%	53%	40%	35%	32%	29%	28%	79%	55%	43%	33%	28%	26%	23%	23%	56%	39%	31%	23%	20%	18%	17%	16%	16%
4.0	100%	91%	71%	52%	43%	39%	34%	32%	100%	74%	57%	42%	35%	31%	27%	26%	77%	53%	41%	30%	25%	22%	20%	19%	18%
5.0		100%	92%	66%	54%	47%	40%	37%		96%	74%	53%	43%	38%	32%	30%	100%	69%	53%	38%	31%	27%	23%	22%	21%
6.0			100%	82%	66%	57%	47%	43%		100%	94%	66%	53%	46%	38%	35%		88%	67%	48%	38%	33%	27%	25%	23%
7.0				100%	81%	69%	55%	49%			100%	82%	65%	55%	44%	40%		100%	84%	58%	46%	40%	32%	28%	26%
8.0					97%	82%	64%	56%				99%	78%	66%	51%	45%			100%	71%	56%	47%	37%	33%	29%
9.0					100%	96%	74%	64%				100%	92%	77%	59%	52%				85%	66%	55%	42%	37%	33%
10.0						100%	84%	72%					100%	90%	68%	58%				100%	78%	65%	49%	42%	36%
11.0							96%	81%						100%	77%	66%					90%	75%	55%	47%	40%
12.0							100%	91%							88%	73%					100%	86%	63%	53%	44%
14.0								100%							100%	91%						100%	79%	65%	53%
17.0																100%							100%	87%	68%
20.0																								100%	86%
22.2																									100%

Table F-2: New Zealand C/VM2 spatial separation actual table

Actual

Minimum distance to relevant boundary (m)	Maximum percentage of unprotected area in the external wall allowed																								
	FLED ≤ 400 MJ/m²								FLED > 400 MJ/m² to ≤ 800 MJ/m²								FLED > 800 MJ/m²								
	Width of enclosing rectangle (m)								Width of enclosing rectangle (m)								Width of enclosing rectangle (m)								
	2	3	4	6	8	10	15	20	2	3	4	6	8	10	15	20	2	3	4	6	8	10	15	20	30
1.0	45%	34%	29%	25%	23%	23%	22%	22%	36%	27%	23%	20%	19%	18%	18%	17%	26%	19%	17%	14%	13%	13%	13%	13%	12%
1.1	47%	35%	30%	25%	24%	23%	22%	22%	38%	28%	24%	20%	19%	18%	18%	18%	27%	20%	17%	15%	14%	13%	13%	13%	13%
1.2	49%	36%	31%	26%	24%	23%	22%	22%	40%	29%	25%	21%	19%	19%	18%	18%	28%	21%	18%	15%	14%	13%	13%	13%	13%
1.3	51%	38%	32%	26%	24%	24%	23%	22%	41%	30%	25%	21%	20%	19%	18%	18%	30%	22%	18%	15%	14%	14%	13%	13%	13%
1.4	54%	39%	33%	27%	25%	24%	23%	23%	43%	32%	26%	22%	20%	19%	19%	19%	31%	23%	19%	16%	14%	14%	13%	13%	13%
1.5	56%	41%	34%	28%	25%	24%	23%	23%	45%	33%	27%	22%	20%	20%	19%	19%	32%	23%	19%	16%	15%	14%	13%	13%	13%
2.0	68%	49%	39%	31%	28%	26%	25%	24%	55%	39%	32%	25%	23%	21%	20%	20%	39%	28%	23%	18%	16%	15%	14%	14%	14%
2.5	82%	58%	46%	36%	31%	29%	27%	26%	66%	46%	37%	29%	25%	23%	22%	21%	47%	33%	27%	20%	18%	17%	15%	15%	15%
3.0	98%	68%	53%	40%	35%	32%	29%	28%	79%	55%	43%	33%	28%	26%	23%	23%	56%	39%	31%	23%	20%	18%	17%	16%	16%
4.0	100%	91%	71%	52%	43%	39%	34%	32%	100%	74%	57%	42%	35%	31%	27%	26%	77%	53%	41%	30%	25%	22%	20%	19%	18%
5.0		100%	92%	66%	54%	47%	40%	37%		96%	74%	53%	43%	38%	32%	30%	100%	69%	53%	38%	31%	27%	23%	22%	21%
6.0			100%	82%	66%	57%	47%	43%		100%	94%	66%	53%	46%	38%	35%		88%	67%	48%	38%	33%	27%	25%	23%
7.0				100%	81%	69%	55%	49%			100%	82%	65%	55%	44%	40%		100%	84%	58%	46%	40%	32%	28%	26%
8.0					97%	82%	64%	56%				99%	78%	66%	51%	45%			100%	71%	56%	47%	37%	33%	29%
9.0					100%	96%	74%	64%				100%	92%	77%	59%	52%				85%	66%	55%	42%	37%	33%
10.0						100%	84%	72%					100%	90%	68%	58%				100%	78%	65%	49%	42%	36%
11.0							96%	81%						100%	77%	66%					90%	75%	55%	47%	40%
12.0							100%	91%							88%	73%					100%	86%	63%	53%	44%
14.0								100%							100%	91%						100%	79%	65%	53%
17.0																100%							100%	87%	68%
20.0																								100%	86%
22.2																									100%

Table F-3: New Zealand C/VM2 spatial separation calculated versus actual table difference

Difference																										
Minimum distance to relevant boundary (m)	Maximum percentage of unprotected area in the external wall allowed																									
	FLED ≤ 400 MJ/m²								FLED > 400 MJ/m² to ≤ 800 MJ/m²								FLED > 800 MJ/m²									
	Width of enclosing rectangle (m)								Width of enclosing rectangle (m)								Width of enclosing rectangle (m)									
	2	3	4	6	8	10	15	20	2	3	4	6	8	10	15	20	2	3	4	6	8	10	15	20	30
1.0	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1.1	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1.2	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1.3	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1.4	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2.0	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
3.0	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
4.0	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
5.0		0%	0%	0%	0%	0%	0%	0%		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
6.0			0%	0%	0%	0%	0%	0%		0%	0%	0%	0%	0%	0%	0%		0%	0%	0%	0%	0%	0%	0%	0%	0%
7.0				0%	0%	0%	0%	0%			0%	0%	0%	0%	0%	0%		0%	0%	0%	0%	0%	0%	0%	0%	0%
8.0					0%	0%	0%	0%				0%	0%	0%	0%	0%			0%	0%	0%	0%	0%	0%	0%	0%
9.0					0%	0%	0%	0%				0%	0%	0%	0%	0%				0%	0%	0%	0%	0%	0%	0%
10.0						0%	0%	0%					0%	0%	0%	0%					0%	0%	0%	0%	0%	0%
11.0							0%	0%						0%	0%	0%						0%	0%	0%	0%	0%
12.0							0%	0%							0%	0%						0%	0%	0%	0%	0%
14.0								0%							0%	0%							0%	0%	0%	0%
17.0																0%								0%	0%	0%
20.0																									0%	0%
22.2																										0%

Appendix G
2020 NBC Sprinklered Spatial Separation Tables Rounding Errors

Table G-1:Calculated low hazard 2020 NBC Table 3.2.3.1.-D

Exposing Building Face	**Calculated Table:** Area of Unprotected Opening for groups A, C, D, and F, Division 3 Occupancies, %											
Max.	Limiting Distance, m											
Area, m^2	0	1.2	1.5	2	2.5	3	4	5	6	7	8	9
10	0%	17%	24%	41%	66%	99%	100%					
15	0%	16%	21%	33%	51%	73%	100%					
20	0%	15%	19%	29%	43%	60%	100%					
25	0%	15%	18%	27%	38%	52%	90%	100%				
30	0%	15%	18%	25%	34%	46%	78%	100%				
40	0%	15%	17%	22%	30%	39%	64%	96%	100%			
50	0%	15%	16%	21%	27%	35%	55%	81%	100%			
60	0%	14%	16%	20%	25%	32%	49%	71%	99%	100%		
80	0%	14%	15%	19%	23%	28%	41%	58%	79%	100%		
100	0%	14%	15%	18%	21%	26%	37%	51%	68%	88%	100%	
150	0%	14%	15%	17%	19%	22%	30%	40%	52%	65%	81%	100%

Table G-2:Actual low hazard 2020 NBC Table 3.2.3.1.-D

Exposing Building Face	**Actual Table:** Area of Unprotected Opening for groups A, C, D, and F, Division 3 Occupancies, %											
Max.	Limiting Distance, m											
Area, m^2	0	1.2	1.5	2	2.5	3	4	5	6	7	8	9
10	0%	16%	24%	42%	66%	100%						
15	0%	16%	20%	34%	50%	74%	100%					
20	0%	16%	20%	30%	42%	60%	100%					
25	0%	16%	18%	26%	38%	52%	90%	100%				
30	0%	14%	18%	24%	34%	46%	78%	100%				
40	0%	14%	16%	22%	30%	40%	64%	96%	100%			
50	0%	14%	16%	20%	28%	36%	56%	82%	100%			
60	0%	14%	16%	20%	26%	32%	50%	72%	98%	100%		
80	0%	14%	16%	18%	22%	28%	42%	58%	80%	100%		
100	0%	14%	16%	18%	22%	26%	36%	50%	68%	88%	100%	
150	0%	14%	14%	16%	20%	22%	30%	40%	52%	66%	82%	100%

Table G-3:Difference of actual versus calculated low hazard 2020 NBC Table 3.2.3.1.-D

Exposing Building Face	**Table Difference:** Area of Unprotected Opening for groups A, C, D, and F, Division 3 Occupancies, %											
Max.	Limiting Distance, m											
Area, m^2	0	1.2	1.5	2	2.5	3	4	5	6	7	8	9
10	0%	1%	0%	-1%	0%	-1%	100%	0%	0%	0%	0%	0%
15	0%	0%	1%	-1%	1%	-1%	0%	0%	0%	0%	0%	0%
20	0%	-1%	-1%	-1%	1%	0%	0%	0%	0%	0%	0%	0%
25	0%	-1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%
30	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%
40	0%	1%	1%	0%	0%	-1%	0%	0%	0%	0%	0%	0%
50	0%	1%	0%	1%	-1%	-1%	-1%	-1%	0%	0%	0%	0%
60	0%	0%	0%	0%	-1%	0%	-1%	-1%	1%	0%	0%	0%
80	0%	0%	-1%	1%	1%	0%	-1%	0%	-1%	0%	0%	0%
100	0%	0%	-1%	0%	-1%	0%	1%	1%	0%	0%	0%	0%
150	0%	0%	1%	1%	-1%	0%	0%	0%	0%	-1%	-1%	0%

Table G-4:Calculated high hazard 2020 NBC Table 3.2.3.1.-E

Exposing Building Face	**Calculated Table:**Area of Unprotected Opening for Groups E and F, Division 1 and 2 Occupancies, %																	
Max.	Limiting Distance, m																	
Area, m^2	0	1.2	1.5	2	2.5	3	4	5	6	7	8	9	10	11	12	13	14	16
10	0%	8%	12%	21%	33%	50%	96%	100%										
15	0%	8%	10%	17%	25%	37%	67%	100%										
20	0%	8%	10%	15%	21%	30%	53%	85%	100%									
25	0%	8%	9%	13%	19%	26%	45%	70%	100%									
30	0%	7%	9%	12%	17%	23%	39%	61%	88%	100%								
40	0%	7%	8%	11%	15%	20%	32%	48%	69%	93%	100%							
50	0%	7%	8%	10%	14%	18%	28%	41%	57%	77%	100%							
60	0%	7%	8%	10%	13%	16%	25%	36%	49%	66%	85%	100%						
80	0%	7%	8%	9%	11%	14%	21%	29%	40%	52%	67%	84%	100%					
100	0%	7%	8%	9%	11%	13%	18%	25%	34%	44%	56%	69%	84%	100%				
150	0%	7%	7%	8%	10%	11%	15%	20%	26%	33%	41%	50%	60%	71%	84%	97%	100%	
200	0%	7%	7%	8%	9%	10%	13%	17%	22%	27%	33%	40%	48%	56%	66%	76%	87%	100%

Table G-5:Actual high hazard 2020 NBC Table 3.2.3.1.-E

Exposing Building Face	**Actual Table:** Area of Unprotected Opening for Groups E and F, Division 1 and 2 Occupancies, %																	
Max.	Limiting Distance, m																	
Area, m^2	0	1.2	1.5	2	2.5	3	4	5	6	7	8	9	10	11	12	13	14	15
10	0%	8%	12%	20%	34%	50%	96%	100%										
15	0%	8%	10%	16%	26%	36%	68%	100%										
20	0%	8%	10%	14%	22%	30%	54%	86%	100%									
25	0%	8%	10%	14%	18%	26%	44%	70%	100%									
30	0%	8%	8%	12%	18%	24%	40%	60%	88%	100%								
40	0%	8%	8%	12%	16%	20%	32%	48%	68%	94%	100%							
50	0%	8%	8%	10%	14%	18%	28%	40%	58%	76%	100%							
60	0%	8%	8%	10%	12%	16%	24%	36%	50%	66%	86%	100%						
80	0%	8%	8%	10%	12%	14%	20%	30%	40%	52%	66%	84%	100%					
100	0%	8%	8%	8%	10%	12%	18%	26%	34%	44%	56%	70%	84%	100%				
150	0%	8%	8%	8%	10%	12%	16%	20%	26%	32%	40%	50%	60%	72%	84%	98%	100%	
200	0%	8%	8%	8%	8%	10%	14%	18%	22%	28%	34%	42%	50%	60%	68%	80%	92%	100%

Table G-6:Difference between actual versus calculated high hazard 2020 NBC Table 3.2.3.1.-E

Exposing Building Face	**Table Difference:** Area of Unprotected Opening for Groups E and F, Division 1 and 2 Occupancies, %																	
Max.	Limiting Distance, m																	
Area, m^2	0	1.2	1.5	2	2.5	3	4	5	6	7	8	9	10	11	12	13	14	15
10	0%	0%	0%	1%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
15	0%	0%	0%	1%	-1%	1%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
20	0%	0%	0%	1%	-1%	0%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
25	0%	0%	-1%	-1%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
30	0%	-1%	1%	0%	-1%	-1%	-1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
40	0%	-1%	0%	-1%	-1%	0%	0%	0%	1%	-1%	0%	0%	0%	0%	0%	0%	0%	0%
50	0%	-1%	0%	0%	0%	0%	0%	1%	-1%	1%	0%	0%	0%	0%	0%	0%	0%	0%
60	0%	-1%	0%	0%	1%	0%	1%	0%	-1%	0%	-1%	0%	0%	0%	0%	0%	0%	0%
80	0%	-1%	0%	-1%	-1%	0%	1%	-1%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%
100	0%	-1%	0%	1%	1%	1%	0%	-1%	0%	0%	0%	-1%	0%	0%	0%	0%	0%	0%
150	0%	-1%	-1%	0%	0%	-1%	-1%	0%	0%	1%	1%	0%	0%	-1%	0%	-1%	0%	0%
200	0%	-1%	-1%	0%	1%	0%	-1%	-1%	0%	-1%	-1%	-2%	-2%	-4%	-2%	-4%	-5%	0%

Appendix H
Sample CFAST Input File

Input File No. 11804

```
&HEAD VERSION = 7500, TITLE = 'KDC_Thesis' /

!!Scenario Configuration
&TIME SIMULATION  = 6000
      PRINT       = 60
      SMOKEVIEW   = 10
      SPREADSHEET = 1 /

&INIT PRESSURE             = 101325
      RELATIVE_HUMIDITY    = 50
      INTERIOR_TEMPERATURE = 20
      EXTERIOR_TEMPERATURE = 20 /

&MISC LOWER_OXYGEN_LIMIT  = 0.15
      ADIABATIC           = .FALSE.
      MAX_TIME_STEP       = 1
      OVERWRITE           = .TRUE.
      SPECIFIC_EXTINCTION = 8700, 4400 /

!! Compartments
&COMP ID                = 'Main_Compartment'
      DEPTH             = 3.426484962580458
      HEIGHT            = 2.1
      WIDTH             = 2.970247974223168
      CEILING_MATL_ID   = 'GYPSUM'
      CEILING_THICKNESS = 0.076
      WALL_MATL_ID      = 'GYPSUM'
      WALL_THICKNESS    = 0.076
      FLOOR_MATL_ID     = 'FIR'
      FLOOR_THICKNESS   = 0.15
      ORIGIN            = 0,0,0
      GRID              = 50,50,50
      LEAK_AREA_RATIO   = 0.00017, 5.2E-05 /

!! Material Properties
&MATL ID            = 'GYPSUM'
      MATERIAL      = 'Gypsum'
      CONDUCTIVITY  = 0.18
      DENSITY       = 2100
      SPECIFIC_HEAT = 1.1
      THICKNESS     = 0.076
      EMISSIVITY    = 0.9 /

&MATL ID            = 'FIR'
      MATERIAL      = 'Fir wood'
      CONDUCTIVITY  = 0.11
      DENSITY       = 420
      SPECIFIC_HEAT = 2.72
      THICKNESS     = 0.15
      EMISSIVITY    = 0.8 /
```

```
&MATL ID            = 'GLASS'
      MATERIAL      = 'Window glass'
      CONDUCTIVITY  = 0.78
      DENSITY       = 2700
      SPECIFIC_HEAT = 0.84
      THICKNESS     = 0.013
      EMISSIVITY    = 0.83 /

&MATL ID            = 'POLYURETHANE'
      MATERIAL      = 'Polyurethane'
      CONDUCTIVITY  = 0.05
      DENSITY       = 50
      SPECIFIC_HEAT = 2.076
      THICKNESS     = 0.005
      EMISSIVITY    = 0.4 /

&MATL ID            = 'POLYSTYRENE'
      MATERIAL      = 'Polystyrene'
      CONDUCTIVITY  = 0.14
      DENSITY       = 1050
      SPECIFIC_HEAT = 1.25
      THICKNESS     = 0.005
      EMISSIVITY    = 0.4 /

!! Openings
&VENT TYPE                = 'WALL'
      ID                  = 'Window_1'
      COMP_IDS            = 'Main_Compartment','OUTSIDE'
      WIDTH               = 0.42583687554828253
      TOP                 = 1.351071643314655
      BOTTOM              = 0.7489283566853453
      FACE                = 'FRONT'
      OFFSET              = 0.5296435557816507
      CRITERION           = 'TEMPERATURE'
      SETPOINT            = 300.0
      DEVC_ID             = 'Window_1_device'
      PRE_FRACTION        = 0
      POST_FRACTION       = 1 /

&DEVC ID                  = 'Window_1_device'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 0.7425619935557919, 0.0, 1.0500000000000003
      SURFACE_ORIENTATION = 'RIGHT WALL'
      MATL_ID             = 'GLASS'
      TEMPERATURE_DEPTH   = 0.001
      DEPTH_UNITS         = 'M' /

&VENT TYPE                = 'WALL'
      ID                  = 'Window_2'
      COMP_IDS            = 'Main_Compartment','OUTSIDE'
```

```
      WIDTH               = 0.42583687554828265

      TOP                 = 1.351071643314655
      BOTTOM              = 0.7489283566853453
      FACE                = 'FRONT'
      OFFSET              = 2.014767542893235
      CRITERION           = 'TEMPERATURE'
      SETPOINT            = 300.0
      DEVC_ID             = 'Window_2_device'
      PRE_FRACTION        = 0
      POST_FRACTION       = 1 /

&DEVC ID                  = 'Window_2_device'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 2.227685980667376, 0.0, 1.0500000000000003
      SURFACE_ORIENTATION = 'RIGHT WALL'
      MATL_ID             = 'GLASS'
      TEMPERATURE_DEPTH   = 0.001
      DEPTH_UNITS         = 'M' /

!! Openings
&VENT TYPE                = 'WALL'
      ID                  = 'Door'
      COMP_IDS            = 'Main_Compartment','OUTSIDE'
      WIDTH               = 1.0
      TOP                 = 1.8
      BOTTOM              = 0.0
      FACE                = 'REAR'
      OFFSET              = 0.5 /

!! Fires
&FIRE ID                 = 'f1_Sofa'
      COMP_ID            = 'Main_Compartment'
      FIRE_ID            = 'f1_Sofa_ID'
      LOCATION           = 1.1654231620449258, 1.901957130717518 /

&CHEM ID                      = 'f1_Sofa_ID'
      CARBON                  = 1
      CHLORINE                = 0
      HYDROGEN                = 4
      NITROGEN                = 0
      OXYGEN                  = 0
      HEAT_OF_COMBUSTION      = 21841.9
      RADIATIVE_FRACTION      = 0.35
      FLAMING_TRANSITION_TIME = 0 /

&TABL  ID  =  'f1_Sofa_ID'  LABELS  =  'TIME',  'HRR',  'HEIGHT',  'AREA',  'CO_YIELD',
'SOOT_YIELD', 'HCN_YIELD', 'HCL_YIELD', 'TRACE_YIELD'  /
&TABL ID = 'f1_Sofa_ID', DATA = 0, 0, 0.46, 0, 0, 0, 0, 0, 0 /
&TABL ID = 'f1_Sofa_ID', DATA = 422.75, 1842.68, 0.46, 1.19, 0, 0, 0, 0, 0 /
```

```
&TABL ID = 'f1_Sofa_ID', DATA = 845.49, 0, 0.46, 0, 0, 0, 0, 0, 0 /

&FIRE ID                 = 'f2_Recliner_chair'
      COMP_ID            = 'Main_Compartment'
      FIRE_ID            = 'f2_Recliner_chair_ID'
      LOCATION           = 0.6991718030756826, 1.524558733853814
      IGNITION_CRITERION = 'FLUX'
      SETPOINT           = 12.5
      DEVC_ID            = 'f2_Recliner_chair_device' /

&CHEM ID                      = 'f2_Recliner_chair_ID'
      CARBON                  = 1
      CHLORINE                = 0
      HYDROGEN                = 4
      NITROGEN                = 0
      OXYGEN                  = 0
      HEAT_OF_COMBUSTION      = 28362.93
      RADIATIVE_FRACTION      = 0.35
      FLAMING_TRANSITION_TIME = 0 /

&TABL ID = 'f2_Recliner_chair_ID' LABELS = 'TIME', 'HRR', 'HEIGHT', 'AREA', 'CO_YIELD',
'SOOT_YIELD', 'HCN_YIELD', 'HCL_YIELD', 'TRACE_YIELD'  /
&TABL ID = 'f2_Recliner_chair_ID', DATA = 0, 0, 0.46, 0, 0, 0, 0, 0, 0 /
&TABL ID = 'f2_Recliner_chair_ID', DATA = 432.47, 1264.66, 0.46, 0.88, 0, 0, 0, 0, 0 /
&TABL ID = 'f2_Recliner_chair_ID', DATA = 864.95, 0, 0.46, 0, 0, 0, 0, 0, 0 /

&DEVC ID                  = 'f2_Recliner_chair_device'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 0.6991718030756826, 1.524558733853814, 0.46
      SURFACE_ORIENTATION = 'CEILING'
      MATL_ID             = 'POLYURETHANE'
      TEMPERATURE_DEPTH   = 0.001
      DEPTH_UNITS         = 'M' /

&FIRE ID                 = 'f3_Side_table'
      COMP_ID            = 'Main_Compartment'
      FIRE_ID            = 'f3_Side_table_ID'
      LOCATION           = 1.4281519043019895, 0.7683399890740037
      IGNITION_CRITERION = 'FLUX'
      SETPOINT           = 12.5
      DEVC_ID            = 'f3_Side_table_device' /

&CHEM ID                      = 'f3_Side_table_ID'
      CARBON                  = 1
      CHLORINE                = 0
      HYDROGEN                = 4
      NITROGEN                = 0
      OXYGEN                  = 0
      HEAT_OF_COMBUSTION      = 17761.51
      RADIATIVE_FRACTION      = 0.35
```

```
      FLAMING_TRANSITION_TIME = 0 /

&TABL ID = 'f3_Side_table_ID' LABELS = 'TIME', 'HRR', 'HEIGHT', 'AREA', 'CO_YIELD',
'SOOT_YIELD', 'HCN_YIELD', 'HCL_YIELD', 'TRACE_YIELD'  /
&TABL ID = 'f3_Side_table_ID', DATA = 0, 0, 0.5, 0, 0, 0, 0, 0, 0 /
&TABL ID = 'f3_Side_table_ID', DATA = 169.49, 550.81, 0.5, 0.45, 0, 0, 0, 0, 0 /
&TABL ID = 'f3_Side_table_ID', DATA = 338.97, 0, 0.5, 0, 0, 0, 0, 0, 0 /

&DEVC ID                  = 'f3_Side_table_device'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 1.4281519043019895, 0.7683399890740037, 0.5
      SURFACE_ORIENTATION = 'CEILING'
      MATL_ID             = 'FIR'
      TEMPERATURE_DEPTH   = 0.001
      DEPTH_UNITS         = 'M' /

&FIRE ID                 = 'f4_Ottoman'
      COMP_ID            = 'Main_Compartment'
      FIRE_ID            = 'f4_Ottoman_ID'
      LOCATION           = 1.5947041612428665, 1.5539865294151818
      IGNITION_CRITERION = 'FLUX'
      SETPOINT           = 12.5
      DEVC_ID            = 'f4_Ottoman_device' /

&CHEM ID                      = 'f4_Ottoman_ID'
      CARBON                  = 1
      CHLORINE                = 0
      HYDROGEN                = 4
      NITROGEN                = 0
      OXYGEN                  = 0
      HEAT_OF_COMBUSTION      = 18490.19
      RADIATIVE_FRACTION      = 0.35
      FLAMING_TRANSITION_TIME = 0 /

&TABL ID = 'f4_Ottoman_ID' LABELS = 'TIME', 'HRR', 'HEIGHT', 'AREA', 'CO_YIELD',
'SOOT_YIELD', 'HCN_YIELD', 'HCL_YIELD', 'TRACE_YIELD'  /
&TABL ID = 'f4_Ottoman_ID', DATA = 0, 0, 0.44, 0, 0, 0, 0, 0, 0 /
&TABL ID = 'f4_Ottoman_ID', DATA = 547.92, 563.88, 0.44, 0.46, 0, 0, 0, 0, 0 /
&TABL ID = 'f4_Ottoman_ID', DATA = 1095.83, 0, 0.44, 0, 0, 0, 0, 0, 0 /

&DEVC ID                  = 'f4_Ottoman_device'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 1.5947041612428665, 1.5539865294151818, 0.44
      SURFACE_ORIENTATION = 'CEILING'
      MATL_ID             = 'POLYURETHANE'
      TEMPERATURE_DEPTH   = 0.001
      DEPTH_UNITS         = 'M' /

&FIRE ID                 = 'f5_TV'
```

```
      COMP_ID            = 'Main_Compartment'
      FIRE_ID            = 'f5_TV_ID'
      LOCATION           = 2.389494732041789, 1.3160708358967963
      IGNITION_CRITERION = 'FLUX'
      SETPOINT           = 12.5
      DEVC_ID            = 'f5_TV_device' /

&CHEM ID                      = 'f5_TV_ID'
      CARBON                  = 1
      CHLORINE                = 0
      HYDROGEN                = 4
      NITROGEN                = 0
      OXYGEN                  = 0
      HEAT_OF_COMBUSTION      = 24688.61
      RADIATIVE_FRACTION      = 0.35
      FLAMING_TRANSITION_TIME = 0 /

&TABL ID = 'f5_TV_ID' LABELS = 'TIME', 'HRR', 'HEIGHT', 'AREA', 'CO_YIELD', 'SOOT_YIELD',
'HCN_YIELD', 'HCL_YIELD', 'TRACE_YIELD'  /
&TABL ID = 'f5_TV_ID', DATA = 0, 0, 0.74, 0, 0, 0, 0, 0, 0 /
&TABL ID = 'f5_TV_ID', DATA = 1416.01, 227.91, 0.74, 0.22, 0, 0, 0, 0, 0 /
&TABL ID = 'f5_TV_ID', DATA = 2832.02, 0, 0.74, 0, 0, 0, 0, 0, 0 /

&DEVC ID                  = 'f5_TV_device'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 2.389494732041789, 1.3160708358967963, 0.742
      SURFACE_ORIENTATION = 'CEILING'
      MATL_ID             = 'POLYSTYRENE'
      TEMPERATURE_DEPTH   = 0.001
      DEPTH_UNITS         = 'M' /

&FIRE ID                 = 'f6_Loveseat'
      COMP_ID            = 'Main_Compartment'
      FIRE_ID            = 'f6_Loveseat_ID'
      LOCATION           = 2.314821907892663, 0.574031240080997
      IGNITION_CRITERION = 'FLUX'
      SETPOINT           = 12.5
      DEVC_ID            = 'f6_Loveseat_device' /

&CHEM ID                      = 'f6_Loveseat_ID'
      CARBON                  = 1
      CHLORINE                = 0
      HYDROGEN                = 4
      NITROGEN                = 0
      OXYGEN                  = 0
      HEAT_OF_COMBUSTION      = 21686.45
      RADIATIVE_FRACTION      = 0.35
      FLAMING_TRANSITION_TIME = 0 /
```

```
&TABL ID = 'f6_Loveseat_ID' LABELS = 'TIME', 'HRR', 'HEIGHT', 'AREA', 'CO_YIELD',
'SOOT_YIELD', 'HCN_YIELD', 'HCL_YIELD', 'TRACE_YIELD' /
&TABL ID = 'f6_Loveseat_ID', DATA = 0, 0, 0.46, 0, 0, 0, 0, 0, 0 /
&TABL ID = 'f6_Loveseat_ID', DATA = 298.59, 1656.16, 0.46, 1.09, 0, 0, 0, 0, 0 /
&TABL ID = 'f6_Loveseat_ID', DATA = 597.18, 0, 0.46, 0, 0, 0, 0, 0, 0 /

&DEVC ID                  = 'f6_Loveseat_device'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 2.314821907892663, 0.574031240080997, 0.46
      SURFACE_ORIENTATION = 'CEILING'
      MATL_ID             = 'POLYURETHANE'
      TEMPERATURE_DEPTH   = 0.001
      DEPTH_UNITS         = 'M' /

&FIRE ID                 = 'f7_Magazine_rack'
      COMP_ID            = 'Main_Compartment'
      FIRE_ID            = 'f7_Magazine_rack_ID'
      LOCATION           = 0.7985651720527924, 2.3324034431018608
      IGNITION_CRITERION = 'FLUX'
      SETPOINT           = 12.5
      DEVC_ID            = 'f7_Magazine_rack_device' /

&CHEM ID                      = 'f7_Magazine_rack_ID'
      CARBON                  = 1
      CHLORINE                = 0
      HYDROGEN                = 4
      NITROGEN                = 0
      OXYGEN                  = 0
      HEAT_OF_COMBUSTION      = 18131.53
      RADIATIVE_FRACTION      = 0.35
      FLAMING_TRANSITION_TIME = 0 /

&TABL ID = 'f7_Magazine_rack_ID' LABELS = 'TIME', 'HRR', 'HEIGHT', 'AREA', 'CO_YIELD',
'SOOT_YIELD', 'HCN_YIELD', 'HCL_YIELD', 'TRACE_YIELD' /
&TABL ID = 'f7_Magazine_rack_ID', DATA = 0, 0, 1.0, 0, 0, 0, 0, 0, 0 /
&TABL ID = 'f7_Magazine_rack_ID', DATA = 20.03, 3488.38, 1.0, 1.98, 0, 0, 0, 0, 0 /
&TABL ID = 'f7_Magazine_rack_ID', DATA = 40.07, 0, 1.0, 0, 0, 0, 0, 0, 0 /

&DEVC ID                  = 'f7_Magazine_rack_device'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 0.7985651720527924, 2.3324034431018608, 1.0
      SURFACE_ORIENTATION = 'CEILING'
      MATL_ID             = 'FIR'
      TEMPERATURE_DEPTH   = 0.001
      DEPTH_UNITS         = 'M' /

&DEVC ID                  = 'Floor_Heat_Flux_01'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
```

```
      LOCATION            = 1.485123987111584, 1.713242481290229, 0.0
      SURFACE_ORIENTATION = 'CEILING'
      MATL_ID             = 'FIR'
      TEMPERATURE_DEPTH   = 0.01
      DEPTH_UNITS         = 'M' /

&DEVC ID                  = 'Floor_Heat_Flux_02'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 2.227685980667376, 0.8566212406451145, 0.0
      SURFACE_ORIENTATION = 'CEILING'
      MATL_ID             = 'FIR'
      TEMPERATURE_DEPTH   = 0.01
      DEPTH_UNITS         = 'M' /

&DEVC ID                  = 'Floor_Heat_Flux_03'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 2.227685980667376, 2.5698637219353433, 0.0
      SURFACE_ORIENTATION = 'CEILING'
      MATL_ID             = 'FIR'
      TEMPERATURE_DEPTH   = 0.01
      DEPTH_UNITS         = 'M' /

&DEVC ID                  = 'Floor_Heat_Flux_04'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 0.742561993555792, 0.8566212406451145, 0.0
      SURFACE_ORIENTATION = 'CEILING'
      MATL_ID             = 'FIR'
      TEMPERATURE_DEPTH   = 0.01
      DEPTH_UNITS         = 'M' /

&DEVC ID                  = 'Floor_Heat_Flux_05'
      COMP_ID             = 'Main_Compartment'
      TYPE                = 'PLATE'
      LOCATION            = 0.742561993555792, 2.5698637219353433, 0.0
      SURFACE_ORIENTATION = 'CEILING'
      MATL_ID             = 'FIR'
      TEMPERATURE_DEPTH   = 0.01
      DEPTH_UNITS         = 'M' /
```

Appendix I
Law EVF: Compartment Correlations and Algorithms

Compartment Parameters

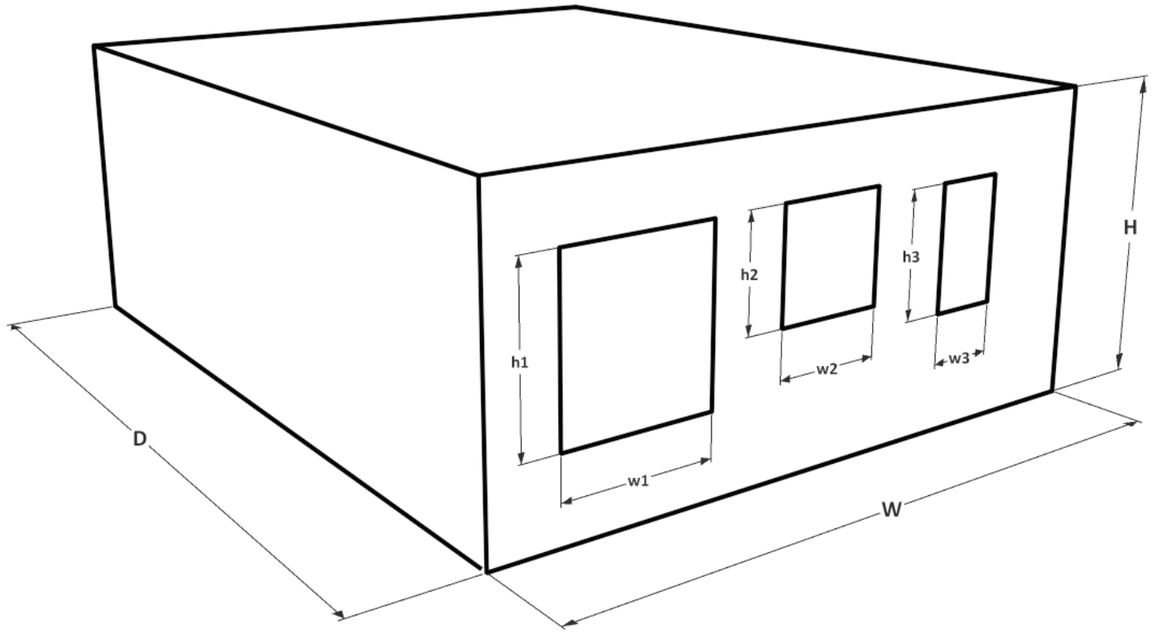
Parameter	Equation	Diagram
Floor Area (A_f)	$A_f = D \cdot W$	
Individual Window Area (A_{w1})	$A_{w1} = h1 \cdot w1$	
Total Window Area (A_w)	$A_w = A_{w1} + A_{w2} + \cdots + A_{wn}$	
Total Wall Area (A_T)	$A_T = 2 \cdot A_f + 2 \cdot H(D + W) - A_w$	
Total Opening Width (w_T)	$w_T = w1 + w2 + \cdots + wn$	
Averaged Opening Height (h_a)	$h_a = \frac{A_{w1} \cdot h1 + A_{w2} \cdot h2 + \cdots + A_{wn} \cdot hn}{A_w}$	
Fuel Load (FL)	$FL = A_f \frac{L_E}{H_c}$	
Rate of Burning Ventilation Controlled (R_{fc}) Fuel Controlled (R_{vc})	$\eta = \frac{A_T}{A_w\sqrt{h_a}}$ $R_{fc} = \frac{FL}{1200}$ $R_{vc} = \frac{0.18(1 - e^{-0.036 \cdot \eta})A_w\sqrt{h_a}}{\sqrt{\frac{W}{D}}}$	
Compartment Fire Temperature (T_f)	$\psi = \frac{FL}{\sqrt{A_w \cdot A_T}}$ $T_f = 6000\frac{(1 - e^{-0.10 \cdot \eta})}{\sqrt{\eta}}\left(1 - e^{-0.05 \cdot \psi}\right) + T_a$	

Figure I-1: Law EVF compartment dimensions

Parameter	Equation	VBA Code

Pi	$\pi = 4 \cdot \tan^{-1} 1$	`Public Static Function pi()`
		`  pi = 4 * Atn(1)`
		`End Function`

Degrees to Radians	$R = \frac{D \cdot \pi}{180}$	`Public Static Function DtR(Degrees)`
		`  DtR = Degrees * (pi() / 180)`
		`End Function`

Floor Area (A_f)	$A_f = D \cdot W$	`Public Static Function Af(D As Double, W As Double)`
		`  Af = D * W`
		`End Function`

Parameter	Equation	VBA Code

Individual Window Area (A_{w1})	$A_{w1} = h1 \cdot w1$	`Public Static Function Aw(R As Range)`
		`  Dim v_A As Double`
		`  Dim c As Range`
		`  v_A = 0`
		`  For Each c In R.Cells`
		`  v_A = v_A + c.Value`
		`  Next`
		`  Aw = v_A`
		`End Function`

Total Window Area (A_w)	$A_w = A_{w1} + A_{w2} + \cdots + A_{wn}$	

Total Wall Area (A_T)	$A_T = 2 \cdot A_f + 2 \cdot H(D + W) - A_w$	`Public Static Function AT(D As Double, W As Double, h As Double, Aw As Double)`
		`  Dim v_Af As Double`
		`  v_Af = Af(D, W)`
		`  AT = 2 * v_Af + 2 * h * (D + W) - Aw`
		`End Function`

Total Opening Width (w_T)	$w_T = w1 + w2 + \cdots + wn$	`Public Static Function wT(R As Range)`
		`  Dim v_w As Double`
		`  Dim c As Range`
		`  v_w = 0`
		`  For Each c In R.Cells`
		`  v_w = v_w + c.Value`
		`  Next`
		`  wT = v_w`
		`End Function`

Averaged Opening Height (h_a)	$h_a = \frac{A_{w1} \cdot h1 + A_{w2} \cdot h2 + \cdots + A_{wn} \cdot hn}{A_w}$	`Public Static Function ha(Aw_r As Range, h_r As Range, Aw As Double)`
		`  Dim v_Awh As Double`
		`  Dim i As Integer`
		`  v_Awh = 0`
		
		`  For i = 1 To Aw_r.Cells.Count`
		`  v_Awh = v_Awh + Aw_r.Cells(i) * h_r.Cells(i)`
		`  Next`
		`  ha = v_Awh / Aw`
		`End Function`

Fuel Load (FL)	$FL = A_f \frac{L_E}{H_c}$	`Public Static Function FL(LE As Double, Hc As Double, Af As Double)`
		`  FL = Af * (LE / Hc)`
		`End Function`

Rate of Burning
Ventilation Controlled (R_{fc})
Fuel Controlled (R_{vc})
	$\eta = \frac{A_T}{A_w\sqrt{h_a}}$	`Public Static Function eta(AT As Double, Aw As Double, ha As Double)`
		`  eta = AT / (Aw * Sqr(ha))`
		`End Function`

	$R_{fc} = \frac{FL}{1200}$	`Public Static Function Rfc(FL As Double)`
		`  Rfc = FL / 1200`
		`End Function`

	$R_{vc} = \frac{0.18(1 - e^{-0.036 \cdot \eta})A_w\sqrt{h_a}}{\sqrt{\frac{W}{D}}}$	`Public Static Function Rvc(D As Double, W As Double, eta As Double, Aw As Double, ha As Double)`
		`  Dim dw As Double`
		`  dw = W / D`
		`  If D > W Then`
		`  dw = D / W`
		`  End If`
		`  Rvc = (0.18 * (1 - Exp(-0.036 * eta)) * Aw * Sqr(ha)) / Sqr(dw)`

Parameter	Equation	VBA Code
		`End Function`

Compartment Fire Temperature (T_f)	$\psi = \frac{FL}{\sqrt{A_w \cdot A_T}}$	`Public Static Function psi(FL As Double, Aw As Double, AT As Double)`
		`  psi = FL / Sqr(Aw * AT)`
		`End Function`

	$T_f = 6000\frac{(1-e^{-0.10\cdot\eta})}{\sqrt{\eta}}\left(1-e^{-0.05\cdot\psi}\right)+T_a$	`Public Static Function Tf(Ta As Double, eta As Double, psi As Double)`
		`  Tf = ((6000# / Sqr(eta)) * (1 - Exp(-0.1 * eta)) * (1 - Exp(-0.05 * psi))) + Ta`
		`End Function`

Appendix J
Law EVF: Notional Flame Parameters

Notional Flame Parameters

Parameter	Wall Above	No Wall Above	
Flame Height (z)	$z = 12.8\left(\frac{R_{vc}}{w_T}\right)^{2/3} - h_i$		
Flame Depth (ff)	$ff = \frac{2}{3}h_i$		
Criteria 1	$h_u > \frac{2}{3}z$	$h_u \leq \frac{2}{3}z$	
Criteria 2	Where $h < 1.25 \cdot w_i$	Where $h \geq 1.25 \cdot w_i$	
Criteria 3		distance between windows $< 4 \cdot w_i$	distance between windows $\geq 4 \cdot w_i$
Flame Centre Distance (x)	$x = \frac{1}{3}h_i$	$x = 0.6h_i\left(\frac{z}{w_i}\right)^{1/3}$	$x = 0.3h_i\left(\frac{h_i}{w_i}\right)^{0.54}$
Flame Angle Distance (L)	$L = \frac{\sqrt{2}}{3}h_i$		
Flame Length (X)	$X = z + \frac{\sqrt{2}}{3}h_i$	$X = \sqrt{z^2 + \left(x - \frac{h_i}{3}\right)^2} + \frac{\sqrt{2}}{3}h_i$	
Flame Lift Distance (a)	$a = 0$	$a = x - \frac{h}{3}$	
Plane 1 ($P1$)	$P1 = \frac{h}{3}$		
Plane 2 ($P2$)	$P2 = \frac{2\sqrt{2}}{3}h$		
Plane 3 ($P3$)	$P3 = z$	$P3 = \sqrt{z^2 + \left(x - \frac{h}{3}\right)^2}$	
Flame Angle (β)	$\beta = 0$	$\beta = \tan^{-1}\left(\frac{x}{z} - \frac{h}{3 \cdot z}\right)$	
Flame Temperature ($T_z(l)$)	$\frac{T_z - T_a}{T_o - T_a} = 1 - 0.027\frac{l \cdot w_T}{R}$ $T_a = 293\ K$ $T_z = 813\ K$ $T_z - T_a = 520$ $l = X$ $T_o - T_a = \frac{520}{\left[1 - 0.027\left(\frac{X \cdot w_T}{R}\right)\right]}$ $T_z(l) = \frac{(T_o - T_a)\left[1 - 0.027\left(\frac{l \cdot w_T}{R}\right)\right]}{\left[1 - 0.027\left(\frac{X \cdot w_T}{R}\right)\right]} + T_a$		

Diagram

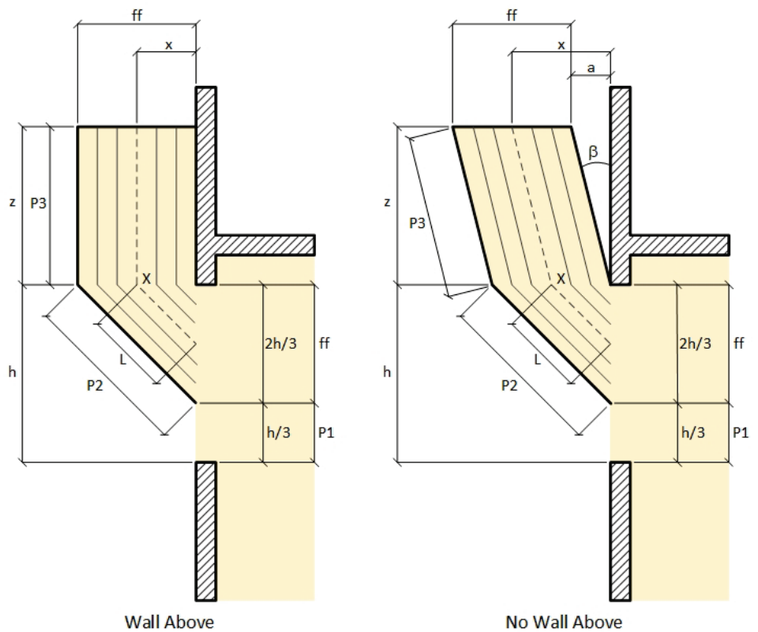


Figure J-1: Elevation view of Law notional flame extension from an opening

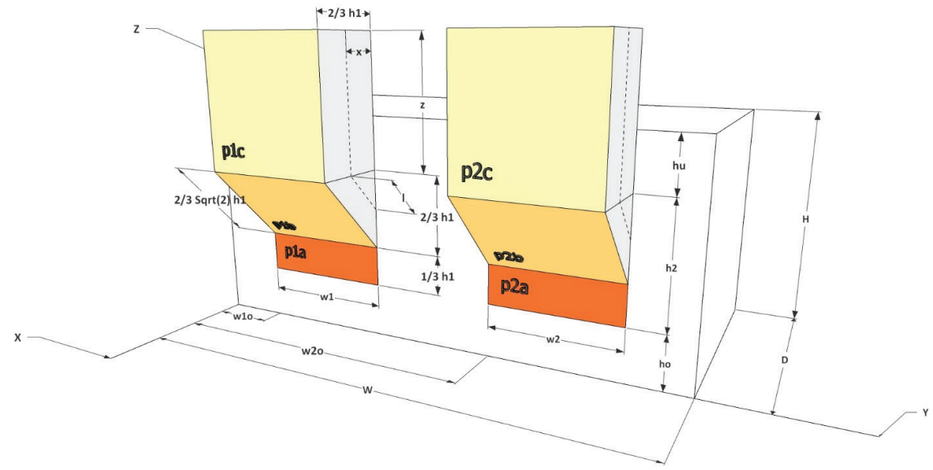


Figure J-2: Isometric view of Law notional flame extension from an opening

Parameter	Wall Above	No Wall Above	Diagram
	$T_z(l) = (T_o - T_a)\left(\frac{R - 0.027 \cdot l \cdot w_T}{R - 0.027 \cdot X \cdot w_T}\right) + T_a$		
Flame Emissivity (ε)	$\varepsilon = 1 - e^{-k \cdot \lambda}$		

Parameter	Wall Above	No Wall Above		VBA Code

Flame Height (z)	$z = 12.8\left(\frac{R_{vc}}{w_T}\right)^{2/3} - h_i$			`Public Static Function z(R As Double, wT As Double, h_i As Double)`
				`  z = (12.8 * ((R / wT) ^ (2 / 3))) - h_i`
				`End Function`

Flame Depth (ff)	$ff = \frac{2}{3}h_i$			`Public Static Function ff(h_i As Double)`
				`  ff = (2 / 3) * h_i`
				`End Function`

Criteria 1	$h_u > \frac{2}{3}z$	$h_u \leq \frac{2}{3}z$		`Public Static Function hu(h As Double, z2 As Double)`
				`  hu = h - z2`
				`End Function`

Criteria 2	Where $h < 1.25 \cdot w_i$	Where $h \geq 1.25 \cdot w_i$		`Public Static Function dw(xa As Double, xb As Double)`
				`  dw = (xb - xa)`
				`End Function`

Criteria 3		distance between windows $< 4 \cdot w_i$	distance between windows $\geq 4 \cdot w_i$	`Public Static Function X(h_i As Double, w_i As Double, z As Double, hu As Double, dw As Double)`
				`  If hu < 1.25 * w_i Then`
				`  X = (1 / 3) * h_i`
				`  Else`
				`  If dw < 4 * w_i Then`
				`  X = 0.6 * h_i * ((z / w_i) ^ (1 / 3))`
				`  Else`
				`  X = 0.3 * h_i * ((h_i / w_i) ^ (0.54))`
				`  End If`
				`  End If`
				`End Function`

Flame Centre Distance (x)	$x = \frac{1}{3}h_i$	$x = 0.6h_i\left(\frac{z}{w_i}\right)^{1/3}$	$x = 0.3h_i\left(\frac{h_i}{w_i}\right)^{0.54}$	

Flame Angle Distance (L)	$L = \frac{\sqrt{2}}{3}h_i$			`Public Static Function L(h_i As Double)`
				`  L = (Sqr(2) / 3) * h_i`
				`End Function`

Flame Length (X)	$X = z + \frac{\sqrt{2}}{3}h_i$	$X = \sqrt{z^2 + \left(x - \frac{h_i}{3}\right)^2} + \frac{\sqrt{2}}{3}h_i$		`Public Static Function XX(z As Double, h_i As Double, w_i As Double, X As Double, hu As Double)`
				`  If hu < 1.25 * w_i Then`
				`  XX = z + ((Sqr(2) / 3) * h_i)`
				`  Else`
				`  XX = Sqr((z ^ 2) + ((X - (h_i / 3)) ^ 2)) + ((Sqr(2) / 3) * h_i)`
				`  End If`
				`End Function`

Flame Lift Distance (a)	$a = 0$	$a = x - \frac{h}{3}$		`Public Static Function a(X As Double, h_i As Double, w_i As Double, hu As Double)`
				`  If hu < 1.25 * w_i Then`
				`  a = 0`
				`  Else`
				`  a = X - (h_i / 3)`
				`  End If`

Parameter	Wall Above	No Wall Above	VBA Code
			`End Function`

Plane 1 ($P1$)	$P1 = \frac{h}{3}$		`Public Static Function P_one(h_i As Double)`
			`  P_one = h_i / 3`
			`End Function`

Plane 2 ($P2$)	$P2 = \frac{2\sqrt{2}}{3}h$		`Public Static Function P_two(h_i As Double)`
			`  P_two = ((2 * Sqr(2)) / 3) * h_i`
			`End Function`

Plane 3 ($P3$)	$P3 = z$	$P3 = \sqrt{z^2 + \left(x - \frac{h}{3}\right)^2}$	`Public Static Function P_three(z As Double, X As Double, h_i As Double, w_i As Double, hu As Double)`
			`  If hu < 1.25 * w_i Then`
			`  P_three = z`
			`  Else`
			`  P_three = Sqr((z ^ 2) + ((X - (h_i / 3)) ^ 2))`
			`  End If`
			`End Function`

Flame Angle (β)	$\beta = 0$	$\beta = \tan^{-1}\left(\frac{x}{z} - \frac{h}{3 \cdot z}\right)$	`Public Static Function Beta(X As Double, z As Double, h_i As Double, w_i As Double, hu As Double)`
			`  If hu < 1.25 * w_i Then`
			`  Beta = 0`
			`  Else`
			`  Beta = Atn((X / z) - (h_i / (3 * z)))`
			`  End If`
			`End Function`

Flame Temperature ($T_z(l)$)	$\frac{T_z - T_a}{T_o - T_a} = 1 - 0.027\frac{l \cdot w_T}{R}$
	$T_a = 293\ K$
	$T_z = 813\ K$
	$T_z - T_a = 520$
	$l = X$
	$T_o - T_a = \frac{520}{\left[1 - 0.027\left(\frac{X \cdot w_T}{R}\right)\right]}$
	$T_z(l) = \frac{(T_o - T_a)\left[1 - 0.027\left(\frac{l \cdot w_T}{R}\right)\right]}{\left[1 - 0.027\left(\frac{X \cdot w_T}{R}\right)\right]} + T_a$
	$T_z(l) = (T_o - T_a)\left(\frac{R - 0.027 \cdot l \cdot w_T}{R - 0.027 \cdot X \cdot w_T}\right) + T_a$
			`Public Static Function T_l(T_o As Double, T_a As Double, R As Double, wT As Double, X As Double, L As Double)`
			`  Dim ONE As Double`
			`  Dim TWO_a As Double`
			`  Dim TWO_b As Double`
			`  ONE = T_o - T_a`
			`  TWO_a = R - 0.027 * L * wT`
			`  TWO_b = R - 0.027 * X * wT`
			`  T_l = (ONE * (TWO_a / TWO_b)) + T_a`
			`End Function`

Flame Emissivity (ε)	$\varepsilon = 1 - e^{-k \cdot \lambda}$		`Public Static Function ee(k As Double, delta As Double)`
			`  ee = 1 - Exp(-k * delta)`
			`End Function`

Notional Flame Discretization

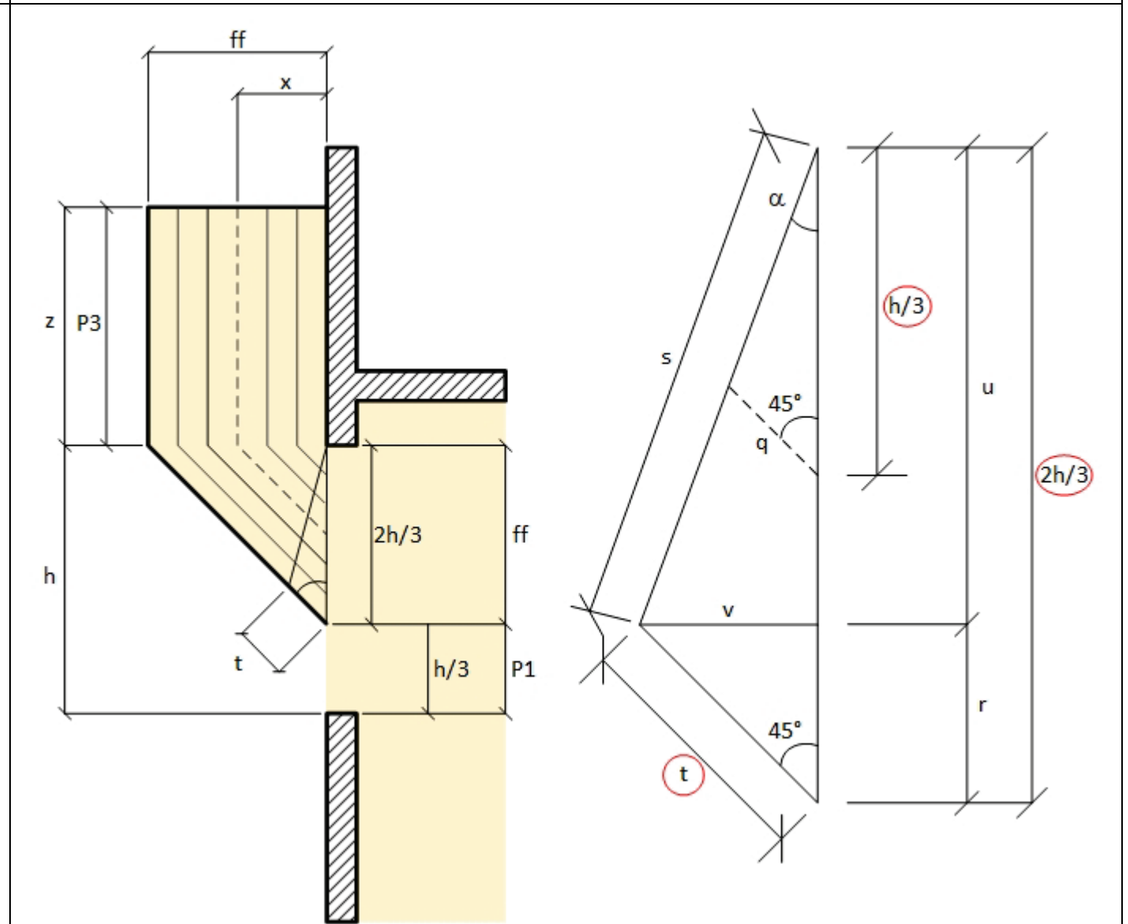
Parameter	Equation	Diagram
Simplification	$\frac{3t}{2h} = \frac{3q}{h}$ $q = \frac{1}{2}t$ $v = t \cdot \sin 45°$ $r = t \cdot \cos 45°$	

Figure J-3: Elevation view of Law notional flame extension from an opening with geometrical calculations

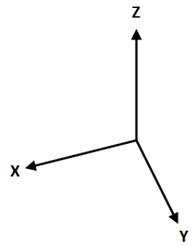
Equations

Plane 1

Single plane

Coordinates

Plane	x1	x2	y1	y2	z1	z2
P1	0	0	y_1	y_2	z_1	$z_1 + \frac{1}{3}(z_2 - z_1)$
						$\frac{1}{3}(z_2 + 2z_1)$



Plane 2

Incremental plane

Height Increments = h_i

Coordinates

Plane	x1	x2	y1	y2	z1	z2	*l*
$P2_1$	0	$h_i \sin 45°$	y_1	y_2	$\frac{1}{3}(z_2 + 2z_1)$	$\frac{1}{3}(z_2 + 2z_1) + h_i \cos 45°$	$\frac{1}{4}h_i$
$P2_n$	$(n-1) \cdot h_i \sin 45°$	$n \cdot h_i \sin 45°$	y_1	y_2	$\frac{1}{3}(z_2 + 2z_1) + (n-1) \cdot h_i \cos 45°$	$\frac{1}{3}(z_2 + 2z_1) + n \cdot h_i \cos 45°$	$h_i\left(n + \frac{1}{4}\right)$

Plane 3

Incremental plane

Height Increments = h_i

Coordinates

Plane	x1	x2	y1	y2	z1	z2	*l*
$P3_1$	$\frac{2}{3}(z_2 - z_1)$	$\frac{2}{3}(z_2 - z_1)$	y_1	y_2	z_2	$z_2 + h_i$	$\frac{\sqrt{2}}{3}(z_2 - z_1) + \frac{1}{2}h_i$
$P3_n$	$\frac{2}{3}(z_2 - z_1)$	$\frac{2}{3}(z_2 - z_1)$	y_1	y_2	$z_2 + h_i(n-1)$	$z_2 + n \cdot h_i$	$\frac{\sqrt{2}}{3}(z_2 - z_1) + h_i\left(n + \frac{1}{2}\right)$

Diagram

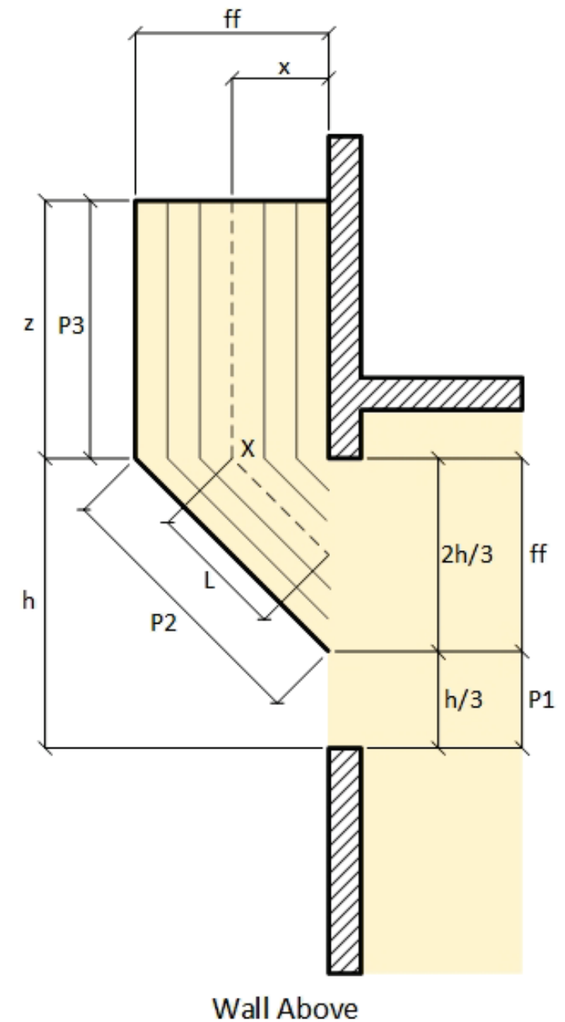


Figure J-4: Elevation view of Law notional flame extension from an opening – wall above

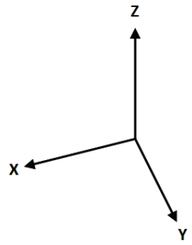
Equations

Plane 1

Single plane

Coordinates

Plane	x1	x2	y1	y2	z1	z2
P1	0	0	y_1	y_2	z_1	$z_1 + \frac{1}{3}(z_2 - z_1)$
						$\frac{1}{3}(z_2 + 2z_1)$



Plane 2

Incremental plane

Height Increments = h_i

Coordinates

Plane	x1	x2	y1	y2	z1	z2	*l*
$P2_1$	0	$h_i \sin 45°$	y_1	y_2	$\frac{1}{3}(z_2 + 2z_1)$	$\frac{1}{3}(z_2 + 2z_1) + h_i \cos 45°$	$\frac{1}{4}h_i$
$P2_n$	$(n-1) \cdot h_i \sin 45°$	$n \cdot h_i \sin 45°$	y_1	y_2	$\frac{1}{3}(z_2 + 2z_1) + (n-1) \cdot h_i \cos 45°$	$\frac{1}{3}(z_2 + 2z_1) + n \cdot h_i \cos 45°$	$\frac{h_i}{4}(2 \cdot n - 1)$

Plane 3

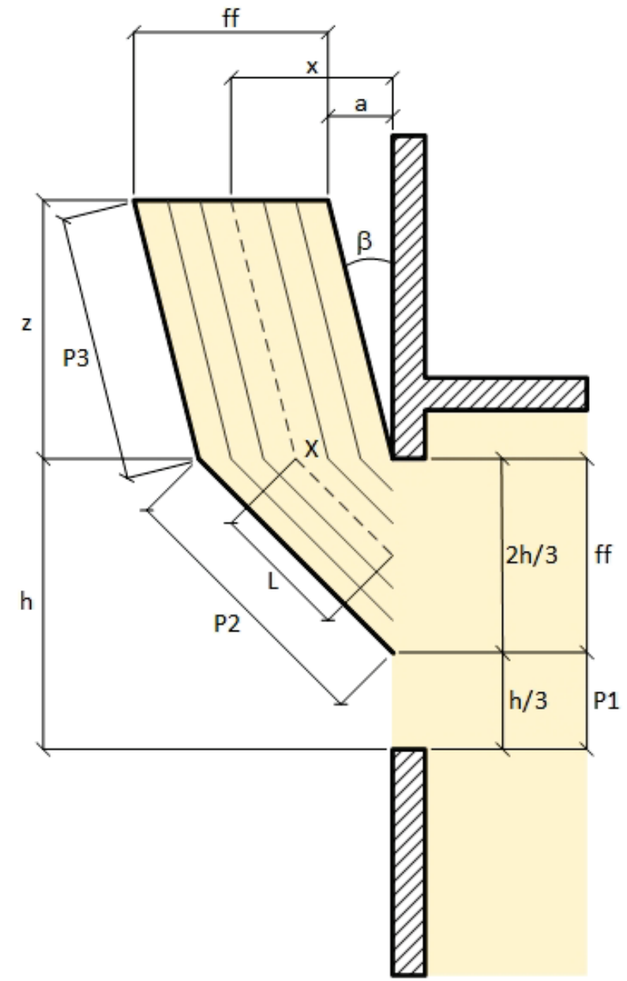
Incremental plane

Height Increments = h_i

Coordinates

Plane	x1	x2	y1	y2	z1	z2	*l*
$P3_1$	$\frac{2}{3}(z_2 - z_1)$	$\frac{2}{3}(z_2 - z_1) + h_i \sin\beta$	y_1	y_2	z_2	$z_2 + h_i \cos\beta$	$\frac{2\sqrt{2}}{3}(z_2 - z_1) + \frac{1}{2}h_i$
$P3_n$	$\frac{2}{3}(z_2 - z_1) + (n-1) \cdot h_i \sin\beta$	$\frac{2}{3}(z_2 - z_1) + n \cdot h_i \sin\beta$	y_1	y_2	$z_2 + h_i(n-1)\cos\beta$	$z_2 + n \cdot h_i \cos\beta$	$\frac{2\sqrt{2}}{3}(z_2 - z_1) + h_i\left(n - \frac{1}{2}\right)$

Diagram



No Wall Above

Figure J-5: Elevation view of Law notional flame extension from an opening – no wall above

Plane 1 Equations

Single plane

Coordinates

Plane	x1	x2	y1	y2	z1	z2
P1	0	0	y_1	y_2	z_1	$z_1+\frac{1}{3}(z_2-z_1)$
						$\frac{1}{3}(z_2+2z_1)$

Plane 1 VBA Code

```
Public Static Function P1_coordinates(x1 As Double, x2 As Double, y1 As Double, y2 As Double, z1 As Double, z2 As Double, c_type As String)
  Select Case c_type
  Case "x1"
    P1_coordinates = 0
  Case "x2"
    P1_coordinates = 0
  Case "y1"
    P1_coordinates = y1
  Case "y2"
    P1_coordinates = y2
  Case "z1"
    P1_coordinates = z1
  Case "z2"
    P1_coordinates = (1 / 3) * (z2 + 2 * z1)
  Case "L"
    P1_coordinates = 0
  End Select
End Function
```

Plane 2 Equations

Incremental plane

Height Increments = h_i

Coordinates

Plane	x1	x2	y1	y2	z1	z2	*l*
$P2_1$	0	$h_i \sin 45°$	y_1	y_2	$\frac{1}{3}(z_2 + 2z_1)$	$\frac{1}{3}(z_2 + 2z_1) + h_i \cos 45°$	$\frac{1}{4}h_i$
$P2_n$	$(n-1) \cdot h_i \sin 45°$	$n \cdot h_i \sin 45°$	y_1	y_2	$\frac{1}{3}(z_2 + 2z_1) + (n-1) \cdot h_i \cos 45°$	$\frac{1}{3}(z_2 + 2z_1) + n \cdot h_i \cos 45°$	$h_i\left(n + \frac{1}{4}\right)$

Plane 2 VBA Code

```
Public Static Function P2_coordinates(x1 As Double, x2 As Double, y1 As Double, y2 As Double, z1 As Double, z2 As Double, h As Double, n As Double, c_type As String)
  Select Case c_type
  Case "x1"
    P2_coordinates = (n - 1) * h * Sin(DtR(45))
  Case "x2"
    P2_coordinates = n * h * Sin(DtR(45))
  Case "y1"
    P2_coordinates = y1
  Case "y2"
    P2_coordinates = y2
  Case "z1"
    P2_coordinates = (1 / 3) * (z2 + 2 * z1) + (n - 1) * h * Cos(DtR(45))
  Case "z2"
    P2_coordinates = (1 / 3) * (z2 + 2 * z1) + n * h * Cos(DtR(45))
  Case "L"
    P2_coordinates = h * (n + (1 / 4))
  End Select
End Function
```

Plane 3 Equations

Incremental plane

Height Increments = h_i

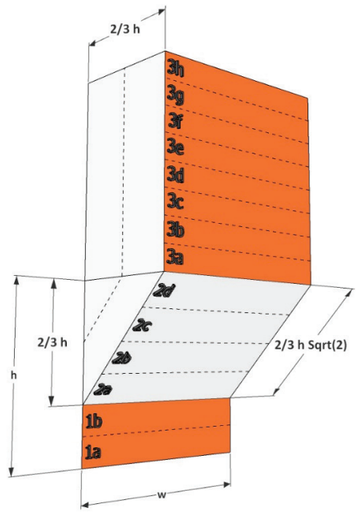
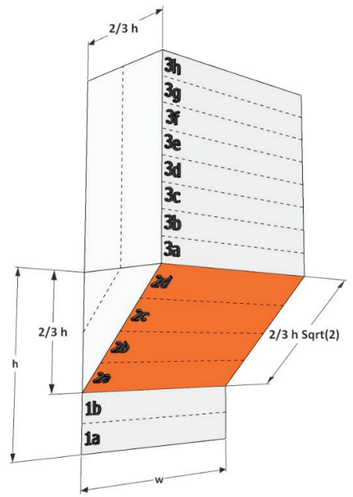
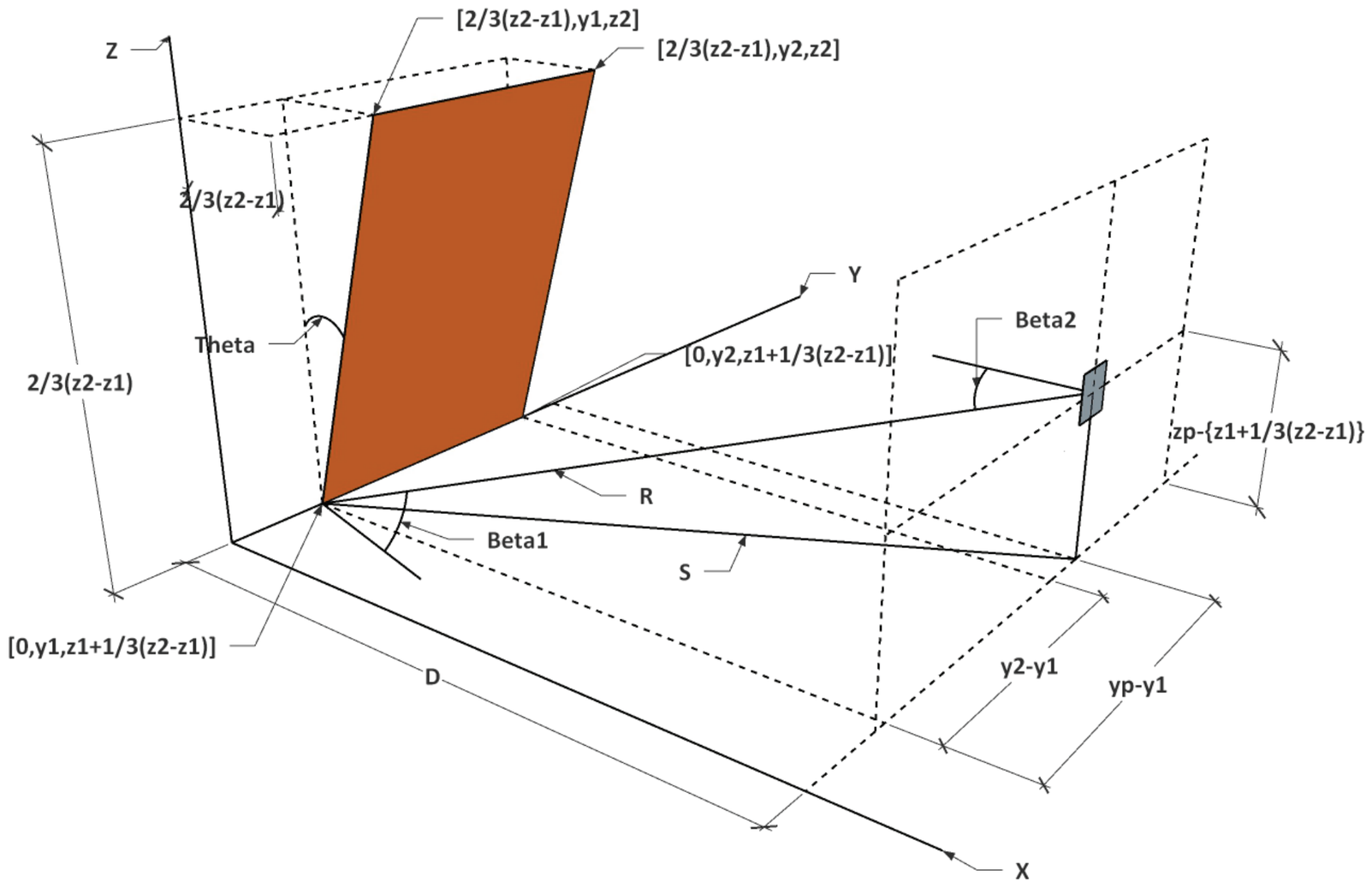
Coordinates

Plane	x1	x2	y1	y2	z1	z2	*l*
$P3_1$	$\frac{2}{3}(z_2 - z_1)$	$\frac{2}{3}(z_2 - z_1) + h_i \sin\beta$	y_1	y_2	z_2	$z_2 + h_i \cos\beta$	$\frac{\sqrt{2}}{3}(z_2 - z_1) + \frac{1}{2}h_i \cos\beta$
$P3_n$	$\frac{2}{3}(z_2 - z_1) + (n-1) \cdot h_i \sin\beta$	$\frac{2}{3}(z_2 - z_1) + n \cdot h_i \sin\beta$	y_1	y_2	$z_2 + h_i(n-1)\cos\beta$	$z_2 + n \cdot h_i \cos\beta$	$\frac{\sqrt{2}}{3}(z_2 - z_1) + h_i\left(n + \frac{1}{2}\right)\cos\beta$

Plane 3 VBA Code

```
Public Static Function P3_coordinates(x1 As Double, x2 As Double, y1 As Double, y2 As Double, z1 As Double, z2 As Double, Beta As Double, h As Double, n As Double, c_type As String)
  Select Case c_type
  Case "x1"
    P3_coordinates = (2 / 3) * (z2 - z1) + (n - 1) * h * Sin(DtR(Beta))
  Case "x2"
    P3_coordinates = (2 / 3) * (z2 - z1) + n * h * Sin(DtR(Beta))
  Case "y1"
    P3_coordinates = y1
  Case "y2"
    P3_coordinates = y2
  Case "z1"
    P3_coordinates = z2 + h * (n - 1) * Cos(DtR(Beta))
  Case "z2"
    P3_coordinates = z2 + h * n * Cos(DtR(Beta))
  Case "L"
    P3_coordinates = (Sqr(2) / 3) * (z2 - z1) + h * (n + (1 / 2)) * Cos(DtR(Beta))
  End Select
End Function
```

Appendix K
Configuration Factor Diagrams and Equations

Equations	Diagram
 Figure K-1: Isometric view of simplified vertical Law notional flame extension planes  Figure K-2: Isometric view of simplified angled Law notional flame extension planes	 Figure K-3: Configuration factor at a point of interest, offset from the centre of an opening angled relative to horizontal

$$\phi = \frac{AB \cdot Y + AC \cdot Y + (AD \cdot W + AE \cdot X) \cdot \cos\theta}{2\pi}$$ Equation K-6

Where:

$A = z1 - zp, \quad B = z2 - zp, \quad C = y1 - yp, \quad D = y2 - yp$

$E = A \cdot \sin\theta + d \cdot \cos\theta$

$F = A \cdot \sin^2\theta + \cos\theta \cdot (A + d \cdot \sin\theta), \quad G = A \cdot \sin^2\theta + \cos\theta \cdot (B + d \cdot \sin\theta)$

$H = A + E \cdot \sin\theta, \quad I = B + E \cdot \sin\theta, \quad J = \sin^2\theta + \cos\theta$

$K = A^2 + E^2, \quad L = B^2 + E^2, \quad M = C^2 + E^2, \quad N = D^2 + E^2$

$O = \frac{A}{\sqrt{M}}, \quad P = \frac{A}{\sqrt{N}}, \quad Q = \frac{B}{\sqrt{M}}, \quad R = \frac{B}{\sqrt{N}}, \quad S = \frac{C}{\sqrt{K}}, \quad T = \frac{C}{\sqrt{L}}$

$U = \frac{D}{\sqrt{K}}, \quad V = \frac{D}{\sqrt{L}}, \quad W = \frac{C}{\sqrt{M}}, \quad X = \frac{D}{\sqrt{N}}, \quad Y = \frac{F}{\sqrt{K}}$

$AB = \tan^{-1} S - \tan^{-1} U, \quad AC = \tan^{-1} V - \tan^{-1} T$

$AD = \tan^{-1} O - \tan^{-1} Q, \quad AE = \tan^{-1} R - \tan^{-1} P$

Appendix L
Furniture Data and Distributions

Table L-1: Model parameter inputs

Item_name	Selection Weight	Number	m_parameters				%m_combustible	length_m	width_m	height_m	Hc_parameters (MJ/kg)				Q_parameters (kW)				HRR_PUA	Fire_height_m	ignition_HF	material_ID	Sources
			m_dist_type	ma	mb	mc					Hc_dist_type	Hca	Hcb	Hcc	Q_dist_type	Qa	Qb	Qc					
Sofa	100	NA	Triangle	46	65	91	100%	2.18	0.86	0.46	Triangle	15	18	33	Triangle	1717	2073	2429	1645	0.46	12.5	POLYURETHANE	[437, 438]
Recliner_chair	100	NA	Triangle	27	41	53	100%	0.73	0.76	0.46	Triangle	15	18	33	Triangle	1054	1455	1856	680	0.46	12.5	POLYURETHANE	[437, 438]
Side_table	100	NA	Triangle	6	16	26	100%	0.55	0.55	0.50	Triangle	16	18	20	Triangle	442	883	1325	170	0.5	12.5	FIR	[437, 438]
TV	100	NA	Triangle	11	50	128	20%	1.32	0.10	0.74	Triangle	23	25	27	Triangle	216	249	281	170	0.742	12.5	POLYSTYRENE	[437, 438]
Entertainment_unit	78	s	Triangle	21	67	130	100%	2.19	0.35	0.86	Triangle	16	18	20	Triangle	1690	3739	5789	2550	0.86	12.5	FIR	[437, 438]
Coffee_table	77	s	Triangle	9	24	32	100%	1.38	0.65	0.52	Triangle	16	18	20	Triangle	1200	1843	2400	1420	0.52	12.5	FIR	[437, 438]
Bookcase	77	m	Triangle	10	30	48	100%	0.89	0.37	1.00	Triangle	16	18	20	Triangle	3000	3500	4000	2550	1.00	12.5	FIR	[437, 438]
Loveseat	55	m	Triangle	38	48	60	100%	1.72	0.90	0.46	Triangle	15	18	33	Triangle	1613	1726	1839	680	0.46	12.5	POLYURETHANE	[437, 438]
Side_table	42	m	Triangle	6	16	26	100%	0.55	0.55	0.50	Triangle	16	18	20	Triangle	442	883	1325	170	0.50	12.5	FIR	[437, 438]
Recliner_chair	10	m	Triangle	27	41	53	100%	0.73	0.76	0.46	Triangle	15	18	33	Triangle	1054	1455	1856	680	0.46	12.5	POLYURETHANE	[437, 438]
Magazine_rack	33	m	Triangle	6	11	15	100%	0.89	0.37	1.00	Triangle	16	18	20	Triangle	3000	3500	4000	170	1.00	12.5	FIR	[437, 438]
Ottoman	20	m	Triangle	32	35	40	100%	0.82	0.60	0.44	Triangle	16	18	20	Triangle	538	575	613	680	0.44	12.5	POLYURETHANE	[437, 438]
Desk	17	s	Triangle	19	43	56	100%	1.55	0.65	0.74	Triangle	16	18	20	Triangle	400	600	800	1420	0.74	12.5	FIR	[437, 438]
Computer	16	s	Triangle	23	30	40	100%	0.58	0.27	0.58	Triangle	18	20	22	Triangle	216	249	281	170	0.58	12.5	POLYSTYRENE	[437, 438]
Futon	13	s	Triangle	44	51	57	100%	1.34	1.87	0.17	Triangle	15	18	33	Triangle	1717	2073	2429	910	0.17	12.5	POLYURETHANE	[437, 438]
Phone_stand	3	m	Triangle	6	11	15	100%	0.50	0.50	0.50	Triangle	16	18	20	Triangle	221	442	662	170	0.50	12.5	FIR	[437, 438]