Challenges Faced in Application of Fire and Life Safety Design in Current Canadian Building Code

by

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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

In the interest of public safety, building designs and construction in Canada are regulated by local legislation which is typically a provincial, or as appropriate municipal, building code based on the National Building Code of Canada (NBCC). The current version of NBCC is an objective-based building code which allow code users to substitute prescribed building designs with a solution achieving the same level of performance defined by intent statements. These intent statements provide rationale behind prescriptive solutions including some degree of baseline as well as factors of safety for building design. However, due to its structure and for practical reasons, it does not and cannot envision every single design possibility in practice. In addition, its slow update cycle cannot keep up with technology advancements currently driven by concerns around energy efficiency, sustainability and development of new materials, and construction methods and climate change. These contribute to some of the challenges that may be faced in application of the NBCC which are investigated through the following five parameters: 'History and Scientific Background', 'Reliability', 'Economic Impact', 'Design Practicality' and 'Guidance for Compliance'.

In order to identify and assess the potential issues, three case studies involving atrium design, design for spatial separation of buildings, and finally, design of a building with exposed mass timber elements are presented. Through these three case studies, this thesis investigates technical challenges that exist in executing different design scenarios under the current NBCC. Further, the case studies identify several important factors that designers should be aware of to avoid inappropriate application of the prescriptive solutions specified by the code or, equally, inappropriate evaluations during assessment of an alternative solution through the performance-based approach to building design in the Canadian context.

Results lead to identification of challenges encountered in utilizing the current NBCC, not only in terms of achieving the intended level of performance of a design, but also, if desired, in pursuing appropriate alternative design solutions. One of the reasons is that the appropriate level of performance for building design is found challenging to establish, as the intent prescribed in the building code is qualitative while the potential catastrophic events considered could have a low probability but a significant consequence. In addition, these prescribed building code provisions may have limited background information or scientific

gaps, as well as outdated technology based on the state of art knowledge available at the time of establishment, some may be from as early as 1960s, leading to overly conservative or even inappropriate design decisions in the present building environment. Inconsistencies in recognizing the relative performance of modern technologies in these provisions are also identified, such as the approximately 90% effectiveness of sprinkler performance, which increases the complexity and uncertainty in building design and review, as they significantly impact the establishment of the baseline for compliant design as well.

Further, some important considerations are not appropriately addressed in the current NBCC. In some designs, costs of the acceptable solutions are demonstrated to be 44 times more than alternative solutions. Similarly, building design performance in natural disasters such as earthquakes is not accounted for. This could result in potentially high consequences. Finally, the current NBCC does not recognize social implications, sustainability, and environmental costs that have become contributing factors to building design, material selections, and construction practices towards a cleaner environment.

Lastly, limitations found in key aspects of design guidance can lead to inappropriate design when following prescriptive solutions specified by the code or, equally important, can lead to inappropriate evaluation during assessment of an alternative solution. Limited guidance and lack of quantitative assessment thresholds on how either the design team should generate, or how a local officer of the Authority Having Jurisdiction (AHJ) should review and evaluate these building design proposals in terms of their level of performance is provided in current building code. As a result, complex and sophisticated designs may require stakeholders to not only possess experience in industry, but also knowledge of modern research, technology, and fire and life safety risks and trade-offs. Such knowledge can only really be obtained through enhanced education which is limited in Canada currently. The existing level of the competence of both designers and reviewers may lead to inappropriate application of a code compliant fire safety solution, let alone an alternative solution to compliant design.

Based on the foregoing, a new paradigm of building design and evaluation in Canada is required. However, with the current Canadian building code environment and challenges identified in this thesis, a long path lies ahead waiting for exploration.

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1 Introduction

1.1 Where it all begins

It has been argued that one of the major distinguishing features between humans and other animals is the unique ability to make complex culture possible and preserve it through generations [1]. It is still unclear when and why human ancestors began to use tools for daily life. However, anthropologists have suggested that the action of toolmaking played a possible role in the emergence of human creativities which distinguish human culture from other species [2]. It is commonly considered that cultural heritage includes both tangible artefacts such as buildings, books, and works of art, as well as intangible attributes inherited from the ancestors to be passed on to the future generation [3]. Language may be a source of misunderstanding, traditions may be inaccessible to the common public, but buildings stand for a long period of time to tell the stories.

From the Great Pyramid of Giza to the Taj Mahal, and from the Great Wall of China shown in Figure 1.1 to the Sagrada Familia, these wonders left us with treasures of times that have been waiting to be discovered. Indeed, architectural work is a preservation of who we were and what historical society left us [4]. Some of them may represent the most advanced technology when they were constructed, while some of them may represent the spiritual or political values of the society at the time.

Figure 1.1.1 The Great Wall of China, the Jinshanling Section [5]

1.2 The Brief History of Building Code

The first known written principles of construction are found in Hammurabi's Code which dates back approximately 4,000 years ago [6]. Unlike modern building codes which include prescriptive provisions and objective methods to define how a building should be constructed and what requirements the construction would have to meet, these principles were written on the basis of the expected performance of the building to be constructed and the punishment that would occur if the building failed to meet these criteria. This is similar to what we now consider as a performance-based code for modern construction design.

Since then, building regulations around the world slowly evolved due to painful mistakes learned from the ancient society they were serving. After several devastating fire tragedies such as the Great Chicago Fire (1871) and the Great Baltimore Fire (1904) [7], an organization formed by the insurance industry, namely the National Board of Fire Underwriters, published the first known building code for application in United States in 1905 – *Recommended Building Code* [8]. After experiencing the conflagration initiated by the earthquake in San Francisco in 1906, a variety of stakeholders in the US, including members from the construction industry, building tenants and owners, engineering professionals, and the federal government, recognized the importance of publishing a comprehensive regulation to govern building construction. During the first few decades of the early 20th century, these stakeholders developed a series of construction regulations supported by the state-of-the-art building science and engineering research at the time.

Unlike our neighbour down in the South, the construction industry in Canada relied on local municipalities to establish building regulations, without technical backup, until the federal government established its first National Building Code for Canada (NBCC) in 1941 [9]. This first edition of the NBC was developed by the National Research Council of Canada (NRCC) and prescribed a series of requirements for different construction types. It has been documented in the literature that this first edition was largely based on the existing recommendations and standards available in the US at the time [10]. In addition, given the consideration of the limited capacity in smaller municipalities, NRCC published "*A Building Code for Small Municipalities*" in 1951. This code was developed with aim to provide prescriptive requirements particularly suitable for those municipalities which did not have professional engineering support in their building departments [9]. Some of the provisions in these standards are arbitrary in origin and all are limited to the scientific background knowledge available at the time of preparation. Recognizing the significance of rationalized uniform building regulations throughout Canada, the 2nd and the 3rd editions of the NBCC were published in 1953 and in 1960 respectively, which started the current regular cycle of NBCC updates. The approximate 5-year update interval was intended to keep building regulations up to date with modern research and input and changes from the industry [9, 10]. It is noted that, in the development of the NBCC 1960, an attempt was made to include a design framework, namely "*long-term approach",* to building design. This framework can be regarded as a "*Hazard Recognition & Mitigation"* methodology. The framework, as documented in recent research, allows building designers to identify and assess the potential severity of fire risk in a building based on several fire protection strategies. These include limitations on building area and definition of appropriate spatial separation. Once a threshold level of risk is identified, building design could follow the technical assessment outlined in the framework to provide mitigating features to address any concerns [10]. This approach could have been a prototype for performance-based design methodologies in the modern building code. Unfortunately, the approach was suspended in the 1960 code-update cycle due to the need for an ongoing and excessive technical review process to maintain the approach [10] combined with lack of the financial support from the government for such a process.

1.3 Objective and Organization of this Thesis

The objective of this thesis is to investigate and define some of the difficulties that may be encountered when preparing building designs that do not directly comply with the acceptable solutions prescribed in Division B of the Canadian Building Code. In order to identify and assess potential issues, three case studies involving atrium design, design for spatial separation of buildings, and finally design of a building with exposed mass timber elements are presented. Through these three case studies, this research investigates technical and economic challenges that exist in executing different design scenarios under our current building code. Further, the case studies identify several important limitations that can lead to inappropriate design when following the acceptable solutions prescribed by the code or, equally important, can lead to inappropriate evaluation during assessment of an alternative solution developed using the objective-based approach to building design in the Canadian context.

Chapter 2 of this thesis presents the current building design framework specifically related to Fire and Life Safety provisions that are prescribed in the NBCC. Followed by the Canadian building industry, two options to achieve compliance are presented: either through the direct application of the acceptable solutions in the Division B of NBCC or through development of an alternative solution design accepted by the local AHJ with documentation demonstrating that its level of performance is equivalent to the ones prescribed in NBCC. Literature review and summary of findings through practical application of current code are also presented in Chapter 2 to identify the challenges that create barriers for the use of the NBCC in building design and evaluations. Key areas of challenges including History and Scientific Background, Reliability, Economic Impact, Design Practicality, and Guideline for Compliance.

Chapter 3 of this thesis presents three case studies involving atrium design, design for spatial separation of buildings, and finally design of a building with exposed mass timber elements to demonstrate and analyze differences in the level of performance obtained between code compliant solutions and several objective-based alternative approaches that also attain building code compliance. These case studies identify several important factors that designers should be aware of to avoid inappropriate application of the acceptable solutions prescribed by the code or, equally, inappropriate evaluations during assessment of an alternative solution through the performance-based approach to building design in the Canadian context.

Based on analysis of the case studies presented, Chapter 4 presents conclusions on identification of challenges encountered in utilizing the current NBCC, not only in terms of achieving the intended level of performance of a design, but also, if desired, in pursuing appropriate alternative design solutions. Limitations found can lead to inappropriate design when following acceptable solutions prescribed by the code or, equally important, can lead to inappropriate evaluation during assessment of an alternative solution under the objective-based approach. It further outlines recommendations for future studies into the development of the current building code as pertaining to potential adoption of a performance-based building code for the Canadian Building code environment.

2 Background

In the interest of public safety, building designs and construction are expected to follow the local legislation which, in Canada, is typically a provincial, or as appropriate municipal, building code. To promote consistency of building design and construction throughout Canada, while maintaining flexibility for local specialties, NRCC published the National Building Code of Canada (NBCC) to be adopted with or without amendment by provincial and territorial governments [11]. The current edition of NBCC is NBCC 2020. This legislation may further be modified by each AHJ to suite their local needs. For example, the Province of British Columbia adopted NBCC 2015[1] with considerable local variations and published the British Columbia Building Code (BCBC) 2018, pursuant to the Building Act [12]. Similarly, the City of Vancouver also published the Vancouver Building Bylaw (VBBL) 2019 which is substantially based on the national model codes.

Currently, there are three main design formats used in building regulations around the world: prescriptive-based, objective-based, and performance-based design.

The prescriptive-based code format prescribes lists of building design and construction provisions that building designers are required to incorporate appropriately into their final design. These provisions are specific and quantitative; for example, prescribing a maximum building area for a certain type of occupancy and construction material. This format supports an efficient building design and review process as it is straightforward to determine compliance with the code. It does not, however, provide any flexibility or alternative approaches to building design if the prescriptive design cannot be achieved.

The objective-based code format prescribes lists of building design and approaches for building design to follow as well [13]. However, it further provides objectives and functional statements which provide qualitative intent attributed to the majority of the building design provisions in the NBCC [14]. This format supports an alternative design solution in lieu of the acceptable solutions in the NBCC,

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[1] It is noted that NBCC 2020 was published on March 28, 2022, however, by time this thesis is accepted, it has not been adopted to be enforce by any jurisdiction in Canada. Therefore, the discussion is based on older version which is NBCC 2015.

provided the alternative design would achieve the same level of performance. One of the limitations of this format is that it provides limited if any methods to quantitatively compare levels of performance [15].

A performance-based code on the other hand, focuses on the overall building performance [16]. It typically prescribes only the objectives and functional statements based on societal expectation for building designs and leaves it to the design team to detail the layout and systems required to satisfy the necessary level of performance of a given design [15]. It provides flexibility to the design team as there is no fixed baseline to follow; however, it also has limitations in that this approach may require advanced and experienced design and review teams to properly vet all the necessary details of the building design [16].

Prior to the 2010 Edition, the NBCC was a prescriptive-based building code, and thus included listings of acceptable design provisions only. After 2010, the NBCC was reconfigured as an objective-based building code in order to permit a certain level of flexibility in building design and allow for innovation [15].

2.1 Current Canadian Building Code Framework

Between the 1960s and 1990s, the NBCC was updated through a limited level of model code development and public review process. In 2005, the NBCC undertook the significant change from being a prescriptive-based building code to being reformulated in an objective-based format [15]. This format consists of three Divisions: Division A contains the compliance requirements and applicable provisions as well as the objectives and functional statements attributed to the code; Division B outlines acceptable solutions prescribed for building design which are typically recognized as Division B solutions; and lastly Division C discusses the administrative provisions of the code [11]. This change has been maintained since its publication and the latest edition of NBCC - National Building Code of Canada (NBCC) 2020, which was published in December 2021, follows the same guidance.

This thesis focuses on the fire and life safety aspect of building design. Therefore, relevant application of the intents and objectives outlined in Division A are reviewed in conjunction with building design provisions outlined in Part 3, Division B of the NBCC. As such, the following discussions are limited to application of these parts of the NBCC, only referencing other sections as appropriate to specific discussions.

The change from a wholly prescriptive version of NBCC to an objective-based format was prompted by a recognition that the prescriptive provisions in the building code would not be able to cover all possible design conditions and keep up with the latest technology development. Thus, the code provisions are supplemented by detailed objective and functional statements in Division A that can be used in developing alternative designs. The objective statements include safety, health, accessibility, and fire/structural protection [11]. More specifically, they can also relate to safeguarding people from injury and protecting other property [17]. The 100 functional statements prescribe the expected performance of the building and its elements that are necessary to assess and comply with a set of selected objectives for each design. Therefore, together, these encompass the intents behind the Division B acceptable solutions, while at the same time facilitating innovation in construction to meet the rapid development of the world in the early 21st century.

Division A, Part 1 of NBCC 2020 indicates that there are two methods of achieving compliance with the code. A designer can either follow Clause 1.2.1.1.(1)(a) to use an acceptable solution prescribed in Division B of the code (Division B solution), or can follow Clause 1.2.1.1.(1)(b) to use an alternative solution accepted by the appropriate AHJ for the location typically in which the building is to be constructed.

In the latter situation, the alternative solution is required to satisfy the minimum level of performance required by Division B solutions in the areas defined by the objectives and functional statements attributed to the applicable prescriptive provisions in the code. It is further elaborated under Appendix A to Division A Part 1 of NBCC 2020 [11], that an alternative solution must be deemed to satisfy the objectives and functional statements linked to those specific provisions:

> *Where a design differs from the acceptable solutions in Division B, then it should be treated as an "alternative solution." A proponent of an alternative solution must demonstrate that the alternative solution addresses the same issues as the applicable acceptable solutions in Division B and their attributed objectives and functional statements. However, because the objectives and functional statements are entirely*

> *qualitative, demonstrating compliance with them in isolation is not possible. Therefore, Clause 1.2.1.1.(1)(b) identifies the principle that Division B establishes the quantitative performance targets that alternative solutions must meet. In many cases, these 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. Nevertheless, Clause 1.2.1.1.(1)(b) makes it clear that an effort must be made to demonstrate that an alternative solution will perform as well as a design that would satisfy the applicable acceptable solutions in Division B – not "well enough" but "as well as."*

A simplified approach to compliance with prescriptive and alternative solutions under NBCC is illustrated in Figure 2.2.1.

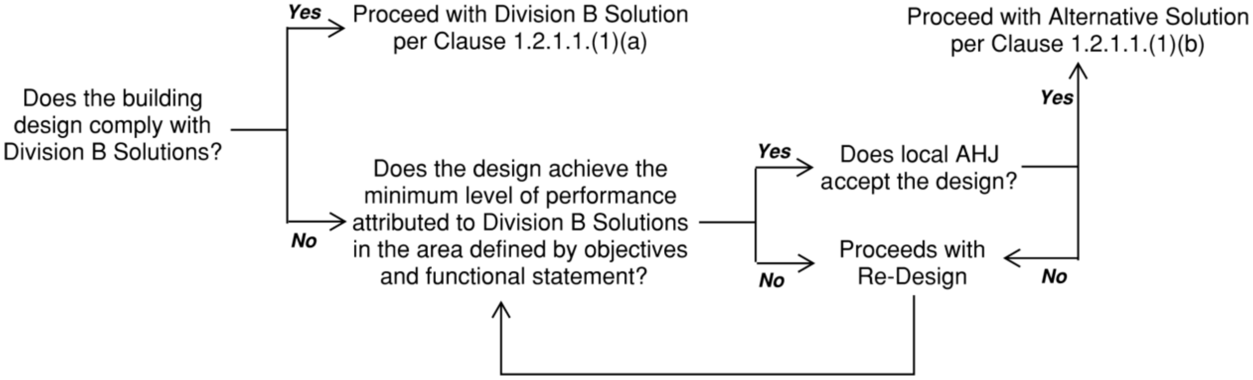

Figure 2.2.1 Illustration of Building Code Compliance in NBC 2020

As shown, if the building immediately complies with the Division B solution, then it will be compliant. On the other hand, if it does not immediately comply, the objective-based approach will be followed to develop an alternative solution. This solution must qualitatively meet the level of performance estimated through the objective and functional statements appropriate to the corresponding Division B solution. Once the solution is believed to satisfy the prescribed level of performance, it must be accepted by the local AHJ before it is constructed. If the local AHJ does not approve the alternative design, then the design must be iterated to meet not only the required minimum performance standards, but also the scrutiny of the local AHJ. Therefore, buildings or structures currently constructed in Canada can follow a design based on either the acceptable criteria written in Division B of the effective version of the building code, or the alternative solution approach of achieving the minimum level of performance of the building code with acceptance by a local AHJ.

In future approaches within the NBCC, one could envision that there would be more quantitative definitions of a set of acceptable levels of fire and life safety performance for buildings, potentially still defined in the context of current objectives and intents in Division A. With this type of format, the code would be more open and flexible in adapting to technological changes within the industry. Designers would be given scope to be more innovative as they would not be expected to comply with Division B solutions. At the same time, any such change would need to be coupled with evaluation and acceptance by an appropriate AHJ. This could open the way for pursuing performance-based design in NBCC. Division B could still be maintained for appropriate subset of building designs and reviews.

At present, however, there can even be difficulties encountered when following the existing objective-based approach when preparing building designs that do not directly comply with the acceptable solutions prescribed in Division B of the Canadian Building Code. As such, the case studies in this thesis are intended to investigate some of the technical and economic challenges currently faced by designers in executing different scenarios under our current code. By identifying some of the existing limitations that may lead to inappropriate design or inappropriate evaluation of acceptable and alternative solutions, this research forms one initial step toward more open, performance-based approaches to design in future Canadian building codes.

2.2 Challenges Faced in Application of NBCC

The current objective-based NBCC has shown advantages for some applications, as the objectives and functional statements provide a rationale behind the prescriptive provisions and respect the flexibility of building design. It also provides some degree of baseline for minimum requirements and factors of safety for building design [11]. However, due to its structure and for practical reasons, objective-based codes, including the NBCC do not and cannot envision every single design possibility in practice [14, 17]. In addition, the slow update cycle of the NBCC means that development of new provisions in Division B cannot keep up with the fast pace of technology advancement, currently driven by concerns around energy efficiency, sustainability and development of new materials, and construction methods and climate change

[14, 18]. These contribute to challenges faced in application of NBCC which are further discussed under the broad headings of ‘History and Scientific Background’, ‘Reliability’, ‘Economic Impact’, ‘Design Practicality’ and ‘Guidance for Compliance’ in the following subsections.

2.2.1 History and Scientific Background

The first edition of the NBCC was published in 1941 [9] and the original provisions have gone through several rounds of updates since that time. A regular 5-year, consensus-driven change and update cycle has been in place since publication of the 1995 edition [9]. Recent reviews of the documents supporting some of the code changes over that time have indicated that all, or part, of the connection to the original fundamental scientific foundations for some of the provisions may have been lost [10]. As such, there may be insufficient, or outdated, scientific background incorporated into some of the provisions in Division B. Without the rationale behind specific performance criteria, it is difficult to evaluate how any alternative design approach can achieve the same level of performance anticipated for a prescriptive (Division B solution) [17]. For example, with respect to the building area limitations in the NBCC, which will be further discussed in Case Study 3 in Chapter 3 of this thesis, the maximum building area allowed for combustible construction is limited to only 80% of the building area permitted for noncombustible construction with same building height and same occupancy. Researchers could not find the rationale for this limit, nor could they determine whether other factors were considered when this criteria was established at the time of the code development [10]. Yet, in the current Canadian regulatory environment, designers are bound by the building area limit for combustible construction that is specified in the code, regardless of whether they may have incorporated any other building components which could contribute to providing the same level of performance as would be required for noncombustible construction.

In other areas, examples can be seen where the scientific bases for the provisions have lagged the recent rapid evolution in knowledge of fundamental fire science and engineering [14]. For example, research into the impacts of sprinkler on fires has been vastly advanced in the last decades [19], but some of the sprinkler related provisions in the NBCC have remained the same since their introduction in the

1980s [20]. The impact of this on innovative building design will be demonstrated in Case Study 2 in Chapter 3.

2.2.2 Reliability

An objective-based building code includes objectives and functional statements attributed to each code provision, but the code documentation is generally lacking provisions or guidelines in terms of how a designer should take a systematic or holistic view of the building systems or design from the perspective of risk and reliability [10, 16, 21]. As a result, the same design objectives can be found in several sections in the code as related to different aspects of their application to a design. As will be demonstrated in Chapter 3 – Case Study 1, the repetition of intent statements in the NBCC creates confusion and can often lead to conservative layers of protection in a final building design.

In other situations, some key elements that need to be addressed during building design are easily related to specific criteria, while other related aspects of the building design, which are not directly related to those criteria, cannot be fully taken into account in the alternative design solution. Take building construction material for example; the use of the combustible material is limited to building with relatively small building sizes (both footprint and height) with the intent including to limit the probability of fire spread and/or structural failure in fire emergencies. However, directly connecting allowable building size with the use of combustible materials does not allow a designer to account for use of other fire safety systems that can significantly influence the building performance. These might include inherent material characteristics under exposure to fire, in contrast to the standard test which is used to determine combustibility [22], or inclusions of an optimized sprinkler system design and layout. The detrimental impact of this to innovative building design will be demonstrated in more detail in Chapter 3 – Case Study 3, in an example where the acceptable Division B solution isolates fire and life safety intent without considering the overall building performance.

A significant aspect that has not typically been explored and is not included in the current NBCC, is the relative reliability of acceptable Division B solutions versus potential alternative solutions over time and/or when subjected to local natural conditions. In the first instance, reliability can be affected by change of use, renovation or lack of maintenance, for example. In the latter, from tornado to flood, from earthquake to wildfire, different provinces may have a different level of potential exposure to natural disasters [23]. Although the NBCC permits a local government to adopt the code-prescribed provisions with specific construction criteria tailored to their own regions [11], in other areas within the current Canadian Building Code system, no account is taken of the impact of these natural hazards on overall building design. These considerations will be discussed in context of fire safety designs in both Case Study 2 and 3 in Chapter 3.

2.2.3 Economic Impact

Construction and building development is a cost-driven industry. As a result, the project owners typically consider a new building project from all aspects including the project schedule and cost effectiveness. In this light, some acceptable Division B solutions may result in ineffective use of space which translates into a loss of profit to a project as further demonstrated in Chapter 3 Case Study 1. In other cases, complying with Division B fire safety solutions lead to significant increases in construction cost, especially with innovative designs such as illustrated in Chapter 3 Case Study 2. Both situations may lead to abandonment of projects that otherwise would have been at the forefront in building innovation and design~~s~~.

2.2.4 Design Practicality

Buildings are expected to stand for long periods of time with landmark heritage buildings expected to last more than a hundred years. As a result, some of the Division B solutions may present challenges at other times during their life cycle since they neglect potential maintenance issues or functional changes that the building may go through over a lifetime. While currently not considered in the NBCC, some of these issues can be shown to result in issues of reliability with the acceptable Division B design solutions possibly even to the extent that the design no longer achieves the minimum requirements for the intended functions. This situation is demonstrated in Case Study 2 in Chapter 3, where the impact of the maintenance and building alteration on an example acceptable design approach will be explored.

2.2.5 Guidance for Compliance

Independent of building design, application of the NBCC involves not only the design team and development group but also the local AHJ who enforces the code provisions through review and approval of building design and construction [11]. In this respect, the objective-based format of the NBCC, while intending to encourage flexibility in building design, still presents challenges at the review stage [21]. This is because in order to be compliant with the NBCC, a building needs to either conform entirely to the prescriptive solutions available in Division B of the NBCC or, if it is an alternative solution, it must be shown to achieve the level of performance required to satisfy the intent behind that prescriptive solution. Evaluation of alternative solutions is therefore complicated by the lack of clear guidance for evaluating the level of performance of a building relative to prescriptive solutions in the code. Objectives and functional statements of the NBCC are qualitative [21]; for example, objectives, functional statements, and intent attributed to Sentence 3.4.2.5.(1) of Division B, Part 3 of the NBCC, which prescribes locations of the exits for occupant evacuation is noted in Table 2.2.5.1. The intent uses wording such as *" ... to limit the probability ..."* which does not provide any statistical, mathematical, or numerical basis for comparison of the design. Thus, the qualitative nature of the current objective-based design methodology adds a layer of difficulty and required expertise in the evaluation process for alternative solutions [24]. This can contribute to confusion in determining whether a design satisfies the appropriate code objectives and consequently results in an inefficient review process and potentially to more stringent building design constraints in some cases.

Table 2.2.5.1 Objective, Functional Statement and Intent Statement for Sentence 3.4.2.5.(1)

Code Reference	Functional Statement	Objective Statement	Function	Link	Objective
Sentence 3.4.2.5.(1)	F10	OS3.7	To facilitate the timely movement of persons to a safe place in an emergency	so that	persons in or adjacent to the building are not exposed to an unacceptable risk of injury due to their being delayed or impeded in moving to a safe place in a fire emergency.
Intent Statements					
The intent is to limit the probability of excessive travel distances to an exit 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.					

These may have significant impact in terms of cost and building design, leading to abandonment of the alternative solution approach. The associated lack of ability to pioneer new building designs can, in turn, lead to a slowdown in advancing the entire building industry which relies on the application of creativity in the real world to inspire generations to come.

The lack of guidance in comparative assessment of alternative and prescriptive designs also impacts stakeholders throughout the building design process. Figure 2.2.5.1 is an attempt by the author to present the simplified example which categorizes building design stakeholders based on different scales, such as background, level of experience, level of education, and their contribution and recognition in industry. From the *general public*, there are people who specifically work in *building industry*. This *building industry* category includes building contractors and trades, designers, developers, and material manufacturers all coming from different backgrounds and serving different purposes, such as the developer who may be looking for profits, and the designer who may seek innovative new designs. Inside this category, *experienced personnel* are recognized to separate people in the *building industry* with more technical experience since members of the entire group may range from foremen, construction site supervisors to designers or building inspectors, all with different levels of experience. It becomes difficult to define "level of experience" too finely and attribute that to an appropriately selected group, as background and standards may differ from person to person. The next category is "*professionals"* who either possess a professional status such as "Professional Engineer" or "Registered Architect" and therefore are licensed by a regulatory body. Typically, stakeholders in this category would require an accredited educational background and defined years of experience in the industry. Within this group fall the final two categories of "*practical researcher"* and *"recognized expert"*. While it may be challenging to define these categories, stakeholders in both would have a level of experience in industry either from pursuing research on specific topics or alternately related to roles in which they have to recognize issues and concerns embedded in current NBCC. Thus, the *practical researcher* may be someone who has spent time investigating or developing solutions for specific situations while *recognized expert* may have proven competence in specific area through already successfully developing design solution to address some of the concerns.

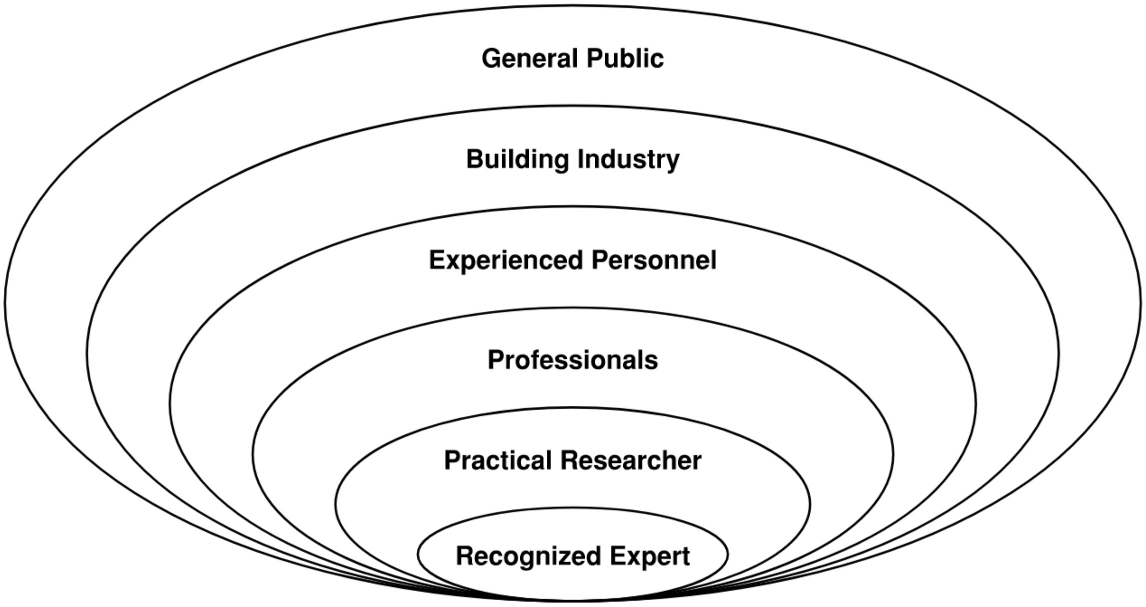

Figure 2.2.5.1 Illustration of Personnel with Different Background [25]

In many cases, without clear and quantified performance metrics, it is difficult for some of these stakeholders to appropriately vet proposed alternative designs. For example, the code officer (typically referred to as AHJ), who is required to review the proposed innovative designs may not possess a level of knowledge or education comparable with the building design engineers or the experience of those in the last two stakeholder categories. Even when stakeholders do possess the necessary technical capability, lack of guidance and flexibility in the alternative design evaluation and acceptance systems result in wide-ranging interpretation of acceptable performance, as well as inappropriate measures with which to compare and assess them [13]. Due to the nature of the design guidance which relies on the parameters outlined previously, as well as the status of the stakeholders, this parameter will be briefly reviewed at end of each case study presented in Chapter 3.

2.3 Summary

This Chapter discussed the current Canadian Building Code framework and the two options by which a building design can be shown to achieve compliance: either through direct application of the design options prescribed in Division B of the NBCC, or through development of an alternative design solution accepted by a local AHJ with documentation explaining how it satisfies equivalent performance to that defined through the intent(s) outlined in the corresponding building code provisions.

Since the current Canadian Building Code is an objective-based regulation, a review of the literature and current code applications identified challenges that create barriers for use of the code in alternative building design and evaluation. These are summarized into the following key areas of

- History and Scientific Background
- Reliability
- Economic Impact
- Design Practicality
- Guidance for Compliance

The following Chapter will explore and illustrate these issues in more detail through use of specific case studies related to atrium design, spatial separation of buildings, and building design involving exposed mass timber elements. The impact of the lack of guidance for assessing compliance of each design situation will also be explored at the end of each case study. Based on the case studies, conclusions will be drawn and recommendations for future work will also be presented.

3 Case Study

Three case studies related to atrium design, spatial separation of buildings, and building design involving exposed mass timber elements are developed based on hypothetical, but commonly encountered, building characteristics to evaluate potential limitations in application of objective-based design principles outlined in NBCC 2020.

Each case study opens with an introduction to the design situation, including the applicable intent statements and building code provisions (Division B solutions) from a fire and life safety perspective. The hypothetical building characteristics are presented to establish the important factors necessary for the subsequent analysis. In each case, the levels of performance of the determined Division B solutions are outlined as appropriate to document the effectiveness of these reference solutions and highlight potential concerns via the four parameters outlined in Chapter 2: fire science and background, design reliability, economic impact, and design practicality. Case Study 1 – Atrium Design reviews the Division B solution for an atrium design focusing on occupant evacuation. Through this case study, potential gaps between Division B solutions and appropriate level of occupant safety are identified. Following this, for Case Study 2 – Spatial Separation and Case Study 3 – Mass Timber Construction, the applicable Division B solutions are presented and discussed. Alternative design solutions are then developed and compared to the reference solutions. The level of performance achieved in the two solutions are assessed and compared. Observations related to the effectiveness of each solution and potential concerns encountered during the analysis are summarized at the end of each case study.

None of the three case studies presented herein represent any specific project and/or relevant building shareholders' perspective. Instead, the case studies reflect typical design challenges encountered in the current Canadian code environment as extracted from real situations for the purposes of this thesis. All three case studies are assumed to be located either in City of Vancouver or City of Richmond, for which the applicable building codes are Vancouver Building Bylaw 2019 Edition (VBBL 2019) and British Columbia Building Code 2018 Edition (BCBC 2018), respectively. Both codes are substantially based on the NBCC (2015) with specific provisions applicable to those local regions. Review of the Division B provisions in both the VBBL or the BCBC and the NBCC indicates that the same minimum standards and objectives attributed to the Division B solutions for these case studies. Therefore, for the purposes of this Chapter, provisions and objectives of VBBL or BCBC will be used.

3.1 Atrium Design

3.1.1 Introduction

The first case study relates to application of Division B solutions for evacuation from an atrium area in the event of a fire. The term atrium or interconnected floor space (IFS) refers to stacked and superimposed floor areas where the individual floor assemblies contain unprotected openings that are aligned to create a path for free air movement vertically through the space. The concept comes from open courtyard spaces in the center of Ancient Roman houses. In modern architecture, an atrium design offers a visual connection between floors as well as admitting natural lighting into the interior space. This is typically achieved by introducing full height glazing panels or guardrails along the perimeter of the floor openings. The free air flow between the storeys provides the opportunity for smoke from a fire to travel between floors which poses risks to public safety. As a result, there are specific provisions in the current NBCC regulating the design approach needed to achieve the code specific intents for fire safety when there are interconnecting floors within the building.

In this subsection, a hypothetical case study related to atrium design is presented to demonstrate the background and level of performance of a code compliant Division B solution under the current Canadian Building Code environment. This case study is simplified to focus only on occupant evacuation. The performance of the applicable Division B solutions is evaluated through the parameters listed previously. As a reference case, this evaluation allows identification of important design factors that should be considered during appropriate application of acceptable Division B solutions, as well as considerations that should be made when developing optimal alternative solutions using an enhanced performance-based approach.

3.1.2 Building Characteristics

A 4-storey office tower located in downtown Vancouver will incorporate a vertically continuous atrium that spans all four storeys as shown in Figure 3.1.2.1. The building is sprinklered to applicable design criteria [26], and has the following characteristics:

- 4 storeys high, all levels will be interconnected.
- Building will be of noncombustible construction with sprinkler protection to NFPA 13 standard.
- Building area is approximately 5,600m^2 with Group D (office) major occupancy.
- Atrium will be at the centre of the building with an area of 60m x 60m.
- Each storey has a ceiling height of 4m and the atrium ceiling height is 18m.
- Three exit staircases serve each floor.

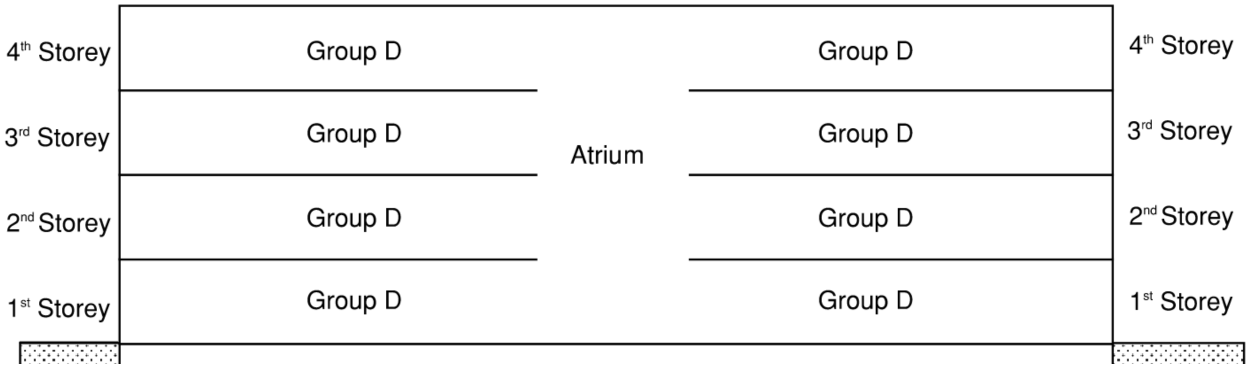

Figure 3.1.2.1 Sketch Illustrating Building in Case Study 1

The number of anticipated occupants on each storey is included in Table 3.1.2.1.

Table 3.1.2.1 Number of Occupants on Each Storey

Storey	Number of Occupants
1st Storey	313
2nd Storey	313
3rd Storey	300
4th Storey	525

3.1.3 Division B Solution

3.1.3.1 Introduction

The acceptable solutions for atrium design are included in Subsection 3.2.8 in Division B of the VBBL 2019. This lists two different methodologies that can be used to achieve code compliance for an atrium design [26]:

> ***Sentence 3.2.8.1.(1)*** *of the Vancouver Building Bylaw 2019 (VBBL) requires the portions of a floor area or a mezzanine that do not terminate at an exterior wall, a firewall, or a vertical shaft to:*
>
> *a. terminate at a vertical fire separation having a fire resistance rating not less than that required for the floor assembly and extending from the floor assembly to the underside of the floor or roof assembly above, or*
> *b. be protected in conformance with the requirements of Articles 3.2.8.3 to 3.2.8.8 (full atrium design).*

In addition, there are several provisions in Article 3.2.8.2 of VBBL which waive the requirements for a fire separation around the floor opening to permit interconnections under certain circumstances. However, as the case study does not fit into any of these provisions, they will not be discussed further here. Rather, the two acceptable solution methods in this case study can further be described as follows:

- ***Fire Separation from Atrium:*** The space on the upper storeys and the atrium space in this case are separated by fire rated assemblies with typical fire resistance ratings prescribed based on the construction requirement (varies from 45 minutes to 4 hours subject to the construction provisions). Therefore, these upper storey spaces would be treated via a normal floor area design; or
- ***Full Atrium Design:*** The floor area will not be required to be separated from the atrium provided the construction of the floor area follows the full atrium design provisions prescribed in VBBL, namely, Article 3.2.8.3 to 3.2.8.8.

Interestingly, observations of existing atria indicate that some of these acceptable solutions may not be used. A comparison of the acceptable Division B solutions to what is typically seen in current building atrium designs are illustrated in

Table ***3.1.3.1***.

Table 3.1.3.1 Full Atrium Design Provisions (Article 3.2.8.3 to 3.2.8.8) in VBBL 2019 [26]

Building Code Provision	Division B Solutions	Typical Building Design
Article 3.2.8.3 Sprinkler protection	Sprinkler designed to NFPA 13.	Usually, the default building design in modern construction industry
Article 3.2.8.4 Smoke protection of exits and elevators	Vestibules to be provided at any openings, elevators serving more than just IFS and exit opening directly into the atrium. Or exit opening into the atrium to meet cumulative exiting or be provided with protected floor space.	Commonly designed through alternative solutions
Article 3.2.8.5 Exiting	Provide protected floor area via: - Cumulative exiting for all IFS floors, or - Stair treads and landings is not less than 0.3m^2 times total occupant load in IFS, or - Protected floor spaces connecting directly to an exit and not less than 0.5m^2 of occupant load of each floor in IFS and are separated from IFS by a 2 hour fire separation.	Commonly designed through alternative solutions
Article 3.2.8.6 Fire Detection	500mm deep draft stops at the edge of floor openings. Smoke detectors provided in vicinity of draft stops. Closely spaced sprinklers may be required at draft stops per NFPA 13 if floor opening dimension is less than 1000sf in area and has a dimension less than 20ft.	Usually, the default building design in modern construction industry
Article 3.2.8.7 Smoke Exhaust	Manual exhaust at 4 air changes/h for the atrium and connected floor areas.	Mechanical system with certain air flow is typical in modern building design
Article 3.2.8.8 Fuel content limit	Combustible content limit of 16g/m^3 within the IFS where the ceiling height exceeds 8m (combustible content generally refers to furniture, excludes interior finishes).	This would typically be achieved by limiting the furniture within the space

Some of these considerations are addressed within other Division B requirements and thus covered through typical construction via the practice of Articles 3.2.8.3 through 3.2.8.8 per

Table ***3.1.3.1***. For example, the provisions for draft stops and closely space sprinklers (water curtains) in Article 3.2.8.6 are intended to address the potential that smoke and fire may bypass fire alarm devices due to the unique arrangement of floor openings. This may, in turn, lead to delay in fire emergency notification and fire spread leading to risks to fire and life safety. For a large atrium where NFPA 13 does not require closely spaced sprinklers (water curtains), the VBBL, however, still requires draft stops to facilitate the activation of smoke detectors that are typically installed at the floor opening for fire detection purposes. Likewise, a manual exhaust system is prescribed in Article 3.2.8.7 to assist attending fire departments with clearing smoke in the event of an atrium fire.

While the above considerations are most often included within typical construction, Division B further mandates measures in Articles 3.2.8.4. and 3.2.8.5 which may more often form the foci of alternative solutions. These relate to cumulative exit design and protection of floor areas to maintain tenable conditions for building evacuation, as investigated in more detail below. Therefore, this case study will focus on the assessment of the performance of the typical Division B solution requirements as outlined in Articles 3.2.8.4. and 3.2.8.5, with reference to other articles where appropriate to demonstrate specific considerations in application of Division B solutions to this design situation.

3.1.3.2 Objectives of Division B Solution

To better understand the design performance of the Division B solutions, it is important to study the intent attributed to the provisions in Sentence 3.2.8.1.(1) and Articles 3.2.8.3 to 3.2.8.8, and thus Articles 3.2.8.4. and 3.2.8.5, that are of most interest here. To this end, the following tables summarize the objectives and functional statements attributed to these requirements from NBCC [27] for the two Division B approaches to atrium design.

Table 3.1.3.2 Functional and Objective Statement Attributes to Sentence 3.2.8.1.(1)

Objective	Function	Link	Objective

Sentence 3.2.8.1.(1)	**F03** To retard the effects of fire on areas beyond its point of origin **F06** To retard the effects of fire on facilities for notification suppression and emergency response	so that	**OS1.2** a person will not be exposed to an unacceptable risk of injury due to fire or explosion impacting areas beyond its point of origin. **OP1.2** to limit a building from being exposed to an unacceptable risk of damage due to fire caused by fire or explosion impacting areas beyond its point of origin.
	F05 To retard the effects of fire on egress facilities		**OS1.5** to limit the delay in the movement to a safe place during an evacuation.
Intent Statements			
The intent is to limit the probability of the spread of fire from the lower floor level to the upper floor level in a fire situation or from floor area to an exit situation, which could lead to delays or ineffectiveness in fire suppression operations, which could lead to the spread of fire, which could lead to harm to persons and damage to buildings.			

The functional statement and objectives from Articles 3.2.8.4. and 3.2.8.5 are as follows:

Table 3.1.3.3 Functional and Objective Statement Attributes to Article 3.2.8.4 and 3.2.8.5

<table>
<tr><th>Objective</th><th>Function</th><th>Link</th><th>Objective</th></tr>
<tr><td>Sentences 3.2.8.4.(1), 3.2.8.4.(2), and 3.2.8.5.(1),</td><td>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
F05 To retard the effects of fire on emergency egress facilities
F06 To retard the effects of fire on facilities for notification, suppression and emergency response
F11 To notify persons, in a timely manner, of the need to take action in an emergency
F13 To notify emergency responders, in a timely manner, of the need to take action in an emergency</td><td>so that</td><td>OS1.2 a person in or adjacent to the building is not exposed to an unacceptable risk of injury due to fire or explosion impacting areas beyond it point of origin.
OS1.3 a person will not be exposed to an unacceptable risk of injury due to collapse.
OS1.5 a person being delayed in or impeded from moving to a safe place during a fire emergency.
OP1.2 the building is not exposed to an unacceptable risk of damage due to fire or explosion impacting areas beyond it point of origin.</td></tr>
<tr><th colspan="4">Intent Statements</th></tr>
<tr><td colspan="4">Articles 3.2.8.4 and 3.2.8.5: The intent of the required vestibule in front of the exit stairs is to limit the probability that smoke will migrate from a floor area into exit stairs or a protected floor space in a fire situation, which could lead to the buildup of smoke in the exit stairs or protected floor space, which could lead to:
▪ delays or inefficiencies in fire suppression operations, which could lead to the spread of fire, which could lead to harm to persons, including emergency responders and to the building, and
▪ delays in the evacuation or movement of persons to a safe place, which could lead to harm to persons, including emergency responders and to the building.</td></tr>
</table>

Review of the objectives and functional statements indicate that the intent of the acceptable design is to limit the probability that fire and/or smoke will spread beyond the fire origin from lower to upper floors or into protected spaces and exits. If this were to happen, it could lead to harm to occupants and emergency responders or damage to buildings. Such harm could occur due to delays in the evacuation or movement of persons to a safe place or to delays or inefficiencies in fire suppression operations. On the other hand, the general intent of incorporating an atrium into a building design is to permit free and natural flow of air through the space and also to allow and profile the interconnections between storeys through the floor openings.

3.1.3.3 Performance of Division B Solutions

Now that the intents of the Division B solution have been identified, it is important to understand the level of performance set up by the acceptable solutions in order to understand the fundamentals that must be met for an atrium design to achieve these intents. In this section, these will be evaluated based on the four parameters identified in Chapter 2: scientific and historic background of the intent, design reliability, economic impact, and practicality of the ensuing designs. As will be outlined below, this serves to identify and illustrate potential gaps in current design methods and points to factors that should be considered in alternative approaches to performance-based design and review of atria.

3.1.3.3.1 History of Division B Solution

Table 3.1.3.4 presents the highlights from Articles 3.2.8.4 and 3.2.8.5 which are prescribed in the Division B solution to address the smoke protection of exits and elevators as well as occupant evacuation. Typical design challenges are also included in Table 3.1.3.4 as context for the discussions below.

Table 3.1.3.4 Division B Solutions in Article 3.2.8.4 and 3.2.8.5 and Typical Design Concerns

Building Code Provision	Division B Solutions	Typical Building Design Concerns
Article 3.2.8.4 Smoke protection of exits and elevators	Pressurized vestibules with doorways not less than 1.8m apart to be provided at any openings, elevators serving more than just IFS and exit opening directly into the atrium. Or exit opening into the atrium to meet cumulative exiting or be provided with protected floor space.	Floor space may not be available to compensate the provision of additional vestibules.
Article 3.2.8.5 Exiting	Provide protected floor area via: - Cumulative exiting for all IFS floors, or - Stair treads and landings is not less than 0.3m^2 times total occupant load in IFS, or - Protected floor spaces connecting directly to an exit and not less than 0.5m^2 of occupant load of each floor in IFS and are separated from IFS by a 2 hour fire separation.	- Cumulative exiting will result in unrealistic stair width. - Stair treads and landing may not be reasonably used. - Floor space may not be desired to compensate the provision of Protected floor spaces.

Historically, major concerns with respect to fire safety in atrium design have come from the potential for rapid spread and progressive development of fire between levels in the open structure, coupled with lack of barriers to limit smoke from entering all the connected levels simultaneously [28, 29]. Three items specifically related to occupant evacuation during fire emergencies in full atrium designs include:

- Occupants on all atrium floors start to evacuate simultaneously leading to potential delays for occupants to move to a safe area in a timely manner.
- There is potential for damage to building if the building structure lacks high enough resistance to a lasting fire condition leading to delay of occupant evacuation.
- There is a potential for delayed notification of the fire department and lack of a staging area leading to inefficient firefighting operation potentially delay of occupant evacuation.

Per the provisions in the Division B solution, the above concerns are addressed using vestibules (Article 3.2.8.4) located presumably to provide protection from smoke contamination and fire for elevators and exits within the interconnected floor space [29]. For these, the code further prescribes a minimum distance of 1.8m between the opposite doors of the vestibule, although no clear historic or scientific basis for this specification is evident. It potentially relates to provision of a large enough volume for the vestibule so that the temperature of the hot smoke layer generated from a fire might be reduced, thus decreasing the momentum of smoke flow into the exit or elevator shaft. This is a curious requirement, however, since the atrium is now required to be provided with sprinkler protection, making it unclear why a particular size would be required when it is expected that the sprinklers would control the fire growth and reduce the quantity and temperature of the smoke layer, thus functioning similar to the required vestibule.

With respect to the provision for occupant evacuation, it is noted in the NBCC User's Guide that the stairs must be designed to accommodate the aggregate occupant load from all the interconnected floor spaces (IFS) as these occupants are assumed to simultaneously evacuate when responding to a fire alarm notification in a building with an atrium. The basis for this is again curious, since in a similar building without floor interconnections, one acceptable design of the fire alarm system is to notify all occupants immediately upon any fire alarm device activation, but in other buildings it is not necessary to design the stairs to accommodate simultaneous evacuation of the occupants. Rather, exits in other buildings without floor interconnection in most scenarios are only required to accommodate the occupant load by floor basis per Article 3.4.3.2. Therefore, the levels of performance of the Division B solutions for these two cases do not appear to be consistent with respect to prudent design in the interest of occupant safety.

Only two of many elements of the background that can be attributed to Division B atrium design provisions are reviewed here to highlight potentially conflicting provisions that arise. While the various provisions may have been/or are state of art at the time of code development, others have clearly been carried through over the years as other elements in the code have changed and thus should be revisited for consistency in approach. These same, and certain additional, elements are discussed as appropriate in the following sections as they relate to assessment of other specific aspects of the design performance.

3.1.3.3.2 Reliability of Division B Solution

As the intent of the Division B solution is to maintain a tenable area such that occupants can evacuate safely and firefighters are able to perform their duties for both life and property safety, it is important, in this context, to study the reliability of the acceptable Division B solutions used in atrium design.

One important consideration in this respect is again encompassed in Article 3.2.8.4 of the Division B solution which indicates the need for vestibules as shown in Table 3.1.3.5.

Table 3.1.3.5 Division B Solutions in Article 3.2.8.4

Building Code Provision	Acceptable Division B Solution
Article 3.2.8.4 Smoke protection of exits and elevators	Pressurized vestibules with doorways not less than 1.8m apart to be provided at any openings, elevators serving more than just IFS and exit opening directly into the atrium. Or exit opening into the atrium to meet cumulative exiting or be provided with protected floor space.

As noted above, the presence of these vestibules is to limit smoke migration into exits which in turn might negatively impact occupant evacuation and fire suppression activity [27]. In the Appendix-3.2.8.4.(1)(c) of the VBBL, it prescribes that these vestibules are expected to be pressurized to be minimum "*… 12Pa higher than the adjacent floor area with all vestibule door closed and the expected outdoor temperature is equal to January design temperature on a 2.5% basis.*"[26]. It is further documented in other literature that use of vestibules will limit the possibility of direct connection via doorways between the floor area and the exit stair to further limit smoke migration into the exit [30]. However, the presence of a vestibule may not achieve the reliability of performance that is anticipated in terms of limiting smoke migration. As shown in Figure 3.1.3.1, the vestibule is in the direct path of evacuation by the occupants. Thus, in a high occupant load scenario, occupants may actually queue up in front of the exit and into the vestibule area due to reduced movement speeds through exit stairs (0.85m/s) as compared to travel across typical floor areas (1.13m/s) [31]. If occupants open the vestibule doors and attempt to push forward into the exits for safety, this can create a path for smoke to migrate into the exit stairs and, as reported in fire tests, the smoke may migrate into the exit via overlap in door openings with the vestibules [32]. In this case, the presence of the vestibule reverses the original intent of employing a vestibule to control migration of smoke and contamination of the air in the exit stair.

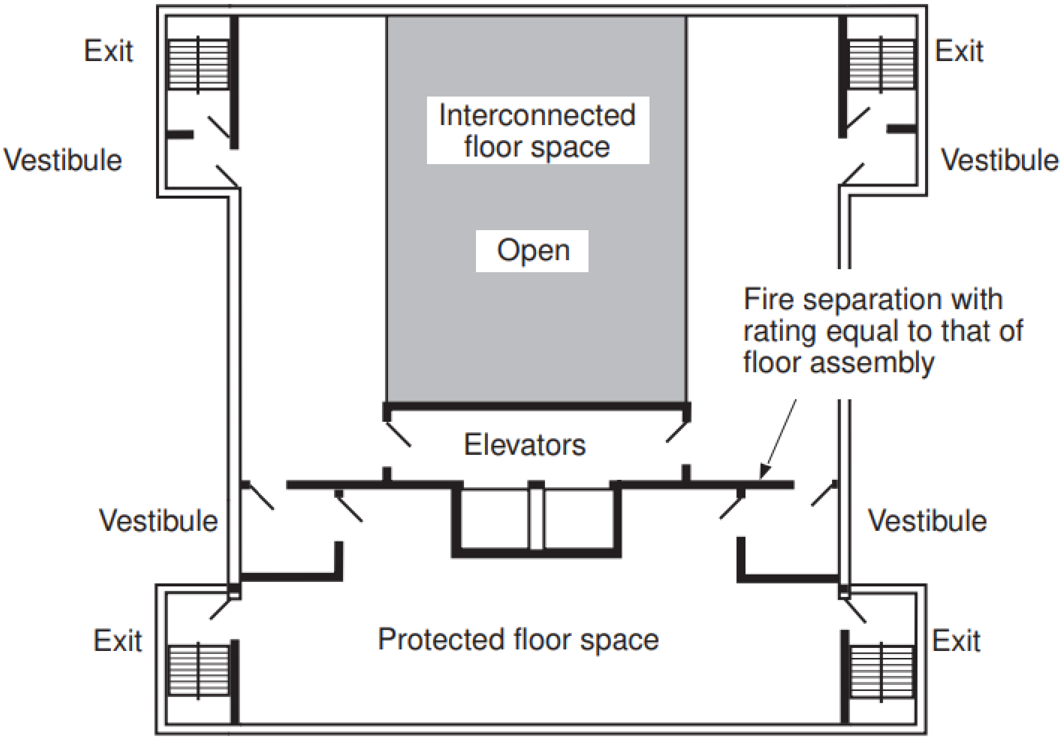

Figure 3.1.3.1 Typical Illustration of Vestibule Protecting Exit in Atrium Design

Another important provision for atrium design in a Division B approach is exit strategy. For an atrium, Division B solutions dictate that it must be assumed that occupants from all floors evacuate simultaneously. Further, there are three code compliant approaches for determining the necessary exits in atrium design. These include approaches of cumulative exiting, of sizing the stair treads and landings as large holding spaces accounting for 0.3 m^2 space per occupant, and of use of protected floor areas of sufficient size and with appropriate fire separation as shown in Table 3.1.3.6.

Table 3.1.3.6 Division B Solutions in Article 3.2.8.5

Building Code Provision	Acceptable Division B Solution
Article 3.2.8.5 Exiting	Provide protected floor area via: Cumulative exiting for all IFS floors, or Stair treads and landings is not less than 0.3m^2 times total occupant load in IFS, or Protected floor spaces connecting directly to an exit and not less than 0.5m^2 of occupant load of each floor in IFS and are separated from IFS by a 2 hour fire separation.

The acceptable exit design that specifies a total size of stair treads and landing that equals 0.3m^2 / person times the occupant load of each floor will be examined further here. Taking the 3rd storey of the present building as an example, the required surface area of stair treads and landings between the 3rd and 2nd storey would need to be not less than 90m^2 (300 persons × 0.3m^2/person). If each stair was designed equivalently, each would have to be at least 30m^2 in size. As illustrated in Figure 3.1.3.2, a code compliant Division B solution might envision the path for an occupant from the 3rd storey as following the red solid arrow along the main landing down the stairs and intermediate landing, and stopping before they encounter occupants on 2nd storey who are following a similar path to descend from the 2nd to the main floor (pink dashed lined).

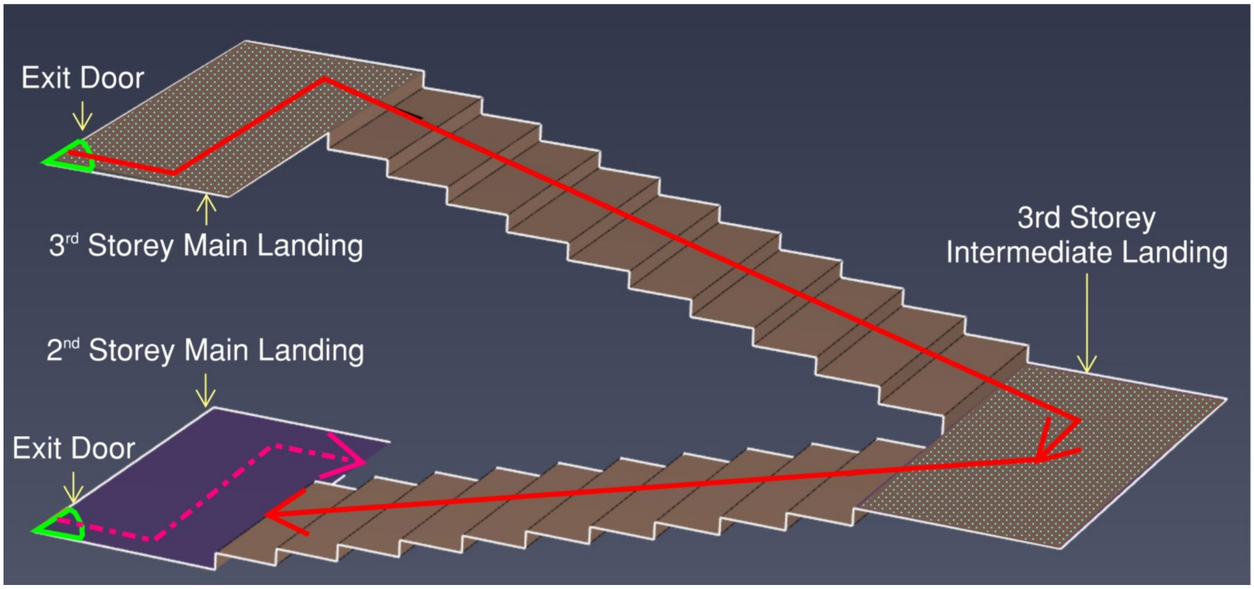

Figure 3.1.3.2 Sketch of Code Compliant holding space in a 3rd storey exit stair

While the intent of this approach is to provide a holding space in the exit stairs for occupants to be protected from the fire and smoke, the Division B design only prescribes the total surface area necessary to hold all the occupants. It does not include any guidance on how to coordinate the locations or use of the exit doors, stair landings, and stair directions. Since exit doors are critical elements for smoke management, and stair directions, landings, and flow of occupants are critical to evacuation, these elements need to be integrated together in a successful design. In this respect, it is clear that the Division B requirements are limited in terms of the overall reliability of final designs.

At the same time, recent research suggests that an exit stair door should be located on the opposite side of a landing as the incoming stair for the benefit of the overall evacuation of a building [33]. This door location is illustrated in Figure 3.1.3.3 and this approach could also be taken to achieve code compliance, with the red arrow illustrating the occupant flow when evacuating. At the same time, however, other research demonstrates that when an exit door is located directly in front of a flight of stairs going down, the surface space of the main landing on a given storey may not be used by occupants from that storey as intended. Instead, since atrium design is commonly adopted in office or assembly occupancies[2], it would be predicted that people would tend to leave the building through the exit stair as soon as possible rather than staying in place, unless being instructed by authorities (Fire Department, Building General Announcement). Further, in assembly type spaces occupants tend to favour interaction over privacy such that in the present design, occupants can be expected to travel down floors and collect together on the landings/stair treads on the lower floors. As a result, the surface space of the landings and even the stair treads may be occupied by occupants from a higher storey (in this case 4th storey) such that the holding space on the 3rd storey stair may not have sufficient area for all of the occupants on the 3rd storey. Therefore, in reality, even though configurations such as these meet the requirements of Division B, the occupants on each floor may have less protected space than intended and in the event of fire, the compliant design may fail to permit efficient and safe evacuation of all interconnected floors.

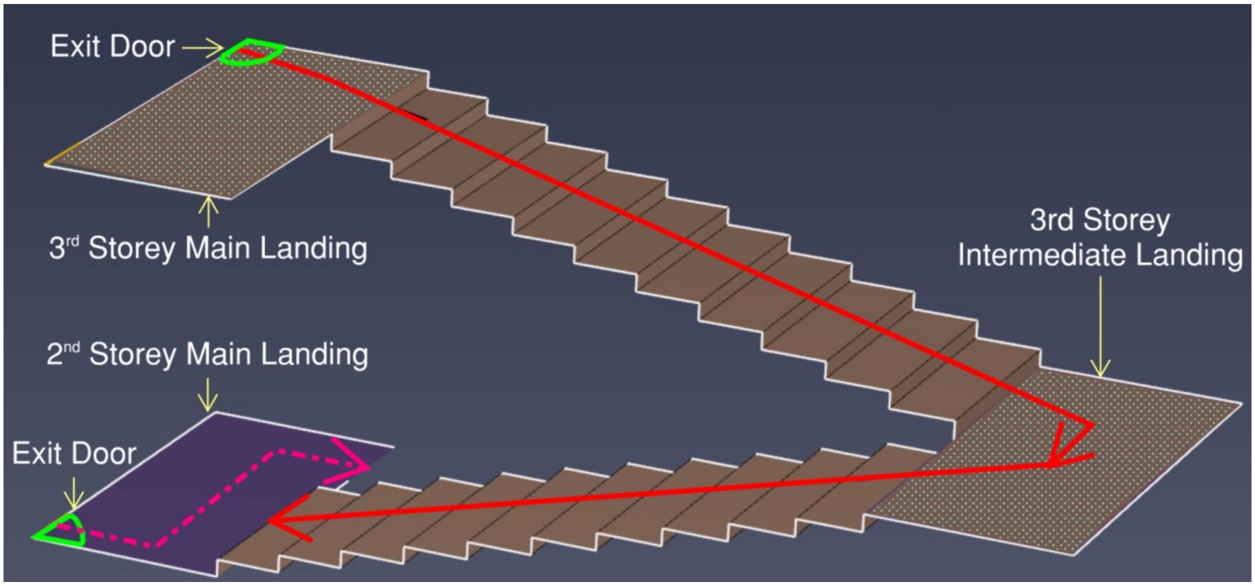

Figure 3.1.3.3 Sketch of Code Compliant holding space in 3rd storey exit stair with different door location

Based on the foregoing, it can be pointed out that some provisions in Division B solutions for atrium design are very general and do not provide any guidance on how to account for human behavior in

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[2] It is noted that in residential occupancy, human behavior in emergency may react differently.

different occupancies. As shown briefly here, the reliability of Division B designs for atria can raise significant concerns in some situations, yet these solutions are set as the baseline for building design across the industry. Thus, if the designers or reviewers strictly follow Division B design requirements without appropriately coordinating those with other building characteristics or without having sufficient knowledge (in this instance) in human behavior during fires, an atrium building design may meet the letter of the code provisions but underperform or even fail to meet the intent for public safety during a fire.

3.1.3.3.3 Economic Impact

Financial considerations play a large role in building design in many instances. Although they are not assessed in determining compliance of a design with respect to fire and life safety, they do play a significant role in decision making during selection of design options. To encourage a holistic approach to design, the economic impacts of various ways to achieve code compliance should be factored into the decision-making process. On the positive side of course, this can lead to alternate solutions that may be more cost effective than those designed using Division B approaches. On the other hand, unique projects or innovative designs may not be pursued when the cost of the design and construction become financially intractable whether the design is via Division B or an alternative method. As an illustration, a specific case is presented for the atrium building discussed here. One of the Division B solutions for this building would be to provide fire rated shutters around the floor openings to the atrium through the 2nd to 4th storeys. Aside from any other considerations related to use of fire rated shutters, it is of interest to further examine the cost of this solution. The cost for fire rated shutters varies depending on type, size, and manufacturer. Based on recent experience, this cost ranges from around \$10,000.00/piece to \$25,000.00/piece with a standard piece being as large as 15m^2 [34]. The present design requires approximately 192 pieces to isolate the 2nd to 4th storeys from the atrium space in the event of a fire. To provide this Division B solution, then, the cost of the shutters is estimated to be \$ 4,800,000.00, excluding labor. By way of perspective, typical construction costs in the City of Vancouver for a building similar to the one postulated here would be approximately \$90,000,000.00. Thus, the material cost for the fire shutters alone would already increase construction costs by at least 5% before any challenges with installation or operation were addressed. Since this could well contribute a potential financial burden in some projects[3], the idea of including an atrium in the design might be abandoned when this Division B solution is specified, even though there may well be several other, less costly design solutions that could meet or exceed the fire and life safety intent of the code.

3.1.3.3.4 Design Practicality

The practicality of a final design is another important factor that should be considered when evaluating the performance of any fire and life safety design solution. Again, to illustrate some of the considerations related to design practicality, two Division B design solutions, specifically use of a manual exhaust system and cumulative exiting design, are assessed to determine their practicality in the context of the present building design.

The first aspect of the Division B solution that is examined is the use of atrium manual exhaust as outlined in

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[3] It should further be noted that reliability of fire shutters will be identified as a limitation during the analysis made in Case Study 2, which should also be considered when assessing this solution relative to other options.

Table ***3.1.3.1***, Article 3.2.8.7. The acceptable solution in this article necessitates a minimum of 4air change/h of atrium space. For the present building with an atrium floor area of 5,600m^2, this exhaust volume is significant at 403,200m^3/h (4 air change/h × 5,600m^2 × 18m). Based on past experience with projects requiring similar volumes of exhaust, it is very difficult to find appropriate locations for exhaust and makeup air supply to avoid building damage. In addition, the configuration of the exhaust system becomes critical since removal of this volume of exhaust, and replacement with makeup air, can result in significant temperature drops in some locations. This can lead to the unintended impact of delay in sprinkler activation which then, in turn, compromises the overall control of the growth and spread of the fire. As such, the practicality of this type of exhaust system must be questioned in designs such as the one considered here.

Next, the cumulative exiting design approach listed in Division B is assessed for practicality in the current building design. This approach requires that the exit stair width be sufficient for all occupants in all floor areas interconnected with the atrium to egress simultaneously. The total occupant load from the 2nd to the 4th storey would be 1,138 persons (313 + 300 + 525 persons). The exit capacity factor that is used for Division B design is 8mm / person per Sentence 3.4.2.3.(1) of VBBL. Therefore, the total exit stair width on the 2nd storey is required to be a minimum of 9.1m (1138 persons x 8mm / person). Divided equally by three staircases would result in approximately 3.04m per stair. This number may appear to be practical, but it has to be remembered that there are only four interconnected storeys in the present building. For buildings with more interconnected storeys or with higher occupant load per floor, the exit stair width can become significant and there have been situations where it could potentially exceed the floor size. Thus, in addition to the questions raised earlier about the need to design under assumption of simultaneous evacuation of all occupants, for different reasons cumulative exiting design may also not be feasible in some atrium designs.

Based on the above analysis, it is clear that some of the Division B solutions are not necessarily practical in actual design, construction, or building operation. Yet the Division B solutions are intended as the references cases against which to assess any alternative solution. Thus, in these instances, alternative solutions would be difficult to appropriately benchmark against Division B solutions since the latter would inherently have difficulty defining a workable code compliant design.

3.1.4 Conclusion

This case study presented the Division B solution approaches for an atrium design in a sprinklered building with office occupancy. It did not expand on any possible alternative solutions for atrium design. Instead, it investigated the performance of the Division B solutions which are to form the reference case against which to benchmark an alternative design through the parameters listed in Chapter 2 of this thesis. Based on the foregoing, the following limitations were identified:

1. For atrium design, the Division B requirements prescribe a wide range of possible solutions from full openness between storeys through to use of costly construction materials to meet the code intent. The full history of the design approach was not reviewed in depth; however, based on the limitations uncovered, it is clear that much of this history is no longer affiliated with specific requirements. Instead, it can be supposed that some of the design approach may have relied on state of art of construction practice, design, and fire safety knowledge at the time of original code development and then have been carried through over the years. As alternative solutions through performance-based approaches become more commonplace, future work should certainly be conducted to investigate this in further depth and better define the science and evidence for the basis for each requirement.
2. The intent of the atrium design in Division B is to maintain a tenable condition in the building to allow safe occupant evacuation and assist in fire department response. However, there is only one set of prescriptive solutions to be applied across all possible occupancies and these do not recognize different occupant profiles. This lack of sufficient acknowledgement of differences in human behavior may lead to designs that underperform and could pose significant safety concerns for some situations and occupancy types.
3. The assessment presented in this case study also reviewed the level of performance embedded in some of the atrium design provisions of fire and life safety in the current building code. While the Division B solutions are prescriptive, several of the provisions are very general and open to interpretation in terms of implementation. Some of them appear to be inconsistent and several options could be implemented in a fashion that would pose potential risks in terms of life safety. As such, it

is possible that a Division B design may meet the letter of the code provisions, but it may underperform and even lead to safety concerns in the event of a fire.

4. Atrium design is unique from project to project and proper incorporation of fire safety requires careful and holistic coordination across building characteristics such as building occupancy, exit locations, and floor layout. It is shown that some of the Division B solutions may not provide appropriate baselines against which to assess alternative building designs as they fail to achieve the intended level of performance. In such instances, the current NBCC does not provide appropriate guidance for either the designer or the reviewer to appropriately apply acceptable Division B solutions or develop alternative solutions through a performance-based approach. Care should therefore be taken in applying even the existing design approaches to unique situations. Importantly, to fully address this issue requires appropriate understanding of the interactions of the overall building characteristics with respect to fire safety, as well as knowledge in human behavior in fire. Such understanding is therefore required by both the building designer and reviewer to successfully advance performance-based design.
5. Building design and construction are economic activities so cost will always be an important consideration in decision making. In this respect, some of the Division B solutions are not cost-effective while others present designs that cannot be constructed; in either case, the solution will not satisfy the design intent of having an atrium even if this may be an entirely appropriate design choice for a given building.
6. Another essential factor in advancing performance-based design is the need to assess practicality of both the Division B and any alternative designs. In this instance, some Division B solutions are not feasible as the majority of the floor area would not be available for the occupancy. Other Division B solutions result in very large air flow requirements that would interrupt normal building operation. Clearly neither of these Division B solution options provides a feasible reference case against which to judge an alternative solution, thus pointing to the importance of considering practicality in formulating both reference and alternative design solutions.

Based on the foregoing discussions, the acceptable Division B solutions in some situations may fail to meet the intent in fire and life safety aspects, greatly increase financial burden of construction and compromise practicality in construction and operation. Therefore, a performance-based solution should be considered when approaching the atrium design. However, with the current Division B solutions embedded in the prescriptive NBCC, the performance-based approach for atrium design may prove difficult for both building designers and design evaluators as they attempt to navigate to an appropriate design in terms of public safety.

This case study has pointed to limitations around atrium design as prescribed in the building code. These and other elements of the Division B solutions should form the subject of in-depth future work. In this, the history of the acceptable solutions should be thoroughly researched to better understand the evidence, case studies and scientific background that may have led to the current provisions in the NBCC. At the same time, it is critical that relevant professionals are appropriately trained in subjects such as fire dynamics, modern technologies for fire protection and human behavior in fire emergencies should they be required to work on unique, alternative, and performance-based designs.

3.2 Spatial Separation

3.2.1 Introduction

The case study presented in this Section involves an analysis of spatial separation requirements for a hypothetical building design to demonstrate the current levels of performance of design solutions. In this case, spatial separation requirements are assessed first via the Division B solution prescribed in the NBCC or local building code, and then through an alternative solution that includes non-code-based analysis methods. The results of the two methods are compared to highlight important considerations that arise in current methods for spatial separation design under the NBCC.

3.2.2 Building Characteristics

A 30-storey office tower is proposed to be constructed in downtown Vancouver as illustrated in Figure 3.2.2.1. The building is surrounded on three sides by streets or lanes but on the west side has a distance of only 3m to its property line as shown in Figure 3.2.2.1 below. The building is sprinklered according to the design criteria for its occupancy and function as prescribed in Vancouver Building Bylaw (VBBL) 2019 Edition.

The building has the following characteristics:

Building Height: 30 storeys, 116m from grade to rooftop
West Face Length: 22.84m maximum
Building Occupancy: Group D, Office
Applicable Building Code: Vancouver Building Bylaw (VBBL) 2019 Edition
Sprinkler Condition: Design to NPFA 13 per local Building Code (VBBL)
Interior compartmentalization: Open concept, no interior fire separations

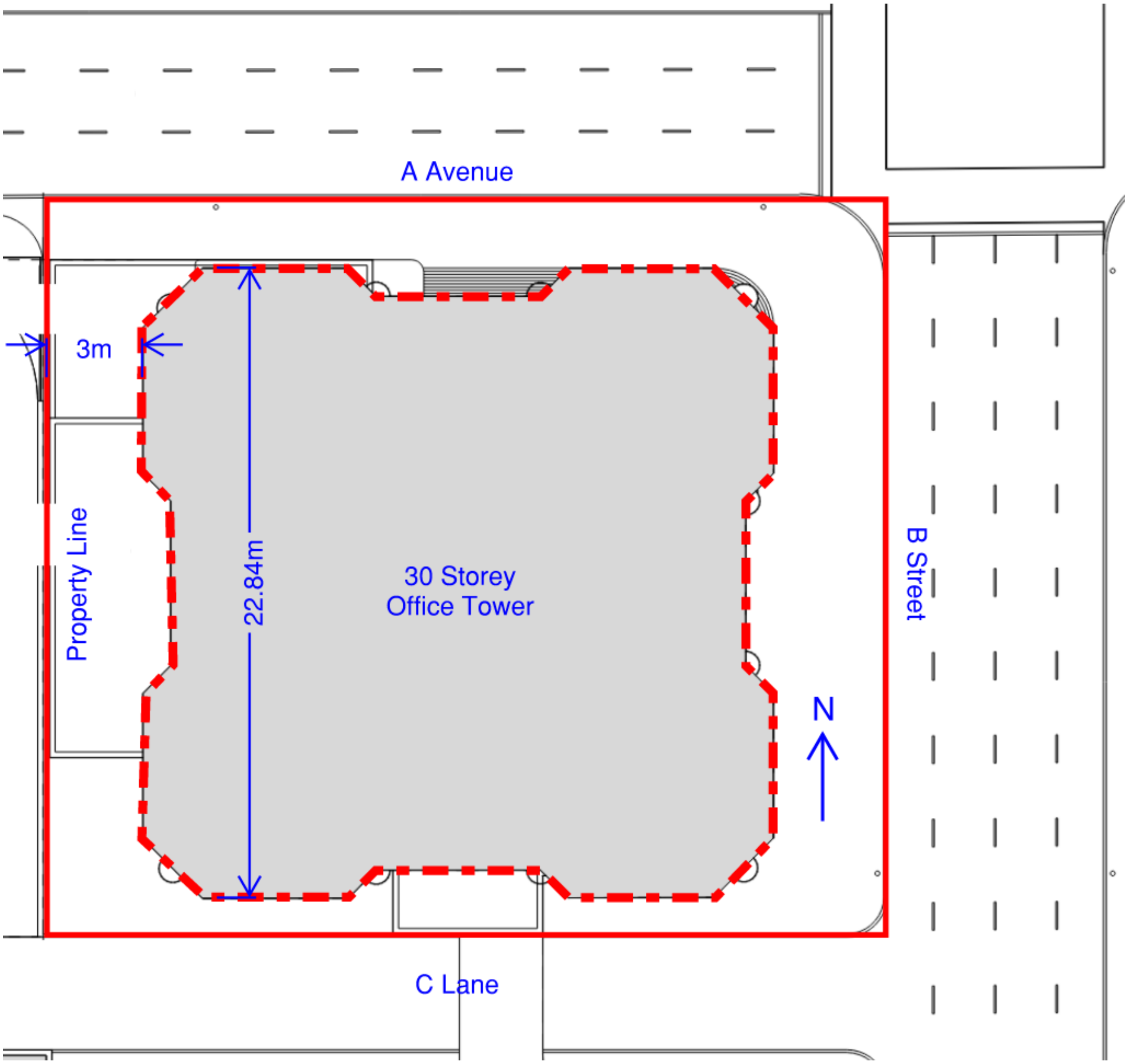

Figure 3.2.2.1 Site Plan of Case Study Office Tower

As documented in recent architectural research, natural lighting plays a significant role in architectural design [35]. In fact, studies show that natural lighting not only offers essential visual connections to the surroundings but also contributes to occupants' wellbeing and mental health [35]. Therefore, to maintain natural lighting and enhance social interaction, the design team plans to retain 100% window opening on the west face for each storey in this case study.

3.2.3 Division B Solution

3.2.3.1 Introduction

The acceptable solutions in Division B of VBBL 2019 for the exterior wall design are included in Subsection 3.2.3 of VBBL. With respect to the desire to design for optimal lighting, however, these provisions limit the amount of unprotected opening that is allowed in a code compliant design for the exterior wall of the exposing building face. The amount of unprotected opening allowed depends on the size of the exposing building face and the available limiting distance. In the instance that the desired unprotected opening is larger than that allowed, the remainder of the exterior wall is required to be protected with an assembly with a required fire resistance rating.

As a first step in assessment of this case study, it is pertinent to investigate the intent statements attributed to the spatial separation provisions in the VBBL to understand the fundamental concepts driving provisions found in Division B solutions in the code.

3.2.3.2 Objectives of Division B Solution

As discussed previously, objectives, intents and solutions in the current code prescribe the minimum level of performance expected for Canadian construction. The objectives and functional statements attributed to the spatial separation requirements from NBCC – Intent Statement website [27] are summarized in Table 3.2.3.1:

Table 3.2.3.1 Functional and Objective Statement Attributes to relevant Division B Solutions

Division B	Function	Link	Objective
Sentences 3.2.3.1.(1), 3.2.3.7.(1) and 3.2.3.7.(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	so that	**OP3.1** adjacent buildings are not exposed to an unacceptable risk of damage due to fire or explosion impacting areas beyond the building of origin.
Intent Statements			
The intent is 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. - Limit the probability that an exposing building face will have insufficient fire resistance and/or exterior cladding will be ignited and contribute to, or be involved in a fire, which could lead to 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			

Therefore, the level of performance anticipated by the VBBL through the acceptable Division B solution is to limit the probability of fire spread beyond the fire origin, thus minimizing impact on adjacent properties which could potentially lead to a conflagration condition with added threat to public health and safety. Since fire spread from one building to another can occur through radiation and/or convection, with the 3m set back from the property line in the present building, it is most likely that the fire would spread via radiation, with some possibility of flame projection [36]. Further, both intents are related to reducing the risk of conflagration due to fire spread between buildings before firefighters are able to arrive and perform their duties. In this respect, the code also notes that a fire in an unsprinklered compartment could spread to adjacent properties in around 16 minutes based on background from the St. Lawrence Burns [37]. Consistent with this, a 10-to-30-minute period before firefighter arrival is presumed for an unsprinklered building in Division B of VBBL as:

> *"…It has been found that periods of from 10 to 30 minutes usually elapse between the outbreak of fire in a building that is not protected with an automatic sprinkler system and the attainment of high radiation levels. During this period, the specified spatial separations should prove adequate to inhibit ignition of an exposed building face or the interior of an adjacent building by radiation. Subsequently, however, reduction of the fire intensity by firefighting and the protective wetting of the exposed building face will often be necessary as supplementary measures to inhibit fire spread."*
>
> *"In the case of a building that is sprinklered throughout, the automatic sprinkler system should control the fire to an extent that radiation to neighbouring buildings should be minimal. Although there will be some radiation effect on a sprinklered building from a fire in a neighbouring building, the internal sprinkler system should control any fires that might be ignited in the building and thereby minimize the possibility of the fire spreading into the exposed building. NFPA 80A, "Protection of Buildings from Exterior Fire Exposures," provides additional information on the possibility of fire spread at building exteriors."*

Therefore, any measures included in the building design related to meeting spatial separation provisions would be expected to limit the flame spread for at least 30 minutes until emergency responders arrived to perform their duties.

In summary, the intent statements attributed to the spatial separation provisions in Division B of the VBBL for this specific case of adjacent buildings with 3m limiting distance and maintaining a 100% opening at west exterior wall of one building indicate that the designer must limit the probability of fire spread between properties by a conflagration due to radiation and potential flame projection between properties for 30 minutes until emergency responders' arrival. With the foregoing intent, the VBBL prescribes several exterior wall design solutions in Subsection 3.2.3 of Division B.

3.2.3.3 Determination of Division B Solution

In order to meet the intent of limiting fire spread between properties, the VBBL restricts the percentage of unprotected openings allowed on the exterior wall of a building. The allowed percentage can be determined based on the methodology prescribed in Subsection 3.2.3 of VBBL 2019 using "*exposing building face*" and "*limiting distance"* for a building, presented as follow.

The exposing building face is the total area of an exterior wall facing in one direction on any side of a building measured from the finished ground level to the uppermost ceiling [26]. Therefore, the exposing building face for the west building face in this case study is determined based on the length (L) of 22.84m times the height (H) of 116m, $A = L \times H = 2649.44\text{m}^2$.

The limiting distance refers to 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 two buildings or fire compartments on the same property, measured at right angles to the exposing building face [26]. Therefore, based on the site layout, the limiting distance of the west building face is 3m measured from the exterior side of the west building face to the property line as shown in Figure 3.2.2.1.

Per Clause 3.2.3.1.(1)(b) of the VBBL 2019, the area of openings permitted on west building face of this sprinklered building will then be determined following *Table 3.2.3.1.D* of the VBBL 2019. As shown in Figure 3.2.3.1 below, based on a limiting distance of 3m and a maximum area of exposed building face of 2,649.5m^2, the maximum % of unprotected opening permitted for the west building face is 22% or 582.9m^2 (2649.5m^2 x 22%). Assuming the maximum area of unprotected opening is used, the reminder (78%) of the west building face, 2,066.6m^2 (2,649.5m^2 – 582.9m^2), then must be provided with a 1 hour fire rated assembly per Table 3.2.3.7 of VBBL 2019 also shown in Figure 3.2.3.1 below. This would be the case whether the building was deemed to be combustible, noncombustible, or constructed of encapsulated mass timber.

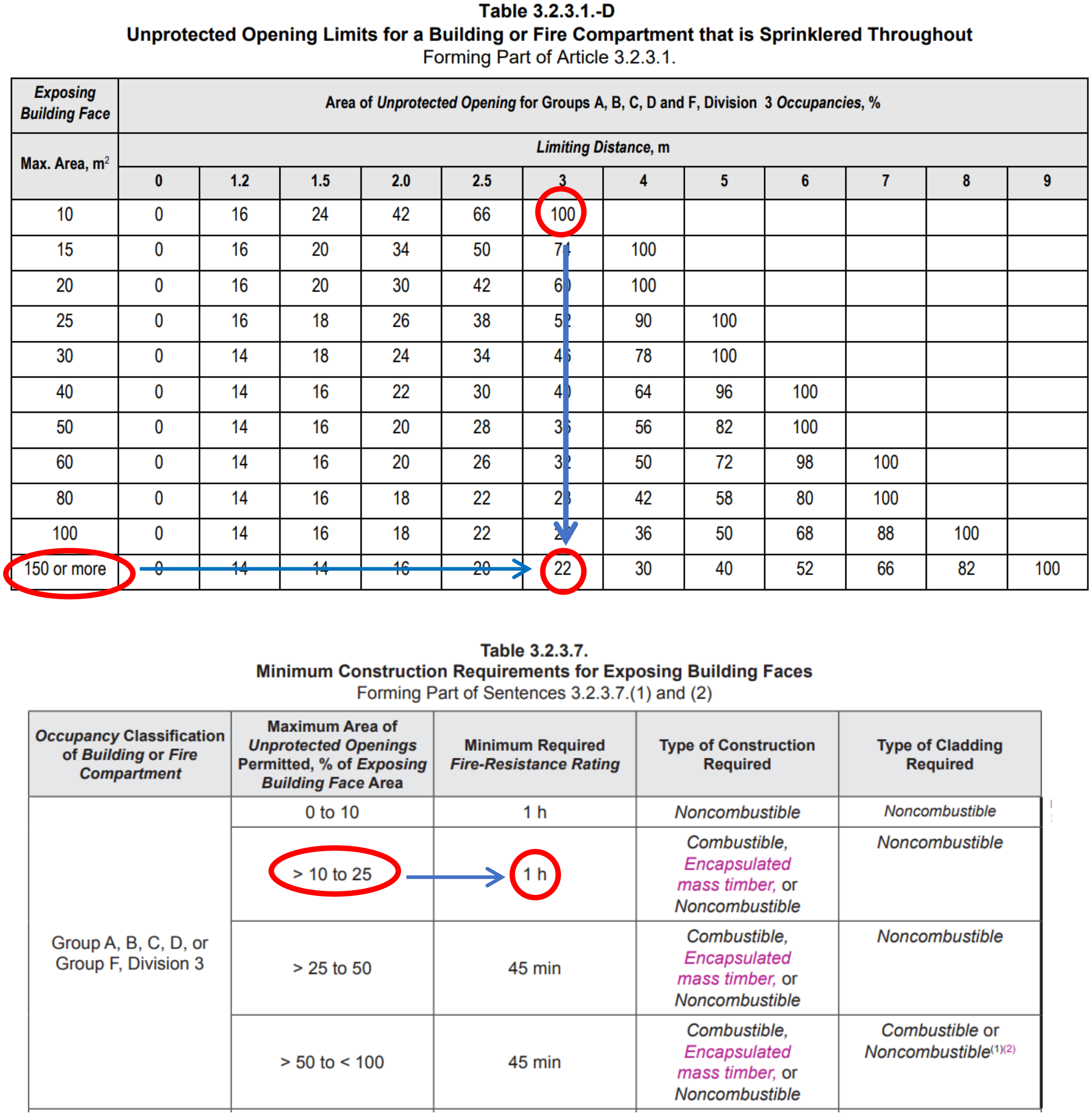

Table 3.2.3.1.-D
Unprotected Opening Limits for a Building or Fire Compartment that is Sprinklered Throughout
Forming Part of Article 3.2.3.1.

Exposing Building Face	Area of *Unprotected Opening* for Groups A, B, C, D and F, Division 3 *Occupancies*, %											
Max. Area, m²	*Limiting Distance*, m											
	0	1.2	1.5	2.0	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	24	36	50	68	88	100	
150 or more	0	14	14	16	20	22	30	40	52	66	82	100

Table 3.2.3.7.
Minimum Construction Requirements for Exposing Building Faces
Forming Part of Sentences 3.2.3.7.(1) and (2)

Occupancy Classification of *Building* or *Fire Compartment*	Maximum Area of *Unprotected Openings* Permitted, % of *Exposing Building Face* Area	Minimum Required *Fire-Resistance Rating*	Type of Construction Required	Type of Cladding Required
Group A, B, C, D, or Group F, Division 3	0 to 10	1 h	*Noncombustible*	*Noncombustible*
	> 10 to 25	1 h	*Combustible*, *Encapsulated mass timber*, or *Noncombustible*	*Noncombustible*
	> 25 to 50	45 min	*Combustible*, *Encapsulated mass timber*, or *Noncombustible*	*Noncombustible*
	> 50 to < 100	45 min	*Combustible*, *Encapsulated mass timber*, or *Noncombustible*	*Combustible* or *Noncombustible*(1)(2)

Figure 3.2.3.1 Area of Unprotected Opening in Table 3.2.3.1.D and Rating for Remainder Exterior Wall per Table 3.2.3.7 from VBBL 2019 [26]

In summary then, for the proposed west building face to be provided with 100% natural lighting, the code compliant Division B solution is summarized in Table 3.2.3.2:

Table 3.2.3.2 Summary of Division B Solutions

	Division B Solution
Area of Opening without Protection	582.9m^2
Area of Opening with 1 hour ULC-S101 Fire Separation or 1 hour ULC-S104 Fire Protection Rating Protection	2,066.6m^2
Total Area	2,649.5m^2

VBBL 2019 prescribes two options to achieve fire separation for the 2066.6 m^2 of the west wall that is to be protected as:

1. 1 hour fire resistance rated assembly that has been determined based on the test result of CAN/ULC-S101, *"Fire Endurance Tests of Building Construction and Materials"* per Sentence 3.1.7.1.(1); or
2. 1 hour fire protection rated shutters that have been determined based on the test result of CAN/ULC-S104, *"Fire Tests of Door Assemblies"*.

This could be achieved by typical 1 hour listed building construction such as two layers of gypsum board (GWB) mechanically fastened to the steel stud. However, this would clearly negate the design intent to maintain the 100% opening at the exterior wall. Alternately, protection for the additional openings conforming to the code (Division B solution) could be provided through use of 1 hour rated glazing product such as "*Pilkington Pyrostop*®" which has been tested to CAN/ULC-S101 or via installation of 1 hour rated fire shutters such as "*FireKing*®" which has been tested to CAN/ULC-S104. At this point also, it is important to note that unique to City of Vancouver or lower mainland Vancouver area, the construction should consider potential post-earthquake impact.

While both these Division B solutions would be acceptable under the VBBL, when their overall level of performance is assessed using the four factors outlined in Section 2, it is found that they present limitations in several respects and may not appropriately address the intended performance prescribed in code. To further illustrate this, detailed investigation into the development of the Division B solutions for spatial separation, as well as reliability of the Division B compliant systems are further evaluated. In the analysis, the historical development of spatial separation requirements is first reviewed. Then, given the nature of the construction, overall design impact and construction feasibility are reviewed. Finally, the economic impact such as construction cost and maintenance related to each option are also explored to review the level of performance of Division B solutions.

3.2.3.3.1 History and Scientific Background of Division B Solution

Determination of allowable spatial separation of buildings is based on limiting the percentage of unprotected opening permitted for each fire compartment or building face to limit the potential for radiation or exterior flaming from a fire in one building to result in fire spread to the next building over. Thus, the calculation procedure shown above, which has been an important element of the NBCC since its inception in early 1990s, is based on the size and percentage of openings in the building exterior walls and available distance to the property line. Use of the Tables provides a simplified approach with which to conduct spatial separation calculations and has gone through several iterations in the code over time. For example, spatial separation provisions in codes prior to the NBCC 1965 only listed 3 allowable windows opening percentages with which to determine spread of fire. These were zero window opening, 20%, or 100% open area based on the area of the exterior wall of a building facing an adjacent building. Walls were assumed to be parallel to one another and a given opening area was allowed based on the anticipated fire load, fire resistance rating of the subject exterior wall, and the distance from the exterior wall to the lot line [38]. Over time, having only three window opening options available was found to be restrictive, so it was desired to explore intermediate values of window openings to provide more flexibility in building design. Therefore, a series of fire tests, known as St. Lawrence Seaway and Hydro-Electric Power Project (St. Lawrence Burns), were conducted during the winter of 1957 to 1958 [37]. A number of full-scale fire experiments were conducted in eight unsprinklered residential buildings. The tests were designed to provide data on occupant survival during a fire, the effect of ventilation rates on fire development, and, of particular importance to spatial separation, the potential spread of fire by radiation via openings in a building exterior wall. The current values of opening area and separation prescribed in the building code spatial separation table are primarily based on the results from Test No. 5 [39]. This test was an experimental fire set in an existing two-storey residential building with an unrated combustible exterior wall construction [40]. The interior layouts are shown in Figure 3.2.3.2 below as extracted from the report. Each floor was approximately 8m in length and 6.3m in width measured from the outer layer of the exterior walls. The fire load used in Test No.5 represented a typical fire scenario based on fuel load data surveys that had been conducted for residential properties at the time of the program. As such, it was set at approximately 3.0lb/ft^2 (14.65kg/m^2) and was provided by two wood cribs. Each consisted of the same number of pieces of wood of different sizes arranged in the same patterns for a total of 670lb (304kg). These two cribs were placed in the living room of 227ft^2 (21.01m^2) in size as shown in Figure 3.2.3.2. Critical to spatial separation determinations, several radiometers were placed at 20ft (6.1m) and 40ft (12.2m) away from the different building exterior walls to view radiation emanating from openings in the exterior wall. These were designed to minimize convective effects of any wind and thus to record the maximum radiation intensity from the openings.

Similar to Test No.5, three radiometers were placed at the same locations (two at leeward and one at windward) for all other tests documented in this sect of experiments [40]. The measurements from all other tests were used as supporting data. All will be discussed together. Table 3.2.3.3 is a reproduction of Table III from the NRC internal report, *Spatial Separation of Buildings* [41], which summarizes the maximum measurement of the radiometers at leeward locations for some of the Tests. It is also noted that there are some inconsistencies buried within the existing tables; however, for the purposes of this thesis, the original values were used.

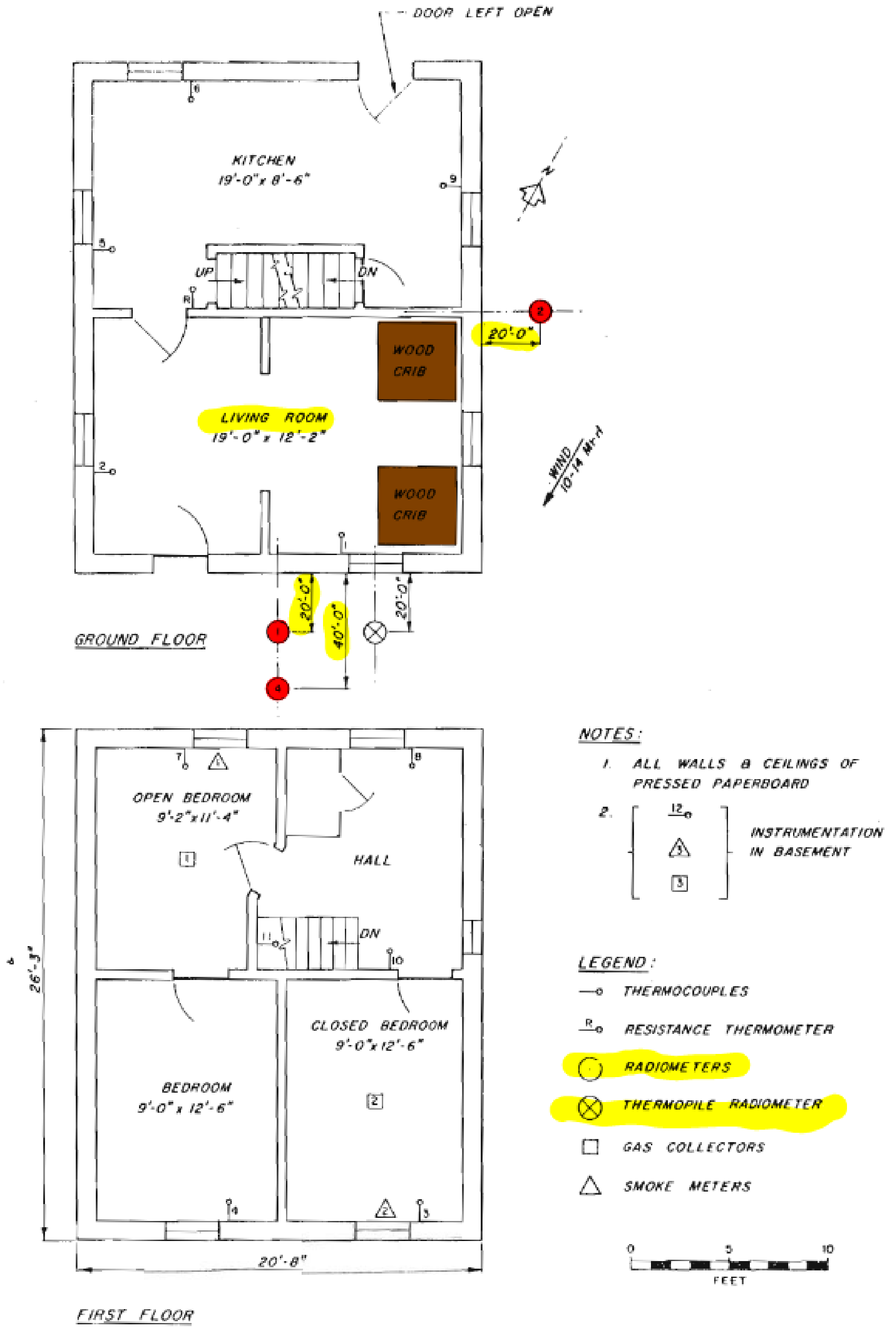

FIGURE 5 - BUILDING No. 5 - TWO - STOREY WOOD FRAME DWELLING WITH CLAPBOARD EXTERIOR

Figure 3.2.3.2 Schematic Layout of Test 5 from St. Lawrence Burn [39]

Table 3.2.3.3 Maximum Radiation Intensities Measurement from St. Lawrence Burn [41][4]

Test #	Exterior Cladding	Interior Lining	Wind Speed (mph)	Leeward Radiometer Location (ft)	Measured Intensity, I (kW/m²)	Configuration Factor of Openings, F	I/F (kW/m²)
3	Brick	Fibreboard	13-14	20 40	52.3 >7.53	0.034 0.013	1548 >585.8
5	Clapboard	Pressed Paper	10-14	20 40	43.9 13.4	0.027 0.008	1548 1673
4	Clapboard	Plaster	11-12	20 40	23.4 7.1	0.032 0.011	753 627
7	Brick	Plaster	13	20 40	37.7 15.9	0.058 0.018	669 878.6

Based on the observations from St. Lawrence burns, the main factor contributing to the spread of fire from the building is through radiation heat transfer [41]. The intensity received at a certain point can be determined using the fundamental radiation heat transfer equations:

$$I = F \times E \tag{1}$$

$$E = \delta \times e \times T^4 \tag{2}$$

Where I = intensity (kW/m^2)

F = configuration factor

E = emissive energy of the full fire development in the room (kW/m^2)

δ = Stefan-Boltzamnn Constant (5.67×10^{-11} kW/m^{2}K^4)

e = Emissivity (assumed black body for conservative analysis, 1)

T = Absolute Temperature of the Flame

In this expression, the emissivity of the burning fire is a variable due to the changing temperature and location of the flame over time. Therefore, to overcome this difficulty in representing the radiation, as well as to simplify the information for spatial separation provisions in the NBCC, the maximum intensity measured during the test was used as the baseline to represent the radiation incident on the side of a building. As the radiometers were placed at 20ft (6.1m) and 40ft (12.2m) away from the building exterior walls,

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[4] It is noted that the original table was using Imperial units and has been recalculated to SI units for consistency of this report.

rearranging Equation 1, the maximum emissive energy from the burning fire can be determined via Equation 3. This is supported by the values reported in the last column of Table 3.2.3.3 as the results from Tests 3 and 5 are in the same order, as are those for Test 4 and 7:

$$E = \frac{I}{F} \tag{3}$$

The report further indicated that, based on the results from Test 3 and 5, the hypothetical maximum emissive energy emanating from openings for fires in spaces containing highly combustible contents ($E_{high\ combustible}$) is 1,548kW/m^2. As the intent of the spatial separation provisions are to limit the fire spread between properties through limiting the distance between the properties, Equation 3 was rearranged to establish a limiting configuration factor between the burning building and a point of receiving radiation at the protected building:

$$F_{BP} = \frac{I_p}{E_B} \tag{4}$$

Where I_p = maximum tolerable radiation level at protected building (kW/m^2)

F_{BP} = configuration factor at point of protected building from the burning building

E_B = estimated an equivalent window radiation level at burning building (kW/m^2)

The maximum tolerable radiation level was then deemed to be the pilot ignition intensity concluded from the Ottawa Dwelling house fire of 12.5kw/m^2 [38]. Using this value with the emissive energy, $E_{B,}$ as determined through St. Lawrence Burns of 1,548kW/m^2, the maximum configuration factor for a second building to be protected from a burning building with highly combustible content was determined to be 0.008 using Equation 3. A similar approach was taken and the maximum configuration factor was found to be 0.016 for a building with less combustible content. In the end, the study concluded that neither of these values represented other practical examples that had been calculated and further, that neither was economically practical as a basis on which to determine spatial separation.

Further review of the data in the St. Lawrence Burns indicated that the value of E_B used, which was the maximum value of emissive energy, was not reached until a minimum of 16 minutes from the start of the fire. It was noted that, in practice, the fire department would have arrived on site and commenced their emergency response before the fire reached this maximum radiation level. Therefore, after review of response times and fire growth rates, the researchers adjusted the value of E_B to be approximately ¼ of the maximum value reported ($387\text{kW/m}^2 = 1548\text{kW/m}^2 \div 4$) and adjusted the configuration factors to values of 0.035 and 0.07. At the time, it was deemed that the assumptions embedded in the “hypothetical maximum emissivity” values used for the burning building brought in conservative results which could be further supported by values observed in other unsprinklered fires [41]. Thus, these values have since been considered acceptable in the building code from both economical and risk-informed grounds. They further noted that 0.035 refers to particularly hazardous conditions which includes, but is not limited to, large amounts of combustible interior finishes (more than 25% of walls and ceiling space), high fuel load or highly flammable building contents. On the other hand, the value of 0.07 represents a configuration factor that could be applied to fire conditions that are not prescribed for 0.035 noted above. Two spatial separation tables were then derived using radiation calculations based on the configuration factors of 0.035 and 0.07 and were adopted in the NBCC 1965. The table prescribed a maximum size of unprotected opening permitted based on the building exterior wall area, available limiting distance and ratio between height and width of building walls. Therefore, the code user can determine the maximum size of unprotected openings permitted at their building exterior walls without going through any complex calculation. The original tables presented in this version of the code, NBCC 1965, did not include any information related to the potential for sprinkler systems in buildings so were intended to be applied to unsprinklered buildings, in part because sprinklers were not widely adopted at the time and also because the buildings in the St. Lawrence Burns were all unsprinklered.

Later in the 1980s’ code revision cycle, two additional spatial separation tables designated for sprinklered building were introduced. At this time, the requirements were updated to acknowledge advancements in sprinkler technology and the requirement for installation of sprinkler systems in the code revision. The existing tables were also retained and were designated for use in the case of unsprinklered buildings. These tables further allowed code users to determine the allowable size of the unprotected openings in an exterior wall, based on the size of the wall and the limiting distance between properties. The opening sizes permitted in these new tables were equivalent to twice the values corresponding to the same wall size and limiting distance criteria listed in the previous tables for unsprinklered buildings. No scientific background in support of this change is referenced in the code, nor is it evident upon review of the literature, what evidence might have been provided to support such a change.

Assuming a typical sprinklered office opening of 5m^2 which has a ceiling height of 4m (*H = 4m)* and a length of 2.5m (*L = 2.5m*) and a limiting distance of 3m, the VBBL permits 100% unprotected opening and the configuration factor found using Equation 4 is calculated to be 0.12 which is approximately 1.71 times larger than the generally accepted value of 0.07 used for unsprinklered conditions. If the threshold value for allowable radiation intensity is kept the same for both sprinklered and unsprinklered conditions, the accepted compartment temperature at the fire origin of a sprinklered building, $T_{sprinklered}$, is 1014C determined through re-arranging Equations 1 to 4 as follows:

$$\frac{Radiant\ Intensity_{sprinklered}}{Radiant\ Intensity_{unsprinklered}} = \frac{\emptyset_{sprinklered}\delta e {T_{sprinklered}}^{4}}{\emptyset_{unsprinklered}\delta e {T_{unsprinklered}}^{4}} = \frac{0.12{T_{sprinklered}}^{4}}{0.07 \times (1200 + 273)^{4}} = 1$$

In contrast to the above results, while unsprinklered fire compartments are assumed to reach temperatures of up to 1200C after 1 hour exposure based on ULC S101 test standard, sprinklers have been shown to effectively maintain fire compartment temperatures circa 200C or less [42]. Therefore, the above calculated and accepted compartment temperature at the fire origin for a sprinklered building, $T_{sprinklered}$ of 1014C is not consistent with results of scientific experiments [42] or accepted sprinkler standards [43].

Furthermore, there are other documents such as NFPA 80A, *"Recommended Practice for Protection of Buildings from Exterior Fire Exposures"*, that provide contrasting evidence in support of the notion that the probability of fire spread to adjacent buildings is limited in sprinklered buildings. In particular, it is stated in Reference 5.6.3 that [44]:

> *"5.6.3. Exposing Building. Where the exposing building or structure is protected throughout by an approved, properly maintained automatic sprinkler system or other approved automatic fire suppression system of adequate design for the hazard involved, no exposure hazard should be considered to exist."*

Interestingly, this acknowledgment of the efficiency of sprinkler systems is not implemented in the spatial separation requirements, although NFPA 80A is referenced in Appendix A-3 of VBBL [26] which presents a significant inconsistency with the spatial separation tables which have not changed since its introduction in 1985, and the values in the tables for sprinklered building are simply doubled from the unsprinklered ones with no apparent supporting experimental data. These types of inconsistencies in code provisions lead to challenges in setting up a baseline level for fire performance, as well as confusion amongst designers and evaluators in recognizing the fundamental concerns that need to be addressed.

In summary, the development of the Division B solution is based on the series of unsprinklered fire tests dated prior to 1970s. Since this time, the methodology was modified to account for the provision of sprinkler systems in some buildings although there is little or no scientific background supporting many of the values presented in these newer provisions. Otherwise, the provisions have undergone only very minor revisions with the majority of the requirements, especially the unprotected opening sizes, remaining unchanged and carrying through into the latest building code as well. Aside from an apparent lack of scientific support and regular updating of the codes, additional limitations related to the performance of the Division B solutions were uncovered during this research and are summarized below.

3.2.3.3.2 Reliability of Division B Solution

The Division B solutions noted above require designs that include passive fire protection systems such as a 1 hour fire rated assembly or a 45 minute rated shutter to delay the fire spread from building to building. These two approaches form the focus of our current code-based solutions to achieving fire safety from the perspective of spatial separation; however, building fire safety systems and assemblies may be susceptible to damage, error in installation or their operation, or installation may be altered over the life of the building as part of renovations or improvements. As such, it is reasonable to assume that the reliability of such systems will be less than 100%. Through the lens of comparison to alternative designs, then, it is important to study the reliability of each of these design solutions with respect to their potential to provide the level of performance anticipated should a fire occur. Unique to high seismic regions such as the City of

Vancouver, it is important to also evaluate the designed system for performance during and after an earthquake.

Recent research suggests that the reliability of fire rated construction (such as the fire rated wall assemblies, fire rated glazing systems and door assemblies) could be as low as 70% based on a 1980 survey of commercial occupancies [45]. Other studies report a reliability of 90% for fire rated noncombustible construction with openings which incorporate a fire rated auto closer [46]. Studies indicated that 15% of all fire doors in industrial facilities fail to operate properly [47]. Significant also is that only 90% of the facilities reported that the fire doors were regularly inspected. Unlike the regularly used fire doors above, the fire shutters prescribed under the Division B solution for this case will be installed and then not used until they are required to protect the full size of an opening to prevent fire spread in an emergency situation. As the shutters will only drop down in a fire emergency, in reality their performance may degrade over the lifetime of the building. For example, since they are never closed, there is a reasonable chance that they may become obstructed due to interior design of a compartment or renovations that impact the required clearance for full height operation of the shutters over the opening. Further, since they do not require regular inspection, there is a high probability that they will not be maintained or that physical damage to their operating mechanisms and/or tracks will occur over time. Taking these factors into account, an assumption of 70% is considered conservative and realistic to represent the reliability of use of fire shutters in a Division B solution.

Another important aspect of reliability for fire safety solutions in the present case is earthquake performance since the City of Vancouver is located within a high seismic hazard zone as identified by Geological Survey of Canada [48]. In the case of fire shutters, the closures are not tested or examined for their reliability during and after a major earthquake so there is no known data available, but it is known that a building can be expected to sustain shifting and damage. Since a fire shutter needs a designated rail to operate [49], in earthquake conditions an estimate of 50% reliability of operation might be considered appropriately conservative. By a different argument, fire shutters come in only limited sizes. Therefore to satisfy the present building design, multiple devices would be required for each floor. Thus, even if the reliability after a seismic event was higher than 50% (for example 70% per device), with two devices per compartment, the reliability of the design solution would not exceed 50% (70% x 70%) since failure of a single device would constitute failure of the whole system. Given that such devices are required to perform as needed throughout the life of the building, 50% reliability is considered conservative.

As summarized in Table 3.2.3.4, then, the reliability of the Division B solutions (either glazing or 45 minute rated fire shutters) is considered to be approximately 70% during normal fire emergency and 50% during a post-earthquake fire emergency.

Table 3.2.3.4 Summary of Probability of Effectiveness of Division B Solutions

	Division B Fire Rated Shutters/Glazing	
	Normal Fire Emergency	**Post-Earthquake Fire Emergency**
Probability of Effectiveness	70%	50%

3.2.3.3.3 Economic Impact

Building design and construction is a complex social activity. In the architect's eye, a building may be the representation of their creativity; in the engineer's eye, it may be an advanced design for public safety and welfare. However, from the developer's perspective, cost is an important factor in building design. Thus, if the cost is not deemed appropriate, a building does not get built. Although this factor is not explicitly listed within any code, it will play a significant role in final decisions. It is therefore important to assess the two compliant Division B solutions, namely the use of fire rated shutters or fire rated glazing, from the perspective of cost as well.

The cost for fire rated shutters varies for different types, sizes and manufacturers, but ranges between around $10,000.00/piece to $25,000.00/piece. A standard unit may be as large as 15m^2 [34] resulting in a need for approximately 180 shutters to cover the west exterior wall in the present building. Thus, to provide the protection required for the Division B solution via fire shutters, the material cost is estimated to be $ 4,417,000.00 excluding labor costs.

For the solution based on use of fire rated glazing, there are currently a limited number of manufacturers capable of producing glazing assemblies that meet the specific fire rating requirements prescribed in the building code. The cost for these is estimated to be approximately \$5,390/m^2 (\$500/ft^2) excluding labor costs. Therefore, for the Division B solution, a rough estimate of material cost would be \$14,281,000.00 (\$5,390/m^2 x 2,649.5m^2), before accounting for the specialized labor forces required for proper installation and inspection of advanced glazing systems.

The cost impact is summarized in Table 3.2.3.5.

Table 3.2.3.5 Summary of Cost Estimation of Division B Solutions

	Division B	
	Fire Rated Shutters	Fire Rated Glazing System
Approximate Cost Estimation	\$4,417,000.00	\$14,281,000.00

It is clear from these results that cost of both Division B solutions are unrealistically high. At the same time, despite being allowable solutions per the spatial separation provisions of the building code, they do not appear to provide reliable fire protection in terms of limiting fire spread in the event of an emergency.

3.2.3.3.4 Design Practicality

The final benchmark that must be assessed is the practicality of the designs that are prescribed via the Division B solutions. According to manufacturer's literature, the prescribed fire rated glazing systems will be tinted which could compromise the architectural intent and outlook of having a fully open west wall on the building. Equally, the fire rated shutters may be impractical for this case study. Since the subject building is an office occupancy, storage and furniture can be pushed close to the openings on the west wall where the fire shutters are installed. As discussed in Section 3.2.3.5.2, this could certainly prevent the fire shutters from fully closing and thus compromise their function. In addition, office buildings are often modified over time to accommodate the needs of different tenants. In this situation as well, the fire shutters may be altered or even removed, resulting in a non-compliant design condition, as future tenants may not realize the importance of the shutters in terms of fire safety.

3.2.3.4 Limitations of Division B Solutions

In summary, the Division B solution for the proposed west building face requires approximately 2,066.6m^2 (78%) of west exterior wall to be provided with protection. The options that are available under Division B greatly inhibit the desire to provide 100% natural lighting. Furthermore, review of the available Division B solutions indicates that the following limitations are embedded within the allowable designs specified to comply with spatial separation requirements for this building:

a. Lack of Traceable Scientific Support: Existing spatial separation provisions are based on the data obtained in a series of unsprinklered residential/institutional fire tests conducted in 1965. There appear to be inconsistencies in data transfer from the test reports to the final numbers listed in the codes. No additional fire tests appear to have been conducted, and no other scientific support is evident within the code documentation, to explain how the provisions were modified later for application to sprinklered buildings. This lack of scientific support for the code provisions raises questions about their universality for use in building design.

b. Reliability of Design System: The Division B solution prescribes the use of fire rated glazing or fire rated shutters. However, the reliability of both of these options has been reported to be less than 100% under normal fire conditions. It may reasonably be assumed to be significantly lower under seismic conditions. Therefore, the reliability of the acceptable Division B solutions comes into question for the proposed design.

c. High-Cost Impact: The cost of both the 1 hour rated glazing assemblies and the 45 minute rated fire shutters is very high and would lead to significant increases in construction cost given the number of shutters or amount of glazing material required, particularly when coupled to the need for specialty installation. If no further options are explored, the additional costs may easily exhaust the estimated construction budget, and lead to a need to make major alternations to the desired design.

d. Design Practicality: A final limitation of the acceptable Division B solutions is practicability of the designs. Fire rated glazing systems are tinted and fire rated shutters are susceptible to obstruction and failure due to furniture or storage containers being pushed close to the opening or they may even be removed during tenant improvements if their importance is not understood.

Based on the foregoing discussions, the acceptable Division B solutions do not appear to simultaneously meet the key design intents of the building. Therefore, it is proposed instead to consider an alternative design approach in order to achieve the desired 100% window opening at the west exterior wall of the building in this case study. This will then be compared to the Division B solutions using the four factors discussed in this Section.

3.2.4 Alternative Solution

3.2.4.1 Introduction

As discussed in Chapter 2, the building code provides an option for a designer to use alternative design approaches to those outlined in Division B, as long as they achieve the same (or better) level of performance than the Division B solution (see Section 2.1.1) and are accepted by the local AHJ. As such, this section discusses a proposed alternative solution approach intended to provide the same level of performance as for the Division B solutions whilst also maintaining the 100% window open on the west wall specified in the original design intent. Once the alternative solution is outlined, it is then compared to the baseline level of performance that was satisfied in the Division B solution.

The proposed alternative solution is illustrated in Figure 3.2.4.1. It consists of a water curtain sprinkler system to be installed adjacent to the west exterior wall to enhance the building sprinkler system. Further, it is supplemented with a backup water tank to provide a secondary water source for the sprinklers if anything happened to the main water supply.

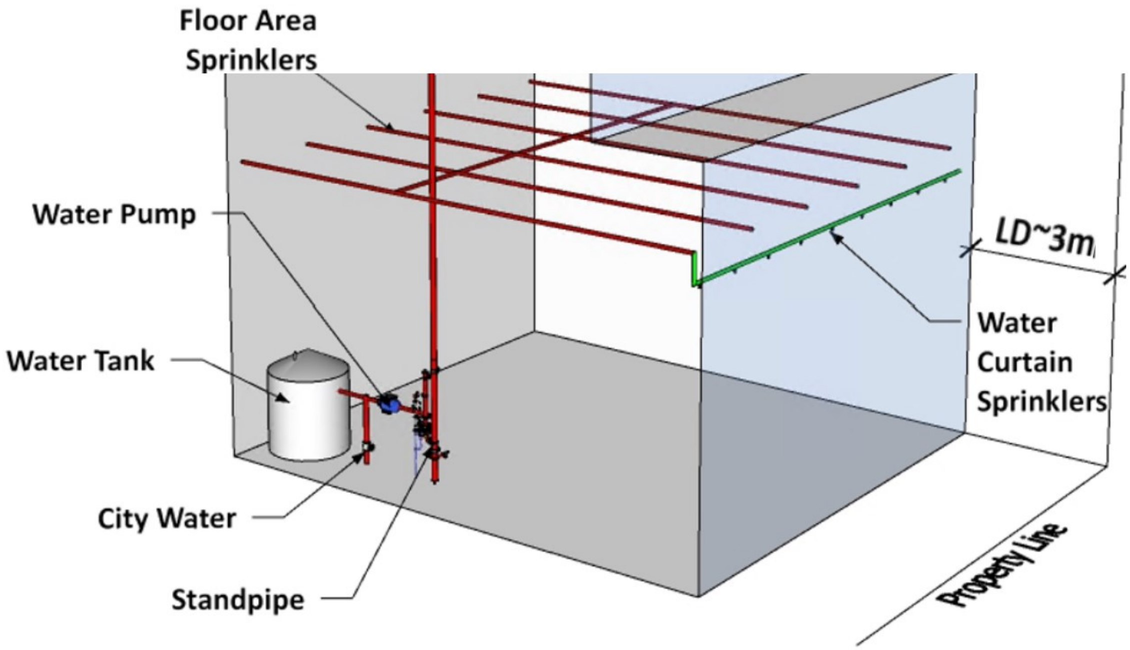

Figure 3.2.4.1 Sketch Illustration of Proposed Alternative Solution Addressing Spatial Separation

Key elements of the alternative design include:

a. Sprinkler System: The entire building is sprinklered to NPFA 13 and VBBL provisions.

b. Tempered Glazing System: Tempered glazing will be installed on the west exterior wall.

c. Water Curtain Sprinkler Design: At all levels of the west exterior wall, a line of closely spaced sprinklers with the following design specifications, namely water curtain sprinklers (WCS) as defined in NFPA 13, will be installed:

sprinkler heads	fast response to match floor area sprinklers.
sprinkler position	6in (150mm) to 12in (300mm) from west exterior wall on the interior side.
sprinkler spacing	for openings under 6ft (1.8m) in width, one sprinkler head will be centered in opening; for openings over 6ft (1.8m), sprinklers will be spaced at 6ft (1.8m) o.c., with no more than 3ft (0.9m) between the outermost sprinkler and the edge of the opening.

sprinkler obstruction	the sprinklers should be located such that the heads are free of obstruction.
sprinkler piping	it will be a wet system to match the floor area sprinkler system.
sprinkler supply	water will be supplied from the floor area system.
pressure/flow	minimum 26 usgpm per sprinkler.
hydraulic calculation	water demand and piping will be hydraulically calculated based on the water curtain sprinkler demand and floor area demand per NFPA 13.
baffles	noncombustible baffles will be provided between any sprinklers located closer than 6ft (1.8m) apart and in accordance with NFPA 13.

d. Back-up Water Supply: A backup water tank will be installed that is capable of supplying the sprinkler system should it be required. For this, the VBBL and NFPA assume that supply is needed one fire at a time. In addition, the tank has to be large enough to supply the floor area sprinklers for the 1 hour water supply duration required for Group D, office occupancy in NPFA 13 design criteria. Therefore, the tank will be sized to supply the necessary sprinkler water to feed both the floor area and water curtain sprinklers on the most demanding floor, which will probably be the floor with the largest floor area in size. Finally, to address seismic stipulations in Vancouver, the tank will be seismically restrained and designed to resist seismic impact such that it should remain operational during and after a major seismic event.[5]

3.2.5 Evaluation of Solutions

3.2.5.1 Differences Between Design Solutions

Table 3.2.5.1 below summarizes key features of the applicable Division B solutions and the proposed alternative solution. Both solutions will include NFPA 13 compliant sprinkler systems. In addition, the Division B solutions include the approximately 582.9m^2 allowable unprotected area on the west exterior wall with the remainder (2,066.6m^2) being protected with 1 hour fire rated glazing or 45

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[5] Discussion of seismic design of tank fall outside the scope of this thesis, so while mentioned here it will not be discussed further.

minute fire rated shutters. The alternative solution includes protection of the entire west exterior wall (2,649.5m^2) with an enhanced sprinkler system including water curtain sprinklers and backup tank.

Table 3.2.5.1 Summary of Division B Solution and Alternative Solution

	Division B Solution	Alternative Solution
Area of Opening without Protection	582.9m^2	-
Area of Opening with Protection	2,066.6m^2	2,649.5m^2
Protection Method	1 hour fire rated glazing or 45 minute fire rated shutters	Enhanced sprinkler system with water curtain sprinklers and backup tank

3.2.5.2 Evaluation of Alternative Solution

The above noted alternative solution achieves the design intent of providing 100% natural lighting at the west exterior wall by allowing 100% glazing system on the wall; however, it is important to review the level of fire and life safety performance in terms of limiting fire spread. As was done for the Division B solution, the comparison will be conducted based on background and scientific support, reliability of systems, economic impact as well as the design practicality.

3.2.5.2.1 History and Scientific Support for the Alternative Solution

General Sprinkler System Effectiveness

The probable mode of fire spread between properties is through radiation due to high temperatures within the room of fire origin as identified in Equation 1 and 2. Also discussed in the history of the Division B solutions, the effectiveness of the sprinkler systems to control the fire growth and spread is recognized in sprinkler standards and other provisions in the VBBL although not clearly captured in the spatial separation provisions. As such, a secondary calculation for the impact of the sprinkler systems is presented here.

A typical quick response floor area sprinkler with a response time index of 50m$^{1/2}$s$^{1/2}$, which is commonly used in most modern buildings, is required to maintain the gas temperature at 76mm (3in) below the ceiling at 316C [50]. Thus, the comparative reduction in radiation between a sprinklered and an unsprinklered fire compartment can be estimated using Equation 1.

$$\frac{Radiant\ Intensity_{sprinklered}}{Radiant\ Intensity_{unsprinklered}} = \frac{\delta e(316+273)^4}{\delta e(1200+273)^4} = \frac{\delta e(589)^4}{\delta e(1473)^4} \sim 2.6\%$$

As shown, when sprinklers operate and control the fire, they can potentially reduce the radiation from a fire compartment by up to 97.4% (100% - 2.6%) compared with unsprinklered conditions. This inherently reduces the probability of fire spread to adjacent buildings and thus, sprinklers can actually meet the fire and life safety intent of VBBL without additional protection. Since the full impact of sprinklers is not fully considered in the Division B solution methodology however, the present alternative solution also features additional protection via the water curtain sprinklers and secondary water tank. These measures are included to overcome the apparent inconsistency in spatial separation design provisions in VBBL already outlined above.

Performance of Water Curtain Sprinklers

Water curtain sprinklers have been recognized by NFPA 13 as one of the methods to protect unrated openings for the purpose of limiting radiation transfer through the opening and thus minimize the spread of a fire. Although this method has not been recognized by the NBC, recent fire science research and full-scale tests have confirmed that the introduction of water curtain sprinklers provide a significant reduction in the radiation heat transfer from an opening. In a 2015 fire test series conducted at Carleton University Fire Research Lab, water curtains with different discharge rates for different design fire sizes were tested. The water curtain sprinklers were placed outside the room containing the fire such that they did not interfere with the fire development within the room. The reduction in radiation observed with the water curtain sprinklers was up to 40%, and thus they can make a significant impact in limiting the probability of fire spread [51].

Performance of Tempered Glazing System

Glazing was first developed to introduce natural lighting to buildings to promote better living environments. Since being invented in the early ages (around 1500BC), glazing has been recognized as fragile material which can be shattered under thermal shock following equation 5 [52]:

$$\varepsilon_b = \frac{\sigma_b}{E} = \beta \Delta T_b \tag{5}$$

and where ε_b is the emissivity at breakage point, σ_b is the radiation stress at breakage, E is Young's Modulus (72GPa), β is the thermal coefficient of linear expansion (9E-6 K^{-1}). In an early study of the performance of non-fire rated glazing, it was determined that ordinary window glass would break before flashover of a fire. A critical breakage temperature for glass was determined to be 80C [52]. As discussed in the sprinkler section, this is approximately the same as the temperature of the ceiling gas layer when sprinklers have activated. Therefore, except in instances where it has been specially designed for a certain fire resistance rating, glazing is not recognized as a protective methodology to limit fire spread. While ordinary window glass may crack and break as it suffers from thermal shock, full scale studies have shown that tempered glazing protected by sprinklers remained intact and could withstand the standard time-temperature exposure for a duration of 2 hours [53, 54]. Further, only 31% of the radiation heat was transmitted through the glass when the temperature of the hot emitting layers reached 1400K, a temperature which is well recognized in the construction industry as a standard temperature in an unsprinklered compartment after 1 hour exposure [54]. In independent full-scale fire research, sprinkler protected tempered glazing systems were found to reduce radiation heat flux even further, by 90%, and thus limit the spread of the fire due to the low radiation transmission [53].

Based on these findings, the proposed tempered glazing is anticipated to improve resistance to thermal shock over ordinary window glass and also to reduce radiation heat transmission, thus significantly increasing the level of performance of the alternative design in comparison to either of the Division B solutions, particularly when coupled with the water curtain and main floor sprinkler systems.

3.2.5.2.2 Reliability of Alternative Solution

The reliability of the alternative design is inherently linked to the sprinkler systems included in the building design. This is in contrast to evaluation of the Division B solutions where sprinklers were inherently included via modifications to the spatial separation tables and thus their impact was not explicitly taken into account in evaluation of design reliability. In regard to the alternative design, further examination of the code (Appendix A of Division B, Part 3.2) elucidates that sprinkler systems are considered a reliable technology for controlling fire spread to adjacent property:

> *"…In the case of a building that is sprinklered throughout, the automatic sprinkler system should control the fire to an extent that radiation to neighboring buildings should be minimal. Although there will be some radiation effect on a sprinklered building from a fire in a neighboring building, the internal sprinkler system should control any fires that might be ignited in the building and thereby minimize the possibility of the fire spreading into the exposed building. NFPA 80A, "Protection of Buildings from Exterior Fire Exposures," provides additional information on the possibility of fire spread at building exteriors."*

Post-fire analysis has shown that office fires in sprinklered buildings were typically limited to an area of 16m^2 or less [55], further demonstrating that an effective sprinkler system will control fire growth to avoid spread to adjacent buildings and thus directly satisfies the intent attributed to the spatial separation requirements. The reliability of sprinkler systems has vastly improved over time with wet pipe sprinklers, including the water curtain sprinklers, expected to have an 89% total effectiveness [56]. While the age of the systems used in the data analysis is not always reported, nor is it always clear whether the systems are supervised or monitored, it is assumed that the overall reliability reported will reflect both monitored and unmonitored sprinkler systems. Other work postulates a 99% reliability for sprinkler systems which are properly designed and maintained [54].

Use of a higher value for reliability might be justified in the present building since the main reason for the ineffectiveness of a sprinkler is that *"water does not reach the fire"* to perform suppression [56]. This cause has contributed more than half of the sprinkler failure statistics (51%) reported [56]. Other causes include "manual intervention", "not enough water discharged" and "system components damaged" which suggests the category "water does not reach the fire" describes the condition where the source of water supply for the sprinkler system is not available and the sprinkler system is thus unable to control the fire spread. Other scenarios may come from the misplacement of sprinklers due to either inadequate design or improper site installation and review. However, given the modern approval and inspection process enforced in current building design and development in the majority of AHJs in Canada, these scenarios are not considered as significant contributors to sprinkler system failure. Instead, it is assumed that the sprinklers are properly installed onsite following the local AHJ's review and approval. Modern sprinkler systems with improved effectiveness and the enforced monitoring and supervision specified in the building code are anticipated to properly operate during the fire emergency to control the fire growth and spread. The comparative reliability of the Division B solution (using fire rated shutters) and proposed alternative solution (water curtain sprinklers) is then summarized in Table 3.2.5.2.

Table 3.2.5.2 Probability of Effective Protection

	Division B Fire Rated Shutters/Glazing	**Alternative Solution** Water Curtain Sprinklers + Tank
Probability of Effectiveness	70%	89% to 99%

To assess the importance of the reliability of an alternative solution in more depth, the reliability of a proposed protection system could be combined with the probability of a fire occurring in the building. In this case then, the reliability of the sprinkler system would be combined with the probability of a fire occurring in an office occupancy in Canada. Data released by Statistics Canada indicates that in 2014, there were 287 fires in Business and Personal Services (office) occupancy. Similar statistics were reported in 2012 (252 fires) and 2013 (238 fires). While finding comprehensive data on total office space was not successful, a private agency in Canada, Colliers International, reported a total area of 448,879,658ft^2 (41,702,284m^2) from inventories for office properties in Canada in 2014. For the year 2014, then there was a probability of 6.9×10^{-6}/year/m^2 (69 fires in 10,000,000m^2 per year) for occurrence of an office fire. For the present building design with aggregate office floor area of approximately 15,650m^2 (22.84m×22.84m) and taking the probability of successful sprinkler operation as 95%[6] for office fires with properly designed and maintained sprinkler systems, a first order estimate of the probability of a fire occurring in the building and there being an ineffective sprinkler system can be calculated to be approximately 1.08×10^{-4} /year or about 1 in 9,260 years. This probability is more frequent than the 10^{-6}/year that is often regarded as the “de minimis risk” probability such that the event is not of regulatory concern [31]. At the same time, the estimated probability, 1 in 9,260 years, suggests that this combination of events (fire without sprinkler

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[6] This value is taken as average of 89% and 99% as reported previously. [56] & [54]

operation) is unlikely to occur during the anticipated lifetime of a building. Therefore, by taking reliability and probability into account when assessing the level of performance of a design, it provides guidance on how to interpret to "*limit the probability…*" as noted in the intent statement of the Division B solutions for designers and reviewers.

Design in Seismic Condition

Another consideration that is not included in a Division B solution but that should be taken into account in a building in the Vancouver area is the potential for a fire, and even possibly an urban conflagration, after a major seismic event. This can again be considered during evaluation of an alternative solution in comparison to a Division B solution for the building. For normal situations, major sources of risk for urban conflagration, such as building to building fire spread are known and their probability mitigated through code-based fire safety measures [57]. However, such a risk remains high in a post seismic event due to damage of structures leading to potential malfunction of fire protection systems (such as fire resistance assemblies, sprinkler system and water supply) coupled with possible delays in firefighting response [72]. Therefore, in a high seismic zone such as Vancouver, it is important to consider whether design protection measures will remain operational in terms of limiting the potential for fire growth and spread after an earthquake.

No estimates of the reliability of fire shutters (as required by Division B) after a major seismic event could be found. Further, fire shutters are not tested or examined for reliability of operation in this situation. However, fire shutters require good alignment with the opening to be protected, as well as free clearance for their operation. Since they can be expected to sustain shifting and damage during a seismic event, their post-earthquake reliability can be questioned, as it may be substantially lower than in a non-seismic situation.

There is similarly little statistical evidence related to the operation of modern sprinkler systems after an earthquake although one study suggests that there could be up to a 2% failure of sprinkler systems [58]. Such evidence and other experience prompted numerous changes to NFPA 13 and recent analysis indicates that the reliability of a system installed to NFPA 13, 1999 edition or later, can be expected to be high even after a seismic event, remaining within the range of 90% to 99% discussed above.

Another possible weak point in sprinkler fire protection systems during or after an earthquake relates to availability of water supply. The current code only requires a municipal water supply to feed a sprinkler system. However, the reliability of municipal water may be significantly decreased after a seismic event. This will lead to ineffective sprinkler activation and thus, poor control of fire growth and spread. To address any potential failure in water supply in the alternative solution, a seismic-resistant water tank with a volume sized to supply the sprinklers for a duration of 1 hour is proposed to tie into the sprinkler system [43]. It is also noted that other components of the sprinkler system are also required to be provided with appropriate seismic-resistance design under Part 4 of the building code [12]. This additional layer of protection, of course, also increases the reliability of the overall sprinkler performance in controlling fire growth and spread to meet the building code intent even under normal fire conditions.

Inconsistent Recognition of Alternative Design Options throughout Canada

It is worth noting that some municipalities have prescribed the use of the sprinkler-based glazing protection designs, in addition to the two acceptable Division B solutions noted in Section 3.2.3, as code compliant solutions. For example, Standata 19-BCV-013 which is enforced in Alberta prescribes a sprinkler-protected-glazing system for interior and exterior fire rated wall assemblies (see *Appendix A*). A design following the provisions prescribed in this Standata is considered as a code compliant solution equivalent to the Division B solution in that province. As such, the design team does not need to provide additional analysis and documentation to gain acceptance by the AHJ. Similarly, Article 3.1.8.18 in Division B of the Ontario Building Code (OBC) indicates that the use of sprinkler-protected-glazing systems is considered as a Division B solution in lieu of the acceptable fire rated wall assemblies (see *Appendix B*). In the context of this case study, however, sprinkler based glazing protection systems are not appropriately recognized in other jurisdictions, such as British Columbia. Further, the solutions outlined in Standata 19-BCV-013 and OBC Article 3.1.8.18 do not include the back-up water tank used here to address the special natural seismic hazards that exist in the Vancouver region. In the national context then, such inconsistencies from province to province are confusing to both design and review teams as they seek to establish the appropriate level of performance for similar designs in different jurisdictions.

Summary of Reliability

Based on the foregoing discussion, the level of performance of the proposed alternative solution is compared to that of the Division B solution in Table 3.2.5.3. Although the performance of fire safety systems in seismic events is not explicitly prescribed in the building code, nor referenced in the intent statement mentioned previously, it may be argued that the alternative solution is better than the traditional solution during seismic conditions. Taking a holistic perspective however, the overall intent for fire protection in the building design is to limit fire spread between buildings and minimize risk of building-to-building conflagration situations. In some regions, such as Vancouver, these are even more probable after an earthquake, so the neglect of consideration of fire protection system performance in seismic conditions potentially increases risk of this happening for the code compliant design, compared with the alternative solution. Even in municipalities where earthquake is not as high a risk as in Vancouver, inconsistency in recognizing similar design solutions in different jurisdictions leads towards confusion to both design and review teams when establishing an appropriate, fundamental level of performance in a certain scenario. Such inconsistencies should again be investigated in future studies aimed toward improving the regulatory environment for Canadian buildings.

Table 3.2.5.3 Probability of Effective Protection in Seismic Condition

	Division B Fire Rated Shutters/Glazing	**Alternative Solution** Water Curtain Sprinklers + Tank
Probability of Effectiveness	50%	~ 99% with additional tank water supply

3.2.5.3 Economic Impact

In this section, the proposed alternative solution is compared to the Division B solutions in terms of cost and thus economic impact of construction. The alternative solution requires additional sprinkler heads for the water curtain systems along the west wall as well as a water supply tank that could either be buried in the basement with water pump to boost the water to floors or located on the roof. Since the building is an office occupancy, the sprinkler heads will be the same sprinkler heads as used to sprinkler the floor area and thus, while there will be an increase in material cost for the heads themselves, their installation does not require any specialized labour. The cost for the additional sprinklers will therefore be much lower than the millions of dollars required for either of the Division B solutions. Based on recent project experience, installation of water curtain sprinklers including labor requirement is instead estimated at approximately $300,000.00 for the entire west building face. In addition, the construction of a concrete water tank in the basement is estimated at approximately $25,000.00, a relatively low cost but with potential for significant positive impacts on reliability of the overall design. A rough estimation for the cost of the alternative solution is $325,000.00 which includes both materials and the labor.

Estimated costs for the Division B and the proposed alternative solution are on different dollar scales as summarized in Table 3.2.5.4. The Division B solution costs almost 44 times as much as the proposed alternative solution, but despite its potential benefits, the alternative solution may not be approved in jurisdictions where it is appropriate. At the same time, the significant additional cost of the Division B solution place pressure on building designers to come up with other design innovations to cover potentially unnecessary costs when an alternative design is cheaper and can still meet, or even exceed, the design requirements and fire performance specified in the intent of the building code.

Table 3.2.5.4 Approximate Cost Estimation of Division B and Alternative Solutions

	Division B Fire Rated Shutters/Glazing	**Alternative Solution** Water Curtain Sprinklers + Tank
Approximate Cost Estimation	$4,417,000.00 / $14,281,000.00	$325,000.00

3.2.5.4 Design Practicality

Comparison of the alternative solution approach to the Division B solution indicates that the former comes with inherent advantages over latter solutions which use fire rated glazing or shutters. First, the alternative solution is based on use of only sprinklers and water tanks both of which have been widely used in industry for other applications. In contrast, the Division B prescribed glazing or fire shutters require special specification and labor which can increase the potential of faulty installation leading to system failure. Secondly, the combination of the sprinklers system and the water tank form an active fire protection system which also improves the reliability of the code prescribed building sprinkler system. In particular, the water tank adds inherent value as it provides a redundant water supply that enhances the performance of the base building sprinkler. The alternative solution thus benefits the overall building design in terms of fire and life safety considerations.

As was discussed for the fire shutters specified in the Division B solutions, the water curtains could be removed during future alteration or improvement of a given space. However, the backup tank is typically inaccessible to be removed from base building and subject to the design, the floor area sprinkler system may also be connected to the backup water tank. Therefore, the alternative solution design in such a space alteration condition would still have a reliable sprinkler design as a layer of protection to be able to control the fire growth and spread, compared with Division B which relies on the presence of the shutters.

3.2.5.5 Summary of Comparison

Based on the foregoing analysis, the level of performance of the alternative solution meets a code compliant level of performance as per the Division B solutions and outperforms the Division B solutions in several benchmarks as summarized in Table 3.2.5.5:

Table 3.2.5.5 Summary of Performance in Division B and Alternative Solution

	Division B Fire Rated Shutters/Glazing	**Alternative Solution** Water Curtain Sprinklers + Tank
History and Scientific Basis	Data based on limited experiments without later account for the full implications of new technology	Takes into consideration more recent related research findings and development of new technologies
Reliability (normal fire emergencies)	70%	89% to 99%
Reliability (post-earthquake fire emergencies)	50%	89% to 98% Subject to design and site operation
Approximate Cost Estimation	$4,417,000.00 / $14,281,000.00	$325,000.00
Design Practicality	May be altered or damaged and thus may not provide full function when needed	Impact of use / changes in the floor area is minimum to the design

Based on the foregoing, the Division B solutions prescribed for the proposed building present two high-cost design solutions requiring specialty trades, one of which is also a highly user-dependent design option. In contrast, the presented alternative solution provides a cost effective and reliable option to a user to achieve both the design intent of permitting 100% natural lighting while also meeting the VBBL fire and life safety intent to limit fire spread should one occur.

3.2.6 Conclusion

The foregoing case study of spatial separation of an office building presented a comparison between Division B solutions and a proposed alternative solution using water curtain sprinklers and seismic-resistant water tank supply. The objectives and functional statement of the spatial separation provisions prescribed in the code were presented and the level of performance of these solutions were studied in terms of satisfying the intent of the code. The following observations were identified based on the case study:

1. The Division B solution does not have a full rational scientific analysis to support the limited opening sizes prescribed in the spatial separation tables and associated requirements. The spatial separation provisions for unsprinklered buildings were based on real fire experiments conducted more than 55 years ago. The later modification of the provisions to account for sprinklered buildings appeared to be arbitrary without traceable fire science support. The Division B solution methods have not been updated since their introduction in 1965 and the fundamental scientific basis for the material has apparently been lost throughout the code revision cycle. Thus, the prescribed acceptable solutions do not take full account of the development of modern sprinkler technology which significantly contributes to achieving the intent of the spatial separation, namely, to reduce the radiation heat transmission and flame projection to limit the fire spread beyond its origin. The lack of account for advancement of technology during the cycle of code development in this case leads to specification of over-conservative and costly approaches to the design.
2. Several inconsistencies were observed between the provisions of the code. While the code recognizes the effectiveness of the sprinklers in certain provisions, it does not appropriately take

this into account in the spatial separation provisions. In addition, sprinkler-based solutions are recognized as code compliant solutions or have even been incorporated into the code in some municipalities, while the rest of the nation has not followed such an approach. These result in significant discrepancies in setting the minimum level of performance expected as defined in Division A of the code. The inconsistency also creates confusion for end users and the AHJ, resulting in different interpretations, lengthy review processes and possible rejection of the new alternative designs even though they may improve the overall fire protection of the building.

3. As the spatial separation is intended to avoid conflagration due to fire spread between buildings, the Division B solution utilizes passive protection measures such as fire-resistant rated assemblies. The proposed solution uses newer methods for active fire protection in the form of water curtain sprinklers and can thus, if designed appropriately, has potential to provide a considerably higher level of performance than the Division B solution. In addition, recent studies have demonstrated that urban conflagration is more likely during or after a major seismic event. However, assessment of the level of performance of spatial separation design solutions in this situation are not clearly required by the existing code even for high seismic regions such as the City of Vancouver. In the present example, the passive measures required in the Division B solutions may suffer decreased reliability, and thus level of performance during and after a seismic event, since these systems rely on structural stability for their operation. In contrast, the alternative solution, based on active fire protection measures, may be designed to provide some operational redundancy during an earthquake. Detailed analysis of all of the issues involved are outside the scope of the present research, but this an area where additional research is merited in order to improve spatial separation regulations in this regard.

4. One of the acceptable Division B solutions prescribes fire rated wall systems to limit the number of openings in a building wall in order to limit fire spread. This kind of system ignores non-fire related implications such as known social benefits of natural lighting. Several Division B solutions are not cost-effective while also presenting challenges in construction or maintenance throughout

the life of the building. For example, installation of fire shutters which are only required in the event of a fire significantly increases construction and associated maintenance costs for a building. Appropriately fire-rated glazing is also not cost effective and may compromise lighting design as well. In the present regulatory environment, such implicit, but important, factors are not being considered during the design and evaluation of solutions. This should be re-evaluated since it results in increased costs, inhibition of innovation in building design and becomes an encumbrance to the development of the Canadian construction industry.

5. The NBCC prescribes in Division A and Division C that an alternative building design (alternative solution) can be deemed acceptable in place of acceptable provisions (Division B solutions) by Authority Having Jurisdictions provided the level of performance is maintained. However, it does not provide any guidance on what to consider or how to evaluate the level of performance. In the subject case study, the intent statement prescribes the solution "to limit the probability" of fire spread. However, it does not set a baseline for what should be considered and what constitutes acceptable probability. Therefore, the baseline factors and thresholds against which to evaluate various alternative designs are not clear for the users, namely the building design team and the reviewer (AHJ).

It is noted that these questions may not be easily addressed throughout a single code update cycle. Nonetheless, the intent here is to open the discussion by identifying factors that present significant challenges faced in the current Canadian Building Code environment for pursuing performance-based design, even for relatively well described situations like spatial separation design.

3.3 Mass Timber Construction

3.3.1 Introduction

This final case study explores some of the current building code provisions as they might apply to mass timber construction which is a rising technology in the construction market in Canada. Wood, typically referred to as "timber" in construction industry, is recognized as a natural and traditional construction material fabricated with reduced energy consumption, and thus contributes to a sustainably built environment. In the past few decades, several engineered timber products, falling under the name, “mass timber”, have been developed [59]. Mass timber construction is defined by the Quebec Government as follows [60]:

> “… *Type of combustible construction in which a degree of fire safety is attained by the use of structural elements as well as floors and roofs from wood elements of large dimension, and the elimination of concealed spaces in floors, walls and roofs. Structural elements of this type of construction include solid lumber, glued-laminated timber or structural composite lumber post-&-beam structural system, and a massive slab system of cross-laminated timber or other structural composite lumber elements…”*

In short, mass timber construction incorporates engineered wood products which are a category of large, prefabricated, wood building assemblies that are comprised of smaller wood components either mechanically fastened or bonded with special adhesives [61]. Based on the different structural designs, the main categories of mass timber include Cross-Laminated Timber (CLT), Nail-Laminated Timber (NLT), Glued-Laminated Timber (Glulam) and Dowel-Laminated Timber (DLT). Among these, CLT panels and GLT beams, and columns are currently the most popular products used in the Canadian construction industry [61].

In this subchapter, a hypothetical case study related to mass timber construction is presented that compares current applicable building code provisions related to requirements on construction materials to recent scientific studies related to mass timber construction. From this, challenges in achieving building code compliance when using a performance-based design approach with this relatively modern material will be investigated.

3.3.2 Brief Introduction of Cross Laminated Timber (CLT)

3.3.2.1 What is CLT

CLT originates in Europe and is rapidly become popular among construction materials due to its high level of prefabrication, which facilitates fast-track construction schedules, and its low carbon footprint, thus contributing to green construction [61]. The desire for sustainable, innovative building design in the Canadian construction industry has raised interest in use of mass timber, including construction using CLT panels. Yet, this manner of construction is not currently appropriately considered in the building code which is still trying to catch up with this latest technology.

The most commonly seen CLT product is a CLT panel which consists of a few of layers of lumber boards stacked in alternating perpendicular directions, bonded with specially designed structural adhesives, and mechanically pressed to form a solid timber panel as shown in Figure 3.3.2.1. The thickness of the individual lumber board varies from 16mm to 51mm with a width that varies from 60mm to 240mm depending on the design [59]. The panels are formed into an odd number of layers, typically ranging from three to seven, subject to the loadbearing and fire resistance requirements of a design.

Figure 3.3.2.1 CLT Panel Configuration Illustration [62]

Design and construction with CLT panel offers advantages including design flexibility and innovation, high thermal performance and energy efficiency, cost effectiveness through fast-track construction scheduling, environmental sustainability as well as improved building performance such as fire resistance rating and seismic performance [71, 59]. As the scope of this thesis is limited to fire protection, design for the fire resistance of CLT construction will form the focus in this discussion.

3.3.2.2 Recognition in Canada

Since its introduction to the Canadian construction industry, research on CLT has been conducted to understand the material and to reach an industry-wide consensus on how to regulate CLT construction.

In 2012, the first CLT standard, ANSI/APA PRG 320 - 2012, *"Performance Standard for Cross-Laminated Timber"* (PRG-320 – 2012), was published by a joint task force including APA-The Engineered Wood Association from the US and FPInnovations from Canada [64]. This standard focuses on quality assurance and regulating the manufacturing process as a first step to standardize commercial use of CLT [59].

In 2014, the Standards Council Canada (SCC) published an updated design guide, CSA O86 "*Engineering Design in Wood"*, which provides specific design criteria for CLT. This standard is referenced in NBCC and other provincial or municipal building codes as design guidance for structural wood materials. Specifically in Annex B of CSA O86, design methodology for assessing fire resistance of large-cross-section wood elements such as CLT is provided for Canadian application.

In the latest NBCC update, namely NBCC 2020, mass timber elements, together with guidance on appropriate fire safety protection, are recognized as a unique construction material in addition to the two traditional construction types (combustible or noncombustible) [11]. This new construction type is named "Encapsulated Mass Timber Construction" (EMTC). Unfortunately, the launch of the 2020 version of the NBCC was delayed until recently due to the COVID-19 pandemic and has yet to be adopted by the appropriate AHJ in British Columbia at the time of writing of this thesis. However, some provincial or municipal building codes, such as the British Columbia Building Code (BCBC) 2018 [12] and Alberta Standata 19-BCV-014 [65], include similar provisions to permit the use of the EMTC. For ease of reference, this thesis will use BCBC 2018 as the example in the following discussion.

BCBC permits building certain types of occupancy up to 12-storeys in building height with EMTC. EMTC is defined as a type of construction which provides fire safety through the use of structural mass timber elements with a certain "encapsulation rating" [12]. The encapsulation rating is further defined in BCBC as the period of time that the method of encapsulation will delay the ignition and subsequent combustion of any mass timber elements when exposed to fire [12]. The proven encapsulation materials typically consist of noncombustible materials such as gypsum board prescribed in BCBC. Following Article 3.1.19.2, a 50 minute "encapsulation rating" is assigned to two layers of Type X gypsum board, each of

12.7mm thickness, mechanically fasted 20mm into the exposed side of the mass timber element with fasteners spaced no more than 400mm on centre.

At the same time, neither CLT nor mass timber are directly defined by BCBC. The closest provisions applicable to mass timber are Sentences 3.1.18.3.(2) and (3) of BCBC as follows:

Article 3.1.18.3 *Structural Mass Timber Elements*

Sentence (2) *Structural mass timber elements referred to in Sentence (1) shall*

a). Except as permitted in Sentence (4), be arranged in heavy solid masses containing no concealed spaces,

b). have essentially smooth flat surfaces with no thin section or sharp projections, and

c). except as provided in Article 3.1.18.15, conform to the minimum dimensions stated in Table 3.1.18.3.

Table 3.1.18.3

Structural Wood Elements	Minimum Thickness, mm	Minimum Width x Depth, mm x mm
Walls that are fire separations or exterior walls (1-sided exposure)	96	-
Walls that require fire-resistance rating, but are not fire separations (2-sided exposure)	192	-
Floors and roofs (1-sided exposure)	96	-
Beams, columns and arches (2- or 3-sided fire exposure)-sided exposure)	-	192 x 192
Beams, columns and arches (4-sided fire exposure)	-	224 x 224

Sentence (3) *Adhesives used in structural mass timber elements referred to in Sentence (1) that are constructed of cross-laminated timber shall conform to the elevated temperature performance requirement in ANSI/AP PRG 320 "Standard for Performance-Rated Cross Laminated Timber".*

The provisions above, although not directly referenced to CLT products, reference the same standard used in industry for quality assurance and manufacturing of CLT. They also prescribe minimum thicknesses of the solid wood elements similar to what is typically defined for CLT [62]. It remains, however, that since CLT products cannot pass the acceptance criteria prescribed in CAN/ULC-S114, "*Test for Determination of Noncombustibility in Building Materials*" [18], they are not recognized by the BCBC as a noncombustible construction material. Instead, the BCBC 2018 specifies three types of construction: the traditional noncombustible construction, the combustible construction, and a new EMTC category. Construction with CLT does not fall under noncombustible construction, but also cannot satisfy EMTC construction requirements without the additional protection prescribed therein. Thus, construction with exposed CLT is still considered as combustible construction similar to light wood frame design for building code compliance purposes. As a result, the BCBC does not take the unique benefits of CLT into consideration, potentially leading to conservatively redundant designs that may not really be necessary with CLT construction.

3.3.2.3 Fire Resistance

A large part of the discussion around code compliance vis a vis use of CLT centers on the issue that, being manufactured of wood, CLT elements can contribute to the growth of a fire potentially leading to a negative impact on overall building performance in a fire [66]. When exposed to heat and fire, all wood elements undergo thermal degradation; as moisture and volatile compounds pyrolyze, the wood is converted to char and flammable gases [31]. Recent experimental data show that CLT, when exposed to radiant heat or fire, burns along the surface leading to charring of the wood elements. The charred layer then tends to protect the remaining layers of CLT from degradation [61]. Once the fire source is removed, the same level of combustion cannot be sustained on a CLT element due to significant heat loss into the mass timber; and eventually the reactions self-extinguish [67]. As long as it is designed appropriately, the remaining portion of the CLT mass timber assembly can be sized to carry the required load and prevent further passage of flame [61]. Therefore, the design of a CLT structural element consists of two portions: the portion that would form a protective char layer during a certain fire exposure, and the portion that would support the full structural load required in the original design. The final fire resistance rating of the assembly would be determined based on assessment of both portions. As this thesis is focused on the fire performance of the

CLT, discussion related to fire resistance rating is centered on characteristics such as char layer formation and does not consider the full evaluation related to the remaining structural capacity of the element.

Charring rates and char layer depth have been determined based on real fire test data by FPInnovations and are incorporated into CSA O86 which was updated as recently as 2019 [68]. Annex B of the standard introduces an equation to determine the char layer depth (mm) of CLT materials as follows [69]:

$$x_C = \beta \times t \tag{6}$$

Where β = charring rate, mm/min

t = fire exposure duration, min

The charring rate β, has two different representations, β_0 and β_n as defined in O86. β_0 is the one-dimensional charring rate with a constant value of 0.65mm/min for CLT and is prescribed when charring sustained only within the first exposed layer. β_n is the notional charring rate with a constant value 0.8mm/min for CLT and is prescribed when charring that extends below first exposed layer [69]. In addition, O86 prescribes including an additional depth, referred a “Zero-Strength Layer depth”, x_t, which is equal to 7mm when the fire exposure duration is over 20 minutes. Therefore, for a typical 5-ply (layer) CLT panel with a thickness of 175mm, a 2 hour fire exposure would leave 73mm (175mm – 0.8mm/min ×120min -7mm) of unaffected thickness on the structural element. This thickness could then be assessed to determine whether the element would maintain its structural integrity during a given fire. In the 2019 version of O86, this methodology remains the same as in the 2014 version indicating a conservative 0.8mm/min for β_n[69]. Looking forward, several recent experimental reports have determined that with the updated *ANSI/AP PRG* 320 [66, 67, 68] requiring improved heat resistant adhesive, the nominal charring rate (β_n) of the CLT has decreased to as low as 0.65mm/min independent of how deep the char penetrates the surface [66]. With this improved charring rate, the unaffected thickness of the structural elements would be 90mm, which is an approximately 20% increase compared with the existing methodology.

In 2019, a series of fire resistance tests on were conducted on several 5-ply (175mm) CLT panels manufactured according to ANSI/APA PRG 320, 2018 Edition [66]. One of the tested assemblies was configured as a ceiling in a full-scale fire test apparatus and exposed to furnace temperatures which followed the "Standard Temperature Curve" from CAN/ULC-S101-14, as also referenced in the NBCC and BCBC to determine the fire resistance rating of construction materials [66]. Although the objective of this research is to determine the charring rate of the assembly as well as the potential contribution to the fire growth and intensity, it is interesting from the point of view of structural integrity that the results of these tests also demonstrated that CLT panels with appropriate thickness and under structural load will achieve 2 hour fire resistance rating as recognized by NBCC. Therefore, exposed CLT panels with appropriately calculated design thickness, although seen as combustible elements, are expected to provide sufficient resistance to fire exposure to maintain structural integrity over the prescribed period of fire exposure.

With the above background, the use of CLT panels in building construction and how their use relates to current code compliance in the NBCC, are discussed further in the case study below.

3.3.3 Building Characteristics

In this final case study, it is proposed to use exposed CLT panels, with no additional protection as floor assemblies in a 3-storey residential building in Richmond, BC. The rest of the building construction is noncombustible. The building has a building area of 3,500m^2/floor as illustrated in Figure 3.3.3.1. Further, it is proposed to sprinkler the building following the applicable design criteria for its occupancy, as prescribed in the local governing Building Code, the British Columbia Building Code 2018 Edition (BCBC).

The building has the following characteristics:

Building Height:	3 storeys
Building Area:	3,500 m^2
Building Occupancy:	Group C, Residential
Sprinkler:	Yes to NFPA 13 per BCBC 2018

Street Facing: 1 Street

Floor Construction Material: Exposed CLT floor panel without protection

Other Construction Material: Noncombustible

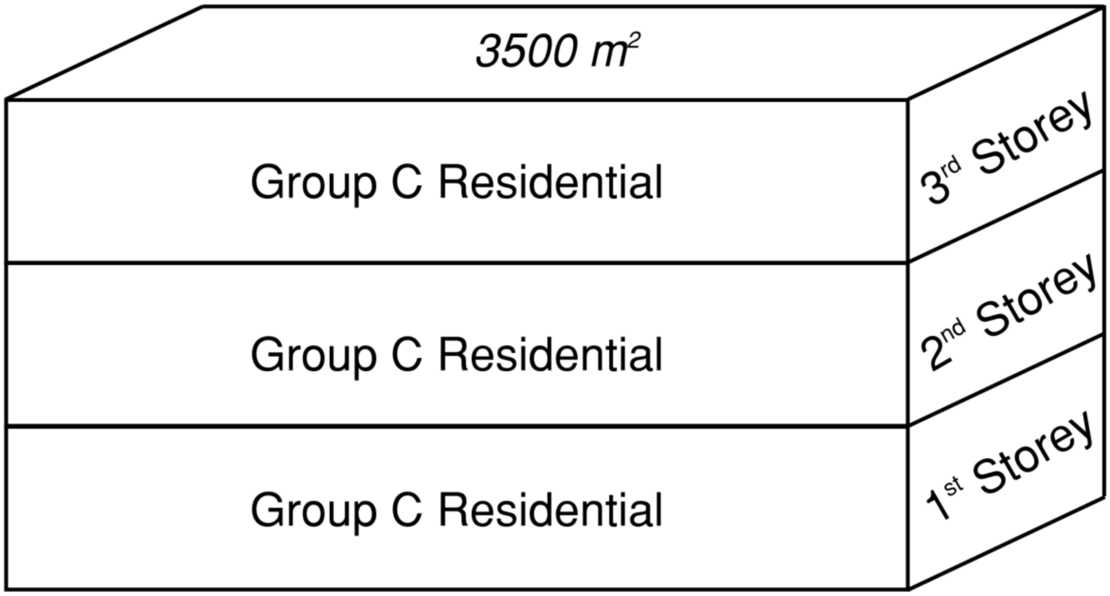

Figure 3.3.3.1 Building Diagram Illustrating Characteristics of Case Study 2

The design intent of the building in this case is to use exposed mass timber as floor assemblies in recognition that mass timber materials, especially CLT assemblies, offer a great range of benefits during construction including sustainability, fast-track construction schedules, improved fire performance and high structural performance, particularly in seismic prone regions, as compared with conventional construction such as light wood frame, light steel frame and concrete and heavy steel [70]. In addition, it is desired to use mass timber flooring to provide the aesthetic and environmental benefits to the occupants that come through use of exposed timber [73].

3.3.4 Division B Solution

3.3.4.1 Introduction

Division B, Subsection 3.2.2 of BCBC 2018 prescribes a list of applicable construction provisions for buildings of different characteristics. These defining characteristics include building height, building area, major occupancy and presence of a compliant sprinkler system. In some situations, the accessibility of the fire department is also assessed for determination of the construction provisions. Based on the combined building characteristics, the BCBC prescribes appropriate construction materials (typically combustible or noncombustible), degree of fire separation (45 minute, 1 hour or 2 hour), and other limitations to set a baseline for fire performance of the building. It is noted that the building in this case will be provided with a code compliant sprinkler system and faces one street only; therefore, provisions related to sprinkler system and fire department accessibility are excluded from further discussion.

To understand the baseline set up by the building code, it is necessary to study the objectives and intent attributed to the construction provisions. Therefore, the following section will review this information.

3.3.4.2 Objectives of Division B Solutions

Review of the construction provisions in Subsection 3.2.2 of Division B of BCBC indicate that similar trends are followed by all provisions in terms of having similar objectives and functional statements attributed to each. As this case study is focusing on the construction material as well as the required fire separation, Table ***3.3.4.1*** and Table 3.3.4.2 summarizes the objectives and functional statements attributed to these requirements from NBCC – Intent Statement website [27]:

Table 3.3.4.1 Intent related to Construction Type

Division B	Function	Link	Objective
Subsection 3.2.2 related to noncombustible construction	**F02** To limit the severity and effects of fire or explosions.	so that	**OS1.2** a person in or adjacent to the building will not be exposed to an unacceptable risk of injury due to the fire or explosion impacting areas beyond its point of origin. **OP1.2** adjacent buildings are not exposed to an unacceptable risk of damage due to fire or explosion impacting areas beyond the building of origin.
Intent Statements			
The intent 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 during the time required to achieve occupancy safety and for emergency responders to perform their duties which could lead harm to persons and damage to the building.			

Table 3.3.4.2 Intent related to Fire Separation

Division B	Function	Link	Objective
Subsection 3.2.2 related to fire separation	**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	so that	**OS1.2** a person in or adjacent to the building will not be exposed to an unacceptable risk of injury due to the fire or explosion impacting areas beyond its point of origin. **OP1.2** adjacent buildings are not exposed to an unacceptable risk of damage due to fire or explosion impacting areas beyond the building of origin. **OS1.3** a person in or adjacent to the building will not be exposed to an unacceptable risk of injury due to collapse of physical elements due to a fire or explosion. **OP1.3** adjacent buildings are not exposed to an unacceptable risk of damage due to collapse of physical elements due to a fire or explosion.
Intent Statements			
The intent is to limit the probability of harms to persons and damage to building due to - Loadbearing walls, columns and arches exposed to fire will prematurely fail or collapse which could lead to the failure or collapse of supported floor assemblies during the time required to achieve occupant safety and for emergency responders to perform their duties. - Floor assemblies exposed to fire will prematurely fail or collapse during the time required to achieve occupant safety and for emergency responders to perform their duties. - Loadbearing walls, columns and arches exposed to fire will prematurely fail or collapse which could lead to the failure or collapse of supported floor assemblies which could lead to the spread of fire from a lower storey of the building to an upper storey or to the exterior during the time required achieve occupant safety and for emergency responders to perform their duties. - Floor assemblies exposed to fire will prematurely fail or collapse which could lead to the spread of fire from a lower storey of the building to an upper storey or to the exterior during the time required to achieve occupant safety and for emergency responders to perform their duties.			

Review of the objectives and functional statements indicate that the intent of the construction requirement, regardless of its article, is to limit the probability that the building construction elements would fail in a fire emergency, potentially contributing to the growth and/or the spread of fire within, or collapse of, a given storey of the building during the time required to achieve occupant safety and for emergency responders to perform their duties. This is consistent with all other provisions in the code since either fire spread or collapse could lead to harm to persons and damage to the building [12].

With these intents, BCBC prescribes several design options for the building in the subject case study.

3.3.4.3 Determination of Division B Solutions

To limit the probability of failure of building elements contributing to fire growth and spread beyond the origin of the fire, the BCBC prescribes construction types and minimum fire separations required based on the building characteristics. The determination of the applicable construction articles is based on the following building characteristics and their definitions from the BCBC:

- *Building Area (m^2): greatest horizontal area of a building above grade within the outside surface of exterior walls or within the outside surface of exterior walls and the centre line of firewalls*
- *Building Height (storey): number of storeys contained between the roof and the floor of the first storey*
- *Major Occupancy: the principal occupancy for which a building or part thereof is used or intended to be used, and shall be deemed to include the subsidiary occupancies that are an integral part of the principal occupancy*
- *Presence of Sprinkler System: Sprinkler system provided and is designed to appropriate BCBC provisions and NFPA standards*

In some cases, the number of streets faced to provide fire department access will also play a role in the construction provisions. However, as noted above, this is excluded here as the criterion is not prescribed in the applicable construction articles for this case study.

The building in the case study has a building area of 3,500m^2, a building height of 3 storeys with Group C (residential) major occupancy. It is provided with a code compliant sprinkler system and faces one street only. Therefore, Articles 3.2.2.47 to Article 3.2.2.49 of the BCBC are all applicable and the key requirements as related to the building are summarized in Table 3.3.4.3 below.

Table 3.3.4.3 Summary of Applicable Construction Articles

Article	Project	3.2.2.47	3.2.2.48	3.2.2.48EMTC	3.2.2.49
Building Height Permitted	3 Storeys	Unlimited	6 Storeys	12 Storeys	3 storeys
Building Areas (m^2) Permitted	3,500m^2	Unlimited	12,000m^2	6,000m^2	4,000m^2
Construction Requirement	Exposed CLT floors with NC rest	NC	NC	EMTC	NC
Sprinkler	Yes	Yes	Yes	Yes	No
Fire Separation of Floor	TBD	2 hour	1 hour	2 hour	1 hour

NC = Noncombustible Construction EMTC = Encapsulated Mass Timber Construction

3.3.4.4 Results of Division B Solutions

Independent of the above, Division A, Article 1.1.2.1 of BCBC sets the minimum level of performance anticipated for the building such that the possible Division B solutions for the proposed building would be narrowed to Articles 3.2.2.48EMTC and 3.2.2.49 noncombustible construction as shown in Table 3.3.4.4.

Table 3.3.4.4 Summary of Applicable Construction Articles

Article	Intended Design	3.2.2.48EMTC	3.2.2.49	3.2.2.50
Building Height Permitted	3 Storeys	12 Storeys	3 storeys	3 storeys
Building Areas (m^2) Permitted	3,500m^2	6,000	4,000	3,000
Construction Requirement	Exposed CLT floors with NC rest	EMTC	Noncombustible	Combustible or Noncombustible
Sprinkler	Yes	Yes	No	Yes
Fire Separation of Floor	2 hour	2 hour	1 hour	1 hour

NC = Noncombustible Construction EMTC = Encapsulated Mass Timber Construction

The Division B solutions based on Article 3.2.2.48EMTC would allow the building to be constructed of EMTC and provided with 2 hour fire rated floor assemblies. In the case of Article 3.2.2.49, the building would be of noncombustible construction with 1 hour fire rated floor assemblies and the additional tradeoff of not needing sprinkler system. Alternatively, the building would fall under the requirements listed in Article 3.2.2.50 and shown in Table 3.3.4.4 if the building area were reduced by approximately 15%. In this case, a code compliant solution would allow the building to be of combustible construction with 1 hour fire rated floor assemblies.

While all of these potential Division B solutions are expected to meet the intent of limiting probability of a building element contributing to fire development and spread beyond its origin due to material combustibility and/or the potential for an assembly failure, none provides a satisfactory solution to the original design intent to use CLT floor assemblies throughout. Article 3.2.2.48EMTC does permit the building to be of mass timber construction provided the mass timber is encapsulated with protection. This encapsulation would cover the desired CLT floor panels as floor assemblies and thus defeats the design intent. Article 3.2.2.49 requires the building to be entirely of non-combustible construction which is defined in BCBC as "*…a material meets the acceptance criteria of CAN/ULC-S114, 'Test for Determination of Non-Combustibility in Building Materials.'…*". Studies show that CLT panels do not pass this standard test for non-combustibility and thus are considered combustible materials [74]. Therefore, Article 3.2.2.49 would not permit the use of CLT floor assemblies. Finally, Article 3.2.2.50 would require significantly downsizing the building which is not a viable solution either.

Thus, none of the Division B solutions provides a design option which can meet the full intent for the proposed building. The solutions also present limitations in terms of reliability and overall design impact, as well as construction and financial difficulties. These are reviewed in more depth in the following sections to further investigate the level of performance that is provided with the applicable Division B solutions.

3.3.4.5 Performance of Division B Solutions

3.3.4.5.1 Background of Division B Solutions

The determination of the applicable construction article is based on the building area, building height, how many streets the building faces and whether or not there is a sprinkler system in the building. Table 3.3.4.4 illustrates three solutions which meet the applicable prescriptions in Division B, although none of them meets the design intents. Closer examination indicates that the desired design of the building fits in between the requirements specified in Article 3.2.2.48EMTC and Article 3.2.2.50 in terms of use of exposed CLT panels; however, the maximum building area of Article 3.2.2.50 is 3,000m^2 which does allow the designers not meet the optimal design area of 3,500m^2.

Review of the documentation attributed to the size requirements prescribed under Article 3.2.2.50 indicates that determination of the building area limit in this Article was calculated as 80% of the area permitted in noncombustible buildings; however, the code documentation contains no clear substantiation of the reasons behind this choice of maximum building area based on engineering principles [75]. Instead, it appears that this 20% reduction in area has generally been accepted through code change cycles and is carried on without technical assessment [75]. Reports in the literature suggest that building height and area limits for combustible buildings were related to limiting fires sizes in consideration of the projected capacity of a responding fire department [10]. As a result, they change depending on several parameters, including the street facing parameter, as shown in Equation 7 [10]:

$$A = \frac{A_B \times S \times SF \times CF}{H} \tag{7}$$

Where $A =$ Building Area (m^2)

$H =$ Building Height (storeys)

$A_B =$ Base Building Area (m^2) = 1,800m^2

$S =$ Sprinkler Factor (1 for unsprinklered, 2 for sprinklered)

$SF =$ Street Facing (1 for facing one street, 2 for facing two streets, 3 for facing three streets)

$CF =$ Construction Factor (1 for ¾ hour fire rated structural components, 1.33 for 1 hour fire rated structural components)

If this area was used for the present building design it would calculate to $1{,}596\text{m}^2 = \frac{1{,}800m^2\times2\times1\times1.33}{3}$ which is less than the 3,000m^2 allowed in Article 3.2.2.50, although it does not appear that the factors assigned in this calculation have particular scientific background either. Instead, it appears that they were developed and then also carried through code change cycles [76]. Without a record of the scientific background, it is difficult to justify the credibility of the building area limitation or how it truly relates to the present building design.

3.3.4.5.2 Design Reliability of Division B Solutions

Design reliability is another consideration that has been shown to be important in the previous case studies but is not incorporated into considerations under the Division B solutions. In terms of building area and construction type, the intents of the requirements are to limit the potential for the building structural elements to contribute to fire growth and spread over the time required for occupants to safely egress and emergency responders to respond fire emergency. Further, they are specified to limit the probability of failure of a building element with consequent damage to the structure. In these respects, each of the three Division B solutions present its own trade-offs. As noted in Table 3.3.4.4, both Article 3.2.2.48EMTC and Article 3.2.2.50 permit combustible construction as long as the required sprinkler protection is also installed. In contrast, Article 3.2.2.49 permits noncombustible construction in the situation where there is no sprinkler protection provided. Comparison of the approaches suggest that the building code relies on noncombustible construction when sprinkler requirements are relaxed, yet there are limited discussions of how to make trade-offs in situations where building area falls between two Articles within the specifications. For the present building, a design to Article 3.2.2.49 includes the major building characteristics (building area and building height) best matched to the design intent, so it was decided to use Article 3.2.2.49 as the baseline case against which to determine the level of performance anticipated by the building code when reviewing any potential alternative building designs.

With respect to the present case, in Table 3.3.4.4, Article 3.2.2.49 prescribes noncombustible floor construction with a fire resistance rating of 1 hour. It is noted in BCBC Article 3.1.7.1 that the fire resistance rating could be determined following the Tables contained in Appendix D-2 of the BCBC or it could be specified via a listed design that has been tested under CAN/ULC-S101 test [12]. Therefore, typical code compliant assemblies range from concrete floor slabs on top of steel frames with fire-resistant spray protection (intumescent paint) to complex steel floor frames with fire rated gypsum board protection.

Fire-resistance spray, including intumescent paint in the fire protection industry, applied on steel structural members is intended to transform into expanded foaming surface coatings to insulate these members when subjected to elevated temperatures encountered under fire exposure [77]. These spray coatings are typically tested under the required CAN/ULC-S101 standards to determine the fire resistance rating a given application would provide. However, recent research has also pointed out that the effectiveness of coating applications are impacted not only by the steel section factor and thickness of spray applied, but also by application procedures and sometimes even by wear and tear over time, [78]. Thus, they may not provide consistent protection per tested condition.

Another code compliant solution commonly used in the industry to achieve fire resistance rating in noncombustible construction would be a floor frame paired with fire rated gypsum board protection tested to the CAN/ULC-S101 standards. One of the listed designs under this category is described in detail in BXUV7.G512 (see *Appendix C*). It requires very specific installation details to be fulfilled onsite. Such complex and detailed installation requirements have the potential to increase the probability of construction error, leading to a potentially higher probability of system failure in the event of a fire. To quantify such interactions visually, an event tree analysis, typically considered appropriate per a recent study on assessing design performance against building code performance [21], is presented in Figure 3.3.4.1 below. Probabilities for each event will be discussed to better quantify reliability considerations related to the present building Division B design options.

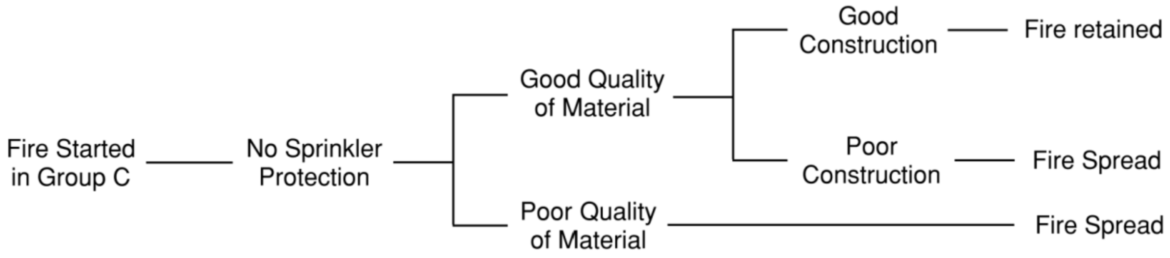

Figure 3.3.4.1 Event Tree Analysis for Article 3.2.2.49

In the event tree, the probability of a fire being initiated in the building is assigned a 100% probability since the purpose is to study the progress of the subsequent fire events. Under Article 3.2.2.49, the building is not required to be protected with sprinklers; therefore, no credit is given for sprinkler protection. Any potential for errors on the part of the designer and the reviewer are excluded from this analysis in order to focus on construction reliability of the code compliant noncombustible construction. To this end, the probability of poor quality of materials and construction error have been studied in Russia and Western Europe [79]. The probability of poor quality of materials was found to be 2%, while potential for construction error was considerably higher at 50% [79]. Given that there is no comparable Canadian data available, and similarities between construction materials and in some measure construction practice between Western Europe and Canada, these values are used in this analysis [79]. Unfortunately, there is no data available to further quantify the possible types of construction errors. Thus, the present analysis has to be simplified for illustration of one method for setting a baseline of the level of performance.

The simplified event tree analysis with example probability analysis is included in Figure 3.3.4.2. As a result, the probability of a fire being retained within the space for the combination of good quality material and construction quality is approximately 49%.

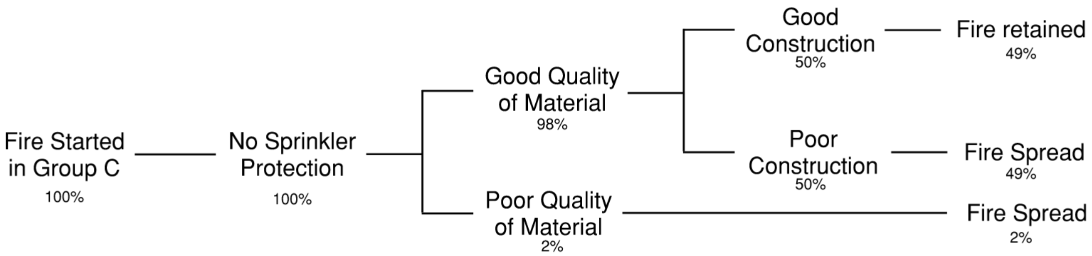

Figure 3.3.4.2 Event Tree Analysis with Probability for Article 3.2.2.49

Based on the foregoing, it becomes clear that some noncombustible construction requires complex installation procedures to satisfy the passive fire protection required by a code compliant solution. This increases the complexity of construction and thus, the probability of poor installation which could lead to a failed system and potentially decrease the level of performance of the intended Division B solution.

3.3.4.5.3 Economic Impact

As discussed in Case Study 2, financial implications of a design choice that is not founded on updated scientific evidence can be another significant factor in building design. For this case study, there are three Division B solutions noted in Table 3.3.4.4**Error! Reference source not found.**. Article 3.2.2.49 prescribed use of conventional noncombustible construction with 1 hour floor fire separation. However, this Division B solution would not achieve the design intent of this case study which is to use a sustainable building material while also providing the aesthetic adaptability to the occupants via exposed timber elements.

Article 3.2.2.48EMTC specified a 2 hour fire separation for the CLT floor. As noted previously, EMTC requires noncombustible materials such as gypsum board to provide “encapsulation” to protect the mass timber elements. For this solution, the increased floor fire separation (from 1 hour to 2 hour) and the additional protection required to achieve the necessary *“encapsulation rating”* contribute to increased material costs, not including the cost of labour required for the additional installation of protective layers.

The cost for the building construction varies from project to project, and it is difficult to estimate the premium based on the current economy. An increase of 5% to 10% compared with conventional non-combustible construction is indicated in past literature [80]. Typical residential buildings similar to the present building (3-storey with 3,500m^2) using hybrid noncombustible construction are reported to be approximately \$2,750.00/m^2 (median of \$220.00/ft^2 and \$290.00/ft^2) in a statistical study undertaken in 2018 [81]. Therefore, if the building were to be designed following the Division B solution, a rough estimate[7] of \$28,875,000.00 (\$2,750.00/m^2 x 3,500m^2 x 3) is required for conventional noncombustible construction prescribed in Article 3.2.2.49 and \$31,726,500.00 is required for encapsulated mass timber construction prescribed in Article 3.2.2.48EMTC.

The third Division B solution, Article 3.2.2.50, would fulfil the design intent of combustible construction, however, would result in a reduction of building area from the desired 3,500m^2 per storey to 3,000m^2 per storey. Therefore, the developer/project owner would lose a marginal revenue of approximately 14.3% (500m^2 ÷ 3,500m^2) due to the loss of the profitable floor area.

Based on the foregoing, it is clear that the costs of constructing the proposed building following Division B code compliant solutions increases construction costs, while at the same time resulting a final building that does not meet the full design intent and therefore is much less attractive to most building developers and owners, particularly in the residential sector.

3.3.4.5.4 Design Practicality

Another benchmark for the performance of the Division B solutions is the practicality of the code compliant acceptable designs. The first two case studies outlined how three elements of practicality could be significant in determination of a final building design in this area of Canada. These were constructability in real life, system maintenance and post-earthquake repair as the building in this case study is also located in an active earthquake zone. Constructability was addressed in the section on reliability of the Division B designs. System maintenance is not as pertinent for this case study as previously so will not be considered further here. Therefore, only the post-earthquake repair will be assessed for the present building design. Recent research has identified some gaps in the seismic response of noncombustible structural elements prescribed in current enforced standards [82]. In addition, noncombustible construction such as concrete and cold formed steel frame are known to present difficulties to repair after a significant earthquake event [83]. Based on current evidence, noncombustible buildings may require demolition and re-construction

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[7] Note that these estimations are based on the information reported in prior years and the current financial impact would have changed significantly given the increased inflation rate due to 2020 – 2022 COVID Pandemic.

after an earthquake, leading to significant financial and social burden. While all the details of structural design would have to be considered in a full building design exercise, it is outside the scope of the present thesis, so has been considered here only in relation to the connection to fire and seismic performance and resilience of the building.

Another consideration of design practicality is construction sustainability. With the rising topic of climate change and characterized negative impacts of the construction industry on the environment, construction sustainability has become a key role in building design. This emerging topic has become significant as discussed in the recent IAFSS white paper [84]. Several studies indicate that processed building materials such as concrete lead to significant emissions of greenhouse gases [85], with emissions estimated to be as high as 13% across the Canadian building sector [86]. Unfortunately, measures of sustainability and impact on climate change have not been incorporated into the building code at present which presents difficulties in terms of evaluation of combined fire safety performance and sustainability of Division B solutions at this stage.

3.3.4.6 Limitations of Division B Solutions

It is clear from the above discussion that none of the Division B solutions can satisfy the design intent since either the solution would require noncombustible construction so a CLT building would not qualify, or the footprint of the building would need to be reduced. Review of the solutions indicated that the following limitations are embedded within Division B solutions.

a. **Fire Science Support**: A review of the history of the applicable building code provisions indicated that the building area limitation does not have well documented substantiation via fire science and engineering principles. Values of building area embedded in the current building code appear to have been generally accepted through the code change cycles and carried on without additional technical assessment. This lack of support presents some uncertainties with necessary adaptation and interpretation of the Division B building designs for the present case study.

b. **Reliability of Design System**: While there are several options to achieve Division B compliance, the reliability varies between these options. For example, one of the Division B solutions permits the use of cold-formed steel frame with single layers of gypsum board which has been reported and has been linked to the potential for installation errors. Therefore, the reliability of the system is another factor that would have to be considered in a full review of the proposed design.

c. Financial Impact: Investigation of the financial impact of the various Division B design solutions indicated that, while the conventional noncombustible construction may appear to be the most cost-effective option, it would not achieve the overall design intent and benefits of using an exposed CLT floor. The other two options of EMTC or acceptance of a reduced building footprint both have cost implications as well. EMTC will result in a significant cost increase given the specialty and the amount of the materials to be used while a reduced building footprint directly translates into marginal revenue due to the floor area reduction. Either choice may easily exhaust the estimated construction budget resulting in a significantly modified design that does not meet the full design intent and is much less attractive to most developers/owners.

d. Design Practicality: None of the Division B solutions would meet the simultaneous design intents of exposed wood elements coupled to the desired building size. In addition, the solutions may present challenges related to post-seismic repair resulting in a need for demolition and re-construction. Finally, none of the Division B solutions consider sustainability in construction which has become a rising topic across the building industry.

Based on the foregoing discussions, the acceptable Division B solutions do not appear to be able to meet the full intent of the proposed building design. Therefore, an alternative design approach is proposed and evaluated against the possible Division B solutions in the following section.

3.3.5 Alternative Solution

As discussed in Chapter 2, the building code provides an option for a designer to use alternative design approaches to those outlined in Division B, as long as they are accepted by local AHJ and provided that the proposed design achieves the same (or better) level of performance than the Division B solution. This avenue is therefore pursued in the present case study in attempts to preserve the simultaneous design intents to construct with exposed mass timber flooring while also maintaining 3,500 m^2 building area. In the proposed alternative solution approach, cross laminated timber (CLT) panels will be used in lieu of the Division B prescribed noncombustible/encapsulated construction for the major building floor components with other necessary structural elements. In addition, sprinkler protection is proposed for this project and a 2 hour floor fire separation is proposed to meet the intents of the BCBC as related to safeguarding against potential fire and life safety risks.

3.3.6 Evaluation of Solutions

3.3.6.1 Difference Between Design Solutions

Based on the foregoing, the proposed alternative design and the applicable Division B solutions are summarized in Table 3.3.6.1 as a basis for discussion in the next sections.

Table 3.3.6.1 Division B Construction Articles Applicable to Proposed Building

Article	Alternative Design	3.2.2.48EMTC	3.2.2.49	3.2.2.50
Building Height Permitted	3 Storeys	12 Storeys	3 storeys	3 storeys
Building Areas (m^2) Permitted	3,500m^2	6,000	4,000	3,000
Construction Requirement	Exposed CLT floor with rest of building non-combustible	EMTC	Noncombustible	Combustible or Noncombustible
Sprinkler	Yes	Yes	No	Yes
Fire Separation of Floor	2 hour	2 hour	1 hour	1 hour

3.3.6.2 Evaluation of Alternative Solution

The above noted alternative solution achieves the design intent to utilize exposed combustible floor elements in a 3-storey residential building with floor area of 3,500m^2. Since the proposed alternative design is not directly code compliant, it is necessary to review the level of performance relative to the code intents outlined in Section 3.3.4.2. Similar to considerations around the Division B solutions, the fire science support, reliability of system, economic impact as well as the design practicality will be used to compare the alternative solution to the baseline level of performance that was satisfied, and discussed above, in relation to the Division B solution.

3.3.6.2.1 Design Reliability of Alternative Solution

As seen in Table 3.3.6.1, the proposed design will have wet sprinkler protection. In addition, it is proposed to have 2 hour rated CLT floor panels as construction materials in lieu of more traditional combustible construction. Therefore, an event tree analysis similar to Section 3.3.4.5.2 for the Division B solution is prepared as shown in Figure 3.3.6.1 to demonstrate the probability of fire being contained in the room of origin based on the relevant systems prescribed in construction article in Division B. Assuming a fire is starting in one of the residential suites (100% probability of fire occur in Figure 3.3.6.1), the first line of defence would be sprinkler activation. As noted in Case Study 2, the sprinkler has a probability of 93% for effectiveness of control fire growth and spread. Should the sprinkler become ineffective or fail to operate, the second line of defence here would be the building's fire separation that can be analysed via consideration of material and construction quality. The assessment focuses on the reliability of CLT in achieving a 2 hour fire separation since it is proposed to use exposed CLT floor panels while the remainder of the construction remains noncombustible. Recent studies on CLT assemblies have demonstrated that CLT panels designed in conformance with the appropriate fire performance and fire resistance standards will achieve the required 2 hour fire separation and maintain the structural integrity when tested to CAN/ULC-S101 standards [87]. In addition, CLT panels are typically manufactured with sizes that are specified to meet the needs of a specific project and the fire resistance characteristics are inherent, therefore, the reliability of the material can be expected to be close to 100%. To undertake a more conservative analysis, however, a probability of 98% has been chosen here as related quality material for CLT panel. In contrast, the quality of CLT construction is somewhat specialized but is still highly subject to human activities; therefore, a 50%/50% potential split between good and poor construction quality has been chosen for the analysis here. The resulting probability of effectively meeting the code intents around protection of the building, occupants and first responders in the event of a fire per requirements in BCBC (sprinkler and building construction) would be 96.4% (3.4% + 93%), the combined probability that a fire would be retained in the room of origin.

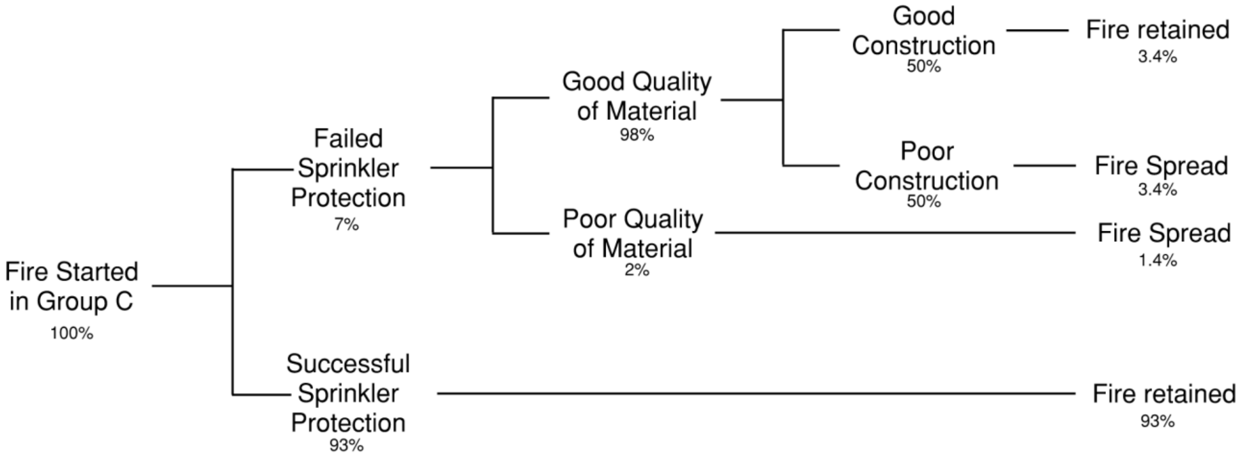

Figure 3.3.6.1 Event Tree Analysis with Probability for Proposed Design

Comparison of the estimated reliability of the Division B solution with Article 3.2.2.49 used as the baseline case and the alternative solution proposed here with a wet sprinkler system and 2 hour rated CLT floors is summarized in Table 3.3.6.2. From the results, it appears that the alternative solution outperforms the Division B solution while satisfying the overall design intents for the building.

Table 3.3.6.2 Probability of Effective Protection in Different Solutions of Case Study 3

	Division B Article 3.2.2.49 No Sprinkler Protection, Noncombustible Construction	**Alternative Solution** Wet Sprinkler Protection, 2 hour rated CLT Construction
Probability of Effectiveness	49%	96.4%

3.3.6.2.2 Economic Impact

The economic implications of the Division B solutions were considered in Section 3.3.4.5.3. It was indicated that mass timber construction, as prescribed there to follow the CSA O86 standard, comes at a disadvantage due to its higher construction cost. As discussed in Section 3.3.2.3, this calculation methodology has not yet been updated to incorporate advancements in mass timber technology which recent fire tests have demonstrated to sustain reduced charring rates, which would result in smaller sections with significant cost reduction. Nonetheless, the proposed alternative design using CLT as the floor material does not come with a cost benefit; however, it will fulfill the design intent of using exposed mass timber on floors in a building with 3,500m^2 floor area whilst maintaining the same level of performance in fire and life safety required.

3.3.6.2.3 Design Practicality

None of the code compliant Division B solutions could meet the full intent of the desired design. In contrast, the proposed alternative solution does provide the necessary level of performance in fire and life safety, while also allowing the designer to maintain the desired aesthetic adaptability with use of exposed natural wood construction while also maintaining the optimal building footprint (building area) of 3,500m^2.

In addition to the above advantages, the proposed alternative building design is practical in terms of post-seismic repair and maintenance as well as maintaining the sustainability of construction [83]. While post-seismic repair of buildings is not the primary focus of building code, it is a key consideration in earthquake prone regions of Canada [88]. While traditional construction, whether based on concrete, cold-formed light steel frame or conventional wood frame, may suffer irreparable damage in a seismic event, mass timber construction has demonstrated seismic durability due to its low self-weight [89]. Thus, repair of an appropriately designed structure with mass timber floor elements is more likely to be limited to replacement of localized damaged portions. This would significantly reduce the extension of the post-seismic building repair, and thus repair cost and time, that is needed with fully noncombustible construction [85]. Both benefit the project owner and the building occupants.

Another consideration of increasing importance related to practicality of building design is the sustainability of construction [85]. Wood is recognized as a natural, renewable and sustainable material by Natural Resources Canada (NRCan). Manufacture of wood-based construction materials produces a limited amount of greenhouse gases compared with the materials employed for noncombustible construction [89]. A typical construction timeline for projects built with mass timber is also significantly shorter compared with the timelines for conventional construction. Since the CLT floor panels are pre-fabricated, each piece will be delivered to site ready for installation and assembly with minimal site-modification [85]. In the case of UBC Brook Common Tallwood Building for an example, one storey was erected per week once all materials were on site [90]. This is significantly less than the one storey per 28 days associated with curing of concrete in conventional concrete construction [85]. Not only does this decrease construction time and thus cost, it also leads to a potential reduction in greenhouse gas emission, providing an increased level of sustainability for the building design and construction [89].

As summarized in Table 3.3.6.3, the alternative solution approach using CLT floor panels, although it suffers from certain potential issues, would provide a building that better satisfies the design intent than any of the Division B solutions.

Table 3.3.6.3 Summary of Comparison between Division B and Alternative Solution

	Division B Article 3.2.2.49 No Sprinkler Protection, Noncombustible Construction	**Alternative Solution** Wet Sprinkler Protection, 2 hour rated CLT Construction
Design Intent	Could not satisfy	Yes, will offer exposed natural wood construction and building area of 3,500m^2
Fire Science Support	Specifications appear to be generally accepted without history of their origin and carried over code review cycles without consideration of development of new technology	Forefront research and takes advancement of technology into considerations
Estimated Reliability (normal fire emergencies)	49%	96.3%
Cost Comparison	-	Typically 5%-10% higher
Design Practicality	Further studies on post-seismic design required, does not present a sustainable solution in building design.	Offers high seismic durability and post-seismic repair may be localized Reduced cost and construction time. Offers high sustainability in building design and construction

As can be seen from Table 3.3.6.3, the level of performance of the alternative solution meets a code compliant level of fire performance that is comparable to that encompassed in a Division B solution and outperforms those solutions in several benchmarks. In contrast to the Division B solutions, it offers a more sustainable and reliable solution that meets the full original intent of the design and at the same time maintains all the necessary fire and life safety level requirements.

3.3.7 Conclusion

This case study for design of a sprinklered residential building presented a comparison between three applicable Division B solutions and a proposed design using exposed CLT floor panels. The case study was simplified and focused on the construction requirements in Subsection 3.2.2 of the building code only. The objectives and functional statement of the provisions prescribed in the code were presented and the level of performance of these solutions were studied in terms of satisfying the intent of the code, as well as the overall design intent. A simplified event tree analysis was presented for both Division B solutions and the proposed alternative design to compare the level of performance and reliability of the two options. Through the case study, the following limitations were identified:

1. For building construction, Division B uses building characteristics such as building area to determine the applicable construction materials. Building area limitations cannot be traced back to a firm scientific basis, but instead remain generally accepted considerations and thus are not re-evaluated as technology changes. They have been carried unchanged through code review cycles for many years. Due to this, the current NBCC format limits direct compliance of new products, such as CLT, in building design and construction. It does not provide appropriate guidance for assessment of risk levels amongst materials options, and thus choice of construction type. This further limits optimal application of modern technology in new designs. Both factors lead to a very conservative approach to building design as prescribed in the current NBCC.
2. The intent of the construction provision in Division B is to limit the contribution of construction material to the fire growth as well as limit the probability of structural failure in fire emergencies. However, the NBCC has simplified possible construction types into combustible and noncombustible materials, with some recognition of the mass timber with encapsulation. This does not allow flexibility to fully assess use of possible materials such as CLT panels even though forefront research is being conducted into the fundamental behavior of such materials and suggests, at least currently, that they can achieve necessary levels of performance in fire and life safety.

3. It is noted that the NBCC has begun to recognize mass timber with encapsulation as a new construction type. However, the application is limited to certain building characteristics with specific design provisions. The history of these new mass timber provisions was not studied but should form the basis for future work. Nevertheless, the provisions do not appear to capture all aspects of the performance of this engineered material. For example, NBCC prescribes the use of new fire resistance glues to enhance the fire performance of the material following the latest manufacturing standards. On the other hand, the methodology in NBCC to determine the fire resistance and overall performance of the material has not been modified to keep abreast of the changes to the glue types and associated charring rates, thus potentially leading to over-conservative designs.

4. Some Division B solutions use passive fire protection measures to achieve the necessary designation of noncombustible construction. Due to the nature of these measures, they can lead to complex installation and construction requirements, resulting in reduced overall system reliability due to the potential for increased installation error. However, current NBCC does not include a method by which consider these factors although they may potentially lead to the structural failure in fire emergencies. On several fronts, the Division B solutions in the current NBCC do not appear to necessarily provide an optimized design baseline against which to compare and, in the end, satisfy a code compliant level of performance. This could mislead the designer or reviewer towards improper application of Division B in development and assessment of alternative solutions through a performance-based approach. More attention should be given to the competence of the design, review and construction team for specific building construction types considering the complexity with the Division B design solutions.

5. Economic impact plays a significant role in the construction industry. For code compliant mass timber construction, i.e. mass timber elements protected with noncombustible encapsulation, the cost of construction is higher than for conventional noncombustible construction such as concrete or light steel frame. However, with ongoing research and evolving technology, it is expected that

cost may be neutralized in future so that it becomes more competitive across the construction industry.

6. The last but not the least factor in assessing the solutions is the practicality of a design which in this thesis focused on two factors: seismic performance and sustainability. It is noted that the performance and post-seismic repair of some of the Division B solutions may not be thoroughly considered in the current NBCC. In general, the code does not provide the appropriate design guidance for designer and reviewer to properly assess a necessary level of performance specific to unique seismic considerations in certain Canadian building locations.
7. Another important consideration that is not been readily addressed in the current NBCC is sustainability. The choice of construction material may offer different levels of sustainability in both the material choice and construction practice. With the rising awareness of green gas emissions in the Canadian building sector, and the desire to build a cleaner environment in the construction industry, mass timber presents several significant benefits. Material production is generally considered to be cleaner and building construction periods are generally shorter than with conventional noncombustible construction materials. Unfortunately, the current NBCC has not yet been adapted to keep pace with advanced initiatives and technologies in terms of assessing their ability to meet levels of performance in many areas, including those outside the realm of fire and life safety.

In summary, this case study again points to some of the challenges faced in pursuing a performance-based design in the current Canadian Building Code environment. At the same time, it is also clear that these are complex questions which may not be easily or immediately be addressed during upcoming code update cycles.

4 Conclusion and Future Work

4.1 Summary

Three case studies involving acceptable Division B solutions and alternative design options related to fire and life safety are presented in this thesis. The cases form the basis for a review and discussion of the design process, and investigation into difficulties that arise in application of several elements of the current building design guidance provided in NBCC. In this, objectives and intents attributed to each provision applicable to a design are studied to understand the expected level of performance for a code-compliant design in terms of fire and life safety. Four parameters – history and scientific background, reliability, economic impact, and design practicality – are then used to investigate technical and economic challenges that exist in executing different design scenarios under the current code. For this, the history and fire science behind the code compliant provisions are explored to uncover traceable scientific fundamentals that may have formed the basis of the building code requirements. Next, various aspects of reliability, cost effectiveness and practicality of the code compliant and alternative design solutions are investigated as appropriate to each case. Key in this also is assessment of the performance of modern technologies with aim to investigate their potential strengths or issues in innovative building designs as different from the code compliant solutions. Results lead to identification of challenges encountered in utilizing the current Canadian Building Code, not only in terms of achieving the intended level of performance of a design, but also, if desired, in pursuing appropriate alternative design solutions. Limitations found can lead to inappropriate design when following acceptable solutions prescribed by the code or, equally important, can lead to inappropriate evaluation during assessment of an alternative solution under the objective-based approach. From the combined analysis across case studies, several conclusions can be drawn as outlined in the next section.

4.2 Conclusions

Based on the foregoing case studies, the following conclusions are identified to elaborate current challenges with, and need for, a new paradigm of building design and evaluation in Canada:

1. The primary fire safety objectives of the building code provisions are to limit the probability of the occupants and the building itself being exposed to an unacceptable risk of injury or damage due to a fire. The current Canadian Building Code, in Division B, provides a list of options that a building designer can follow to achieve generally accepted safety levels from risks due to fire. For simplicity, and to keep the building code to a reasonable length, it does not and cannot address all circumstances. As such, a compliant solution based solely on the provisions in building code cannot be found for buildings with innovative designs. In these cases, establishing the appropriate level of performance for the building can be challenging due to the need to work with often qualitative performance metrics, while also considering potential catastrophic events which have a low probability but a high consequence.
2. There are scientific gaps or poorly documented information in support of the fundamentals behind some of the Division B solutions prescribed in building code. Other parts of the solutions have been carried through code revision cycles without reassessment in light of new research results, changes in design approach or technological developments that have taken place.
3. Many acceptable Division B solutions are based on the state of art knowledge and tools available at the time of their establishment, some from 1960s or before. Due to the slow update process of the NBCC, modern technology may not be incorporated as changes take place. As a result, the designers as well as the AHJ may encounter difficulties, and even barriers in terms of using those technologies in pursuit of, or for evaluating, more modern, innovative designs.
4. Modern technology is not systematically and consistently being considered and included, as appropriate, into all important elements of building code development and overall building design. Thus, there are situations where appropriate credit for emerging technologies is not acknowledged

in the regulatory environment. This can lead to overly conservative or even inappropriate design decisions in the present building environment.

5. There are inconsistencies in, and indeed no clear path for, recognizing the relative performance of modern technologies. Examples include only partial recognition of the more than 90% effectiveness of sprinklers in controlling a fire and delay in recognition of changes in fire resistance performance of mass timber materials with new adhesives. Such inconsistencies add additional complexity and uncertainty in both building design and review since they greatly impact both the set up of, and comparisons with, the baseline requirements for a design.
6. The NBCC currently has not thoroughly considered the impact of natural hazards to building designs. Different provinces may suffer different levels of natural disasters, ranging from tornados to earthquakes. For example, some of the code compliant solutions do not consider fire performance of a design during or after a major seismic event. For some scenarios, this could have extremely high consequences, and possibly even lead to unsatisfactory performance of a code compliant design.
7. Current prescriptive solution approaches do not provide any guidance on how to consider social implications and/or environmental costs associated with design decisions. Yet, both of these factors are growing in importance. As such, they should be included in code compliant solutions, or at a minimum, should contribute a significant component in evaluation of building designs in modern society.
8. Another important consideration that is not readily addressed under the current NBCC is sustainability. The choice of construction materials may offer different levels of sustainability in both the material choice and construction practice. With rising awareness of greenhouse gas emissions in the Canadian building sector, and the desire to build a cleaner environment in the construction industry, new materials will continue to emerge on the market. Thus, there should be a methodology by which these can be recognized and assessed in terms of fire and life safety through appropriate provisions in the NBCC. Due to the length of the code review cycle, items such

as sustainability, although it impacts both fire and life safety, have not been taken into consideration.

9. In addition, economic considerations related to comparative design solutions, which play a significant role in the construction industry, are not addressed in current NBCC. In the case studies outlined, some Division B solutions were shown to cost 44 times more than a corresponding alternative solution. At the same time, the performance of the Division B solutions may sometimes also be lower when comparing with a carefully crafted alternative solution design. In such situations, the financial impact of Division B solutions may put pressures on shareholders to take shortcuts or to abandon an intended building design if the more cost-effective alternative solution is not deemed acceptable by the AHJ.

10. The NBCC, as an objective-based building code, offers an option for a designer to demonstrate building code compliance through evaluation of the performance of an alternative design approach. However, the building code does not provide any detailed guidance on how either the design team should generate, or how a local AHJ should review and evaluate these building design proposals in terms of their inherent level of performance in comparison with an acceptable Division B solution. Without any quantitative assessment thresholds included in regulation, the responsibility lays on the shoulder of both the designer and the reviewer to agree on an appropriate level of performance for the alternative building design. In this instance, complex and sophisticated designs may require a design team to first possess experience in the fire and life safety industry. In addition, they are required to obtain knowledge and keep abreast of modern research and technology in dealing with fire and life safety risks. Such knowledge can only really be acquired through enhanced education. Yet currently, there are no undergraduate, and only very limited numbers of postgraduate programs in Canada that offer the required comprehensive education[8]. The existing level of the competence

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[8] In fact, there are only a handful of undergraduate and postgraduate programs worldwide that offer the full scope of courses needed to fully capitalize on performance-based design for fire and life safety

of both designers and reviewers may lead to inappropriate application of a code compliant fire safety solution, let alone an alternative solution.

4.3 Future Work

Due to the limited scope and length of this thesis, it is impossible to explore every aspect of the provisions in the NBCC to identify all potential concerns that may pose barriers for the development of code compliant designs in the Canadian context. There are a broad range of applications of alternative solutions that have not been demonstrated in this thesis that could uncover many more challenges that are encountered in trying to evaluate levels of performance between a code compliant solution and an alternative solution.

Scientific gaps in the fundamentals behind prescriptive solutions developed in the case studies were identified; future investigation into the code provisions should be conducted to connect updated fire science and engineering research results to provide a technical and evidence-based approach to determining what is required to provide a certain desired level of safety and to reduce the unnecessary redundancy that occurs in building design. In this, further consideration should be given to the examples identified in this thesis.

Another consideration for future development of building code compliant building designs is to define a level of education and expertise necessary in the design and evaluation of complex buildings and also provide specific criteria appropriate for evaluation of performance of the designs. This is necessary since the development of new technology is happening at an accelerated speed such that building code cycles can be one or two rounds behind the introduction of a new approach. As is already happening, a lack of confidence in evaluating innovative designs may result in lengthy and costly review processes leading to delayed project schedules. This concern already leads stakeholders to abandon innovative designs and slows the development of the Canadian building design and construction industry.

Lastly, a final destination in our current building code development is to migrate towards full performance-based design. However, with the current Canadian building code environment and challenges identified in this thesis, a long path lies ahead waiting for exploration.

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