Minnesota Single-Exit Stairway Apartment Building Study

December 30, 2025
WJE No. 2024.7192.0

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The efforts of countless individuals and organizations assisted in making this report possible through their dedication of service and time, in the interest of public safety, to provide their expertise and additional requested information. The members of the Technical Advisory Group and the organizations that they represent provided valuable insights, and their willingness to openly discuss the topic cannot be thanked enough. A special thank you to the dedicated staff of DLI who helped organize and steward the process, and for their support and guidance along the way.

PROPRIETARY USE

EXECUTIVE SUMMARY

Wiss, Janney, Elstner Associates, Inc. (WJE) and Crux Consulting (Crux), the "Consultants," are pleased to present this report to the Minnesota Department of Labor and Industry (the Client) documenting the risk-informed approach (RIA) used to study multi-family residential dwelling unit buildings, hereafter referred to as "MFDs," with a single-exit stairway.

The Minnesota Legislature mandated a data-driven study to evaluate taller and/or larger MFD buildings with a single-exit stairway that could be up to seventy-five feet in height. The Client created a Technical Advisory Group (TAG) that consisted of architects, code officials, developers, firefighters, fire marshals, fire protection engineers, and housing experts to help guide the Consultants during the study.

This report does not address single-family homes or other buildings governed by the Minnesota Residential Code and Minnesota Building Code (MBC). As confirmed with TAG, this study focuses on representative building geometry and fire protection features and systems and does not address individual human behavior and individual fire department response. Additionally, this report does not define acceptable risk or safety levels or propose direct building code language; those decisions remain with policymakers in the State of Minnesota.

Methodology

To conduct this analysis, the Consultants utilized a multi-faceted approach that included meetings with TAG members to understand their perspectives as well as reviewing fire event data for MFDs. Using this information, the Consultants applied a risk informed approach (RIA) that involved the following steps:

- Review literature and data to understand the different types of multi-family residential buildings currently allowed by the MBC, fire loss data, the role of equipment reliability, and identify limitations to the RIA and associated data.
- Align with the TAG on the use of the RIA, identify code-compliant and "prototype" MFD building geometries, and define the fire scenarios and consequence used in the comparative analysis.
- Develop the four building geometries used in this study that are less than seventy-five feet in height: (1) a code-compliant 8-level building with two exit stairways; (2) a code-compliant 4-level building with one exit stairway; (3) a prototype 8-level building, 6,000 square feet (sf) per level, with one exit stairway; and, (4) a prototype 8-level building, 4,000 sf per level, with one exit stairway.
- Based on the reviewed data and TAG input, prepare an event tree to quantify the results of different end states occurring, based on select mitigating features or systems succeeding or failing. This analysis is conditional on a fire occurring (i.e., a probability of 1.0), as discussed with TAG.

  A conditional probability approach allows for comparison of the efficacy of fire protection features and systems without introducing the significant uncertainty associated with trying to estimate frequency of fire ignition, which is not reported nationally or in Minnesota. As discussed with TAG, the consequence is the point when tenability limits are reached in egress pathways, such that further evacuation through that space may not be possible, provided occupants are notified of a fire by a building system, OR, if occupants fail to receive an evacuation cue from a building system. Determination of the consequence for each scenario involved a combination of fire and evacuation modeling, or simple correlations based on engineering judgment.

- Characterize the relative importance of the mitigating features or systems to the overall building performance, "building risk," as defined within and quantify the uncertainty of the estimate. The objective of this report is not to generate an absolute risk to predict the likelihood of certain consequences from occurring in different MFDs; rather, the objective is to use an identical RIA to generate a conditional risk for different MFDs and compare the different building geometries and mitigating features or systems with one another.
- Develop construction cost estimates for potential protection enhancements identified in the RIA to achieve outcomes in the RIA equivalent to or better than those required by the current Minnesota Building Code.
- Provide recommendations based on the data to help inform decision making by the Minnesota policy makers.

Conclusions

After reviewing the data and conducting the analysis, the Consultants have the following conclusions.

1. The addition of common area smoke detectors would reduce the comparative building risk of the prototype single-exit stairway MFDs (Building 4) and for a dwelling unit fire in Building 3 to be less than or equal to that of a code-compliant single-exit stairway MFD.
2. The most comparative risk-significant failure is the sprinkler system failing to flow. Creating a more robust inspection, testing and maintenance program consistent with NFPA standards will increase the reliability of a sprinkler system to flow on demand and for building occupants to be notified. Based on the Minnesota fire data (MFIRS), the current observed mean reliability of a sprinkler system flowing on demand is approximately 88 percent. If this reliability can be increased to approximately 96 percent, the estimated risk of both prototype single-exit stairway MFDs (Building 3 and Building 4) would be less than or equal to that of a single-exit stairway, code-compliant MFD having the observed sprinkler system reliability.
3. A properly operating automatic sprinkler system provides the most significant comparative building risk reduction impact.
4. The number of exit stairways factors into the comparative building risk evaluation only when the sprinkler system has failed to control the fire, AND when the door to the dwelling unit of fire origin is open, AND when the exit stairway door on the floor of fire origin is also open.
5. Almost 97 percent of the building risk for each analyzed scenario can be attributed to the sprinkler system failing to flow on demand. Thus, reliable fire sprinkler systems are important fire risk mitigation measures.
6. When the sprinkler system fails to control the fire and the door to the dwelling unit of fire origin is left open, the combustion products freely flow into the corridor. Thus, reliable door closers are important fire risk mitigation measures if the sprinkler system fails.

7. When the sprinkler system fails to control the fire and the door to the dwelling unit of fire origin in a single-exit stairway MFD is left open AND the exit stairway door is open, the combustion products freely flow into the stairway. Given that the corridor volume is expected to be sufficiently small, the exit stairway quickly fills with smoke and becomes untenable before occupants are anticipated to make the decision to evacuate. However, occupants in multiple-exit stairway MFD buildings on floors other than where the fire originated can use the unaffected exit stairway to egress.
8. The Consultants defer to the MBC where data could not support quantitative conclusions. Examples include construction type requirements based on height and area, fire resistance ratings of structural elements and fire resistance ratings of various other assemblies.
9. The Consultants reviewed mitigation measures via the RIA where the comparative building risk of the prototype MFD exceeded the benchmark building risk using the Event Tree. Several concepts were evaluated where the available data could support quantitative evaluations to compare the building risk of the various prototype building geometries. These options and others not included in this report are ultimately up to policy makers.
10. The lack of available data on fire service operations in single-exit stairway buildings and comments from TAG reinforced that tactical response questions remain for effectively fighting fires in single-exit stairway buildings more than four stories in height.
11. Egress modeling demonstrates that the issue of counter-flow within the prototype single-exit stairway MFD building is not a significant factor due in part to the limited building height and limited number of occupants in the prototype buildings.

Recommendations

Consistent with the stated purpose of this study, recommendations have been developed to reduce the building risk of the prototype MFD single-exit stairway buildings to be less than or equal to that of a code-compliant single-exit stairway MFD building. The recommendations are based upon the RIA to identify features that significantly impact the comparative building risk. The recommendations were developed for the Minnesota policy makers to consider on an individual basis and are not required to be taken together.

1. Provide smoke detectors in the common means of egress in single-exit MFDs more than four stories tall.

Providing smoke detectors in common egress areas, such as corridors, in MFDs that are sprinklered throughout provides a means of activating the building fire alarm system that is independent from the sprinkler system. The addition of the common area smoke detectors would reduce the comparative building risk of the prototype single-exit stairway MFDs, Building 4, and in dwelling unit fires for Building 3 to be less than or equal to that of a code-compliant single-exit stairway MFD.

2. Increase enforcement of NFPA 25 and NFPA 72 inspection, testing, and maintenance (ITM) requirements in single-exit MFDs more than four stories tall.

Implement a more robust ITM program to increase the reliability of a sprinkler system flowing on demand. Based on the MFIRS data, the current observed mean reliability of a sprinkler system flowing on demand is approximately 88 percent. If this reliability can be increased to approximately 96 percent, the estimated comparative building risk of both prototype single-exit stairway MFDs (Building 3 and Building 4) would be less than or equal to that of a single-exit stairway MFD compliant with the MBC having the observed sprinkler system reliability.

The ITM program should also include periodically inspecting that dwelling unit and exit stairway door closers function properly, that doors can fully close and latch automatically, and that doors are not propped open, in accordance with NFPA 80. The RIA risk-significance of the dwelling unit doors and exit stairway doors will rise as the sprinkler system reliability increases.

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INTRODUCTION

Wiss, Janney, Elstner Associates, Inc. (WJE) and Crux Consulting (Crux), the “Consultants,” are pleased to present this report to the Minnesota Department of Labor and Industry (Client) documenting the fire risk-informed approach (RIA) used to study multi-family residential dwelling buildings, hereafter referred to as “MFDs,” with a single-exit stairway up to 75 feet in height. This study is a result of the Minnesota Legislature’s recently adopted legislation mandating a study of this issue. The text of the legislation is included in Appendix A.

Various organizations have documented the issue of a national housing shortage that has garnered increasing headlines in recent years [1].* Several factors affect the cost of housing, including local zoning laws, construction costs, land availability, regulatory compliance, and interest rates. Some housing advocates have cited the current limitation on single-exit stairway buildings as a factor affecting the cost of construction of multi-family buildings that could purportedly be addressed by increasing the allowable height and area for single-exit stairway MFDs, resulting in reduced construction costs, more usable floor area, and more flexibility for infilling urban lots [2].

The Consultants were tasked with reviewing data and conducting an analysis to provide information to allow the Minnesota policy makers to make an informed decision on potential changes to the Minnesota State Building Code to allow taller and/or larger floor plan area single-exit stairway MFDs. The conclusions within this report are based upon an analysis of data on MFD fires, input from project stakeholders, and the application of established fire protection principles. The comparative RIA evaluates two example code-complying MFDs to define a benchmark level of performance, “building risk” as defined within. That same RIA is then applied to calculate the building risk of two prototype single-exit stairway MFD buildings up to 75 feet in height. Where the results of the comparative RIA for the prototypes are greater than that of the benchmark MFDs allowed by the Minnesota Building, mitigation measures are considered to reduce the comparative RIA results to those that are equal to or less than the benchmark MFDs.

The RIA for this comparative assessment is a simplification of reality and building behavior for comparative contextualization and should not be used as an absolute metric for predicting building risk or the individual risk to an occupant within the building.

The construction cost estimates included in this report are intended to provide a relative cost among various construction alternatives. The cost estimates are based upon limited information and should not be construed as being based upon detailed construction drawings and specifications as part of a competitive bid process.

Further, this report does not comment on defining an acceptable level of risk or safety and does not provide language for potential direct adoption into the MBC. Those tasks are left to the policy makers in the State of Minnesota.

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* The bracketed numbers identify the references included in the Endnotes of this report.

BACKGROUND

Single-Exit Stairway Buildings

The potential increase in the utilization of single-exit stairway MFD buildings has recently received national attention as a means to help alleviate the housing shortage in the United States [3]. Other states and cities have or are also looking into this topic, including the states of Colorado, New York, California, and the City of Dallas [4].

Seattle and New York City have allowed single-exit stairway MFD buildings that exceed the height currently permitted in the Minnesota Building Code for many years. For example, Seattle has allowed some version of single-exit stairway MFD buildings since about 1977, with a current allowance of six total stories above grade plane where not more than five stories of a MFD building are served by the single-exit stairway with additional specific conditions [5]. Additionally, New York City has allowances for single-exit stairway MFD buildings dating to at least 1938, with current allowances for a six-story building having not more than 2,000 square feet per story, provided the building is of Type I or Type II construction [6].

There have also been several studies conducted, a national symposium, articles published, and changes proposed to the MBC and the model International Building Code (IBC) related to single-exit stairway building designs to help reduce the cost of construction and increase useable building area in MFDs [7].

Specifically, some studies have explored increasing the limitations of single-exit stairway MFDs with advocates citing the benefits to affordable housing and the safe records of mid-rise residential buildings, but with fire safety advocates concerned about a reduced level of fire safety in such buildings [8]. Some studies cite the height to which single-exit stairway residential buildings are allowed in other countries as a foundational argument, and some include qualitative risk assessments as an attempt to quantify the impacts of such proposed changes [9].

However, much of the previously published work by others generally lacked adequate technical support such as fire loss data, system reliability data, consequence analysis and input from stakeholders. The State of Minnesota commissioned this study to provide additional context via its request for proposals for this Single-Egress Stairway Apartment Building Study. This study differs in that it analyzed state and national fire loss data, used risk analysis tools to evaluate different building geometries and received input from an advisory group of stakeholders organized by the State of Minnesota, the Technical Advisory Group (TAG).

For context, the MBC is based upon the IBC, one of several of its “model codes” published by the International Code Council (ICC), a non-governmental, not-for-profit organization consisting of building officials, fire officials and other industry professionals, developed through a governmental consensus process. Various states, cities and other jurisdictions adopt the ICC model codes with local amendments reflecting the jurisdictions’ unique needs and conditions. The IBC reflects a complex, layered approach to fire protection as documented in the several hundred pages that provide detailed design and construction requirements.

As part of the model code process and in an attempt to stay current, the ICC revises the IBC on a three-year cycle. This revision process typically includes revisions to existing language and occasionally adds new sections but rarely starts with a "clean-sheet" approach looking at things in a comprehensive manner, i.e., a "systems approach," that considers the role of each element working together. See Appendix B for more information.

The development process of the model codes tends to overlay design requirements in part because an acceptable level of risk is not quantitatively specified. Additionally, advancements in reliability and effectiveness of today's passive and active mitigating systems are not generally evaluated in the context of an "acceptable" level of building risk representing a consensus among stakeholders.

The requirement for two independent means of egress from most buildings has been built into the United States building codes for decades. Many pivotal fire events over the past 150 years have served as a basis for such requirements. At the same time, however, many fire safety requirements have recently been added to building codes as well, related to fire compartmentation, fire sprinklers, fire detection, and more. Unfortunately, little analysis within the building codes of how well two-exit stairway buildings perform in fires has been conducted, so data and rationale for modifying the two-stairway requirement are often found lacking. In many cases, the tendency is to focus on a second stairway as being a redundancy, eliminating a potential single point of failure, without looking specifically at two-stairway buildings that fail and identifying the major risk contributors (and risk mitigations). For example, both non-sprinklered two-stairway MFDs and single-exit stairway MFDs can fail to safeguard occupants [10]. A data-supported RIA can help add context to the features and systems in the building codes that are most significant in reducing fire risk associated with this case.

Risk-Informed Approach

Building fire safety decisions are complex, even when data are available. They involve understanding and managing fire impacts to achieve multiple objectives with respect to the protection of people (occupants, emergency responders), property, operations, a building's historic fabric, and the environment. One needs knowledge of the intended use of the building (e.g., residential, public assembly, industrial), the hazards associated with the use, the characteristics of the occupants, and other important design objectives, such as structural stability, occupant comfort, and energy sustainability. Numerous parties have a stake in developing building fire safety decisions, from developer to occupant, lender to insurer, regulator to first responder. There are often numerous regulatory requirements that must be met in the planning, design, construction, and operational stages of a building's life. To achieve desired fire safety performance, or risk outcomes, in such a complex socio-technical system, many items must come into balance [11].

To reduce the number of decision variables for a large percentage of building designs, the current practice is to codify basic building performance expectations into regulations, codes and standards. How this is accomplished can vary based on whether the building regulatory system is performance-based (or function- or objective-based), such as in England, Australia or Canada, or prescriptive-based, such as in the United States. In a performance-based system, the building regulation (or "code") identifies functional or performance objectives and allows engineering analyses to demonstrate that acceptable performance has been achieved, either directly or via a simplified compliance approach (i.e., deemed-to-satisfy solutions or verification methods).

In a prescriptive-based system, requirements are largely specified in detail, but "alternative" designs to the specified requirements are allowed, where the benchmark for acceptability of the alternative design is "equivalent" safety, performance and/or other factors [12].

However, regardless of whether one is working within a performance- or prescriptive-based system, getting agreement on "acceptable" performance based on engineering analysis for a specific building can be challenging, since high-level criteria defining (or benchmarking) acceptable performance, risk or safety are often lacking.

This is particularly the case for fire, since most building regulatory systems do not include system-level performance metrics, such as an overall building fire safety tolerable risk level. This results in complicated discussions around how acceptable performance, safety or risk will be ultimately determined, what data and methods are acceptable for use in the analysis, and how uncertainty and unknowns are to be treated. This need has spawned a plethora of fire safety design guidelines over the past 30 years [13].

This same situation exists when considering regulatory changes associated with building fire safety performance. Because the regulations (model codes) lack definitive criteria defining acceptable performance related to safety or risk, there is often not a common basis for decision-making when a regulatory (code) change is proposed, and so each stakeholder in the process may define key parameters differently, different data and methods may be used, different acceptability targets may be selected, and so forth. In addition, building codes establish minimums that apply to classes of buildings, with the aim to manage risk to a societally-tolerable level. This means not every individual can be assured of having the same level of risk, but on average, the level of risk for all is deemed by the adopting authority to be tolerable. Unsurprisingly, disagreements can be common when comparing options. Lacking a common system-level metric for building fire safety in building regulations, one approach that can be helpful in decision-making for both individual building fire safety design and for building fire safety regulation is the application of an RIA [14].

A RIA uses data to inform decisions and better understand, benchmark, and assess alternatives to regulation-based design requirements for building fire safety. RIA is used in many other industries and in other regulatory areas such as U.S. National Aeronautics and Space Administration (NASA), the U.S. Nuclear Regulatory Commission (NRC), the U.S. Government Accountability Office (GAO), and the U.S. Federal Energy Regulatory Commission (FERC) [15]. A RIA was used in this study for several reasons:

- No building can ever be considered risk free or 100% safe, even when built to building code requirements. This is particularly the case for fire safety, when the building code does not regulate contents, the occupant population is highly variable, and robust measures are not in place to assure compliance with inspection, test and maintenance (ITM) requirements and safety management requirements over time [16].
- In its simplest form, risk can be viewed as the combination of the probability (i.e., the frequency or likelihood) of a specific event occurring, and the consequences of the event should it occur. One can expand this concept to consider multiple possible events (scenarios) and associated risks. Since there are many ways to define risk and consequences, it is important to agree on definitions for these terms as part of a RIA, which was supported by TAG.

- Fire remains a somewhat rare event. One needs the confluence of fuel, a competent ignition source, and adequate oxygen, all reacting to result in combustion. There are many safety measures employed in buildings, systems and products to help control these variables. As a result, in most cases, many things have to go wrong for a fire to occur (in general, fire frequency is very low), and many things must go wrong in response to the fire to result in significant loss (the likelihood of unwanted consequences, given a fire occurs).
- Approaches to managing fire risk in buildings, at a regulatory level, reflect a societal risk management approach. That is, it is not possible for regulations to consider all possible building configurations, and all possible events, as can be done more fully in an individual building design. Rather, the approach is to consider mitigation strategies that work for classes of buildings to manage risk to a tolerable level.
- To determine a baseline building level of fire performance related to risk currently being tolerated by society in buildings designed and constructed to current and prior codes, investigation of fire loss data in the target residential buildings is needed, and an assessment is warranted to determine key contributors, to the extent practicable. Data to consider include the leading causes of fire, fire spread beyond the area of origin, efficacy and reliability of fire protection measures, responses of occupants, firefighter operations, fire safety management, and overall building performance some years after the initial certificates of occupancy were issued. It must be recognized that data are not always available for each of these components. Where data are unavailable or uncertain, this needs to be considered appropriately.
- Estimating specific fire loads and conditions, and specific occupant actions, is highly uncertain for an individual (specific) building analysis, and even more so when considering a portfolio (class) of buildings. However, evaluating the reliability and efficacy of building fire safety systems based on historical performance can be useful to help establish a benchmark to compare contributions of different fire safety systems and strategies in reducing fire risk. The data used in this comparative assessment were obtained from competent national, regional or local jurisdiction and associations that collect and publish such data. Benchmarking also allows an evaluation of enforcement mechanisms, including design review and ongoing audits, to help determine if objectives are being met.
- A RIA for fire then considers fire loss data, fuel loading, and system efficacy and reliability data to develop appropriate scenarios for fire effects modeling and egress modeling [17].
- The assumptions and bases of model input parameters are critical to the quality and validity of modeling. It has been famously said that “All models are wrong, but some are useful”[18]. Models are simplifications of reality. The usefulness of models is that the underlying mathematics is sound, limitations are known and acknowledged, uncertainty and variability is recognized and addressed, and models are used appropriately in the context. A RIA explicitly considers these issues, so that stakeholders understand limits of applicability and boundary conditions of output validity.
- The RIA for this comparative assessment quantifies the building performance of two prototype MFD and two code-compliant structures (CCS) within the same MBC occupancy classification. This RIA provides a quantitative contextual basis to compare the impact of proposed building changes to the MBC. It also allows for additional mitigation features to be evaluated to determine their impact on the building fire performance, or “building risk,” as defined within.

- A RIA is also a “systems” approach: the building’s fire safety features, fire protection systems, the building design, occupants, fire service, etc., are considered part of an integrated system, and the system needs to be viewed holistically to understand whether expected system performance can be achieved [19]. Too often, stakeholders look at only individual components of more complex systems and ignore key interactions and influences. This can result in a small part of a larger system (e.g., a door closer in fire barrier) appearing to meet a small objective but negatively influencing the larger system performance by not being considered holistically (e.g., door closers only meet performance expectation if properly working—just being installed is not enough to assess the performance).
- In this study, the comparative RIA is effective as a tool for the relative comparison of the building risk of different building geometries using a consistent approach. The comparative RIA is a simplification of reality and building behavior and should not be used as an absolute metric for predicting individual building risk, or fire risk to an individual in the building.

METHODOLOGY

Other states and cities have made code modifications to address single-exit stairway buildings, generally based on professional judgment. For this study, the Consultants were given a clear objective by Minnesota DLI concerning the expected performance of prototype single-exit stairway buildings: identify criteria that makes a single-exit stairway residential building four stories in height and up to 75 feet in height equivalent to or better than other types of multi-family housing currently allowed by the MBC.

Buildings having occupied floors more than 75 feet above grade are typically considered high-rise buildings by the building code and are required to have more fire safety features and systems because they are beyond the reach of fire department aerial ladders, have longer evacuation times, and are more subject to stack effect, the natural phenomenon that can cause smoke to move throughout the building. For the purposes of this study, buildings under 75 feet in height are considered "low-rise" buildings.

To conduct this analysis, the Consultants utilized a multi-faceted approach. The Minnesota DLI was concerned that other similar studies did not obtain adequate input from stakeholders. Therefore, the Consultants met with project stakeholders, the TAG, formally and informally, to obtain various perspectives on this matter which proved to be very valuable in the analysis. Rather than simply employ professional judgment, the Consultants used an RIA that involved the following steps:

- Review literature and data to understand the different types of multi-family dwelling (MFD) buildings currently allowed by the MBC.
- Review Minnesota and national fire loss data over a twenty-year period to obtain fire loss history in the MFD configurations of focus, fire events in MFDs that resulted in large casualties, and the role of equipment reliability. The Consultants also identified limitations within the available data that was used in the RIA.
- Review available fire safety system reliability data.
- Review the types of single-exit stairway and multi-exit stairway MFD buildings allowed by the MBC. Select the code-compliant MFD configurations to be used as benchmarks for the prototype single-exit stairway structures and obtain consensus from the Technical Advisory Group (TAG).
- Select an approach to characterize the probability of a fire occurring. For purposes of this analysis, a fire ignition was assumed to have occurred, i.e., a probability of 1.0, as discussed with TAG. Using this conditional probability approach allows for comparison of building fire protection system efficacy without introducing the significant uncertainty associated with estimating frequency of fire ignition, which is not reported nationally or in Minnesota.
- Define fire scenarios based on the types of fires expected in MFDs as revealed from analysis of fire loss data. Assign thermal properties based on fire test data.
- Define the consequence of the fire in the MFD to be used in the study. For this study, consequence is defined as (1) occupants failing to receive the notification to evacuate, or, (2) provided occupants are notified of a fire by a building system, when tenability limits are reached in egress pathways such that further evacuation through that space may not be possible. Determination of consequences ranged from simple correlations based on engineering judgment to the use of smoke / fire / egress modeling.

- Based on the data reviewed, identify potential mitigating features and systems and their associated importance in the fire event; create an event tree to quantify the likelihood of different end states based on systems succeeding or failing.
- Using the RIA, assign a consequence based on qualitative engineering judgment or quantitative fire and egress modeling to the different event tree end states to calculate the resultant performance, or "risk," for each end state. The sum of the individual end state's risk yields the total building fire performance, or "building risk," as defined for this study.
- Compare the building risk of different MFD geometries. Evaluate various mitigation options for the prototype buildings to identify the risk impact. The comparative risk evaluation is based on a building-level; it is not evaluating individual risk to occupants within the building. The objective of this report is not to generate an absolute risk to predict the likelihood of certain consequences from occurring in different MFDs; rather, the objective is to use a consistent RIA to generate a conditional risk for different MFDs and learn how the limited different building geometries and mitigating building features and systems compare to one another.
- As a societal risk assessment (class of buildings, with generalized typology, and not a specific, individual building), there will always be some attributes that dominate. The size of the two-stairway reference building, which influences total occupant load, length of dead-end corridors, travel distance to the exit access and to the exits, are key components. Different building configurations (e.g., different occupant loads, travel distances, etc.) would yield different outcomes. It was agreed by TAG and consistent with the project scope to limit this analysis to a single two-stairway benchmark building configuration.
- Quantify the risk achievement worth (RAW) to identify the critical systems and uncertainty to understand the risk distribution of the identified systems.
- Develop construction costs estimates of selected potential protection feature enhancements identified by the RIA as being significant. The Consultants employed the services of Rockwise Strategies, a Minnesota-based construction consultant, to provide construction cost estimates of various alternative protection features for comparative purposes.
- Provide conclusions and recommendations based upon available data to help inform decision-making by the Minnesota State policy makers.

TECHNICAL ADVISORY GROUP MEETING SUMMARY

Minnesota DLI created a Technical Advisory Group consisting of various stakeholder groups to provide insight and guidance to this study. The TAG included representatives of multi-family building architects, building officials, developers, fire chiefs, the fire sprinkler industry, the fire alarm industry, fire marshals, Governor's Council on Fire Prevention, construction code users, professional firefighters, fire protection engineers, and housing advocates. Members of the TAG and a more detailed summary of the comments discussed at the TAG meetings are included in Appendix C.

The Consultants engaged with the TAG during three formal meetings with two in-person meetings and one virtual meeting, as well as through individual interviews and other communications throughout the course of the project. The TAG provided significant insight during those discussions, summarized as follows:

1. The Consultants presented the RIA as outlined above at the first TAG meeting. The TAG and the Consultants concurred with the RIA that uses event trees to conduct this comparative assessment and calculate the building performance as described within as relative risk of different MFDs, assuming that a fire has occurred.
2. Many TAG members discussed the large variations in staffing, capabilities, and available resources among the various fire departments within the State of Minnesota. Specific concerns focused on the many volunteer fire departments in the state: low staff numbers, and longer response times of the rural departments. Remote departments may only have three or four first responders on a single piece of equipment that arrive up to 30 minutes after the initial call.

   Fire-fighting, search and rescue are presumed roles of the fire department and various building regulations have been written to facilitate those operations in the built environment. However, building code provisions have not been developed assuming specific fire department staffing, response times and operational levels. It is recognized that there is a wide variation in fire department response time, staffing levels, and fire suppression capabilities throughout the State of Minnesota. The analyses in this report are generally based upon no fire department intervention.
3. The TAG members agreed upon the four buildings geometries to include in this study with none taller than 75 feet in height:
   a. A code-compliant, eight-level, two-exit MFD that maximizes exit travel distance, dead-end corridor distance, and common path of exit travel allowances. This is identified as "Building 1" in this report.
   b. A code-compliant single-exit MFD (per MBC Section 1006.3.3), limited to four levels. This is identified as "Building 2" in this report.
   c. A prototype single-exit MFD, up to 6,000 square feet per floor, and up to eight units per level. This is identified as "Building 3" in this report.
   d. A prototype single-exit MFD, up to 4,000 square feet per floor, and up to four units per level. This is identified as "Building 4" in this report.

   The building geometries used in this study are summarized in Table 1.

4. The Consultants presented the key variables proposed for the fire modeling and egress modeling, as addressed in the subsequent sections of this report, including a dwelling unit fire and a corridor fire.
5. The Consultants also presented the determination of consequence for the RIA and received commentary from TAG, ultimately resulting in the building's "consequence" as defined within this report. The comments from TAG included acknowledging the benefits of the fire service anecdotally but not quantifying their impact within the context of this RIA.

Table 1. Building Geometry Summary

Building Geometry (No.)	Building Type	No. of Levels	Floor Area per Level (sf)	No. of Units per Level	No. of Exit Stairways	Occupants Per Level
1	MBC Code-Compliant	8	40,625	No Limit	2	204
2	MBC Code-Compliant	4	4,000	4	1	20
3	Prototype	8	6,000	8	1	30
4	Prototype	8	4,000	4	1	20

DATA SUMMARY

The summary of the Consultants' review of the reported fire loss data is below. Appendix D provides a detailed review of the data received, along with supporting figures and/or tables.

- The death rate of fires for single-family homes is approximately six times higher than the fatality rate of occupants in multi-family residential buildings built in the year 2000 or later [20].
- Approximately 50 percent of MFD fires start in the kitchen; however, fires that start in the living room or bedroom are responsible for more civilian MFD fatalities [21].
- The national civilian fatality rate per fire event in non-sprinklered MFDs is approximately three times as high as in MFDs that are sprinklered throughout [22].
- Within the state of Minnesota, approximately 1 percent of MFD fire events from 2004–2024 resulted in one or more civilian fatalities, a relatively rare event. Where a fire event resulted in a civilian fatality, 91 percent of these fire events involved a single fatality. The multi-fatality fire events occurred in non-sprinklered buildings [23].
- Most civilian fatalities occur in the same area as where the fire started. It is difficult to protect occupants intimate with the fire in MFD regardless of the building's sprinkler protection status or the number of exit stairways [24].
- Fires in common egress pathways such as corridors and stairways were not significant events related to civilian fatalities based on a review of MFD fire events in the State of Minnesota between 2004–2024 [25].
- The following sprinkler system reliability data used in this study were determined based on the MFIRS fire event database for MFDs between 2004–2024 [26]:
  - 42 percent of fires were too small to activate the sprinkler system. This number could be larger given that not all residential fires, such as small cooking fires, are reported to MFIRS.
  - The sprinkler system flowed water in 88 percent of the reported fire events in MFDs that were protected throughout by an automatic sprinkler system.
  - When the sprinkler system flowed on demand, the system successfully controlled the fire in 98 percent of the events, resulting in an operational reliability of 86 percent.
- Properly working doors limit the spread of combustion products, as demonstrated by the Fire Safety Research Institute's "Close Before You Doze" public safety education message [27]. Although there may be some minor leakage through a closed door, it is not expected to compromise the tenability of spaces on the non-fire side for as long as the door stays intact.
- The data supporting the fire sizes used in the fire modeling are provided in the Fire Scenarios section of this report.

BUILDING CODE REVIEW

A review was conducted to identify current building code requirements of various jurisdictions within the United States related to new single-exit stairway multi-family residential (MFD) buildings. In line with the scope of this study, the building code review was limited to MFD buildings that are less than 75 feet above the grade plane. Buildings such as these are generally limited to seven stories above the grade plane, but may include up to eight levels under certain conditions, e.g., when a "garden level" is included.

Both the MBC and the IBC classify multi-family residential buildings as Use Group R-2. The MBC and IBC define R-2 occupancies as those containing sleeping units or more than two dwelling units, where the occupants are primarily permanent in nature. The analysis in this report is based upon criteria applicable to dwelling units.

The codes that were included in the Consultants' review consist of the following:

- Minnesota Building Code, 2020 Edition, based on the 2018 International Building Code (MBC)
- Amendments to the Minnesota Building Code (for the 2026 Edition)
- International Building Code, 2024 Edition (IBC)
- Seattle Building Code, 2021 Edition, based on the 2021 International Building Code (SBC)
- National Fire Protection Association Life Safety Code®, 2024 Edition (NFPA 101)
- Proposed changes to the 2024 International Building Code

The following codes and standards were also referenced in the preparation of this document:

- Minnesota State Fire Code, 2020 Edition (MFC), based on the 2018 International Fire Code
- International Fire Code, 2024 Edition (IFC)
- Seattle Fire Code, 2021 Edition (SFC), based on the 2021 International Fire Code
- New York City Building Code, 2023 Edition
- National Fire Protection Association, Fire Code, 2024 Edition (NFPA 1)
- National Fire Protection Association, Standard for the Installation of Sprinkler Systems, 2022 Edition (NFPA 13)
- National Fire Protection Association Standard for the Installation of Sprinkler Systems in Low-Rise Residential Occupancies, 2022 Edition (NFPA 13R)
- National Fire Protection Association Standard for the Installation of Standpipe and Hose Systems, 2024 Edition (NFPA 14)
- National Fire Protection Association Standard for the Installation of Stationary Pumps for Fire Protection, 2025 Edition (NFPA 20)
- National Fire Protection Association Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems, 2026 Edition (NFPA 25)
- National Fire Protection Association National Fire Alarm and Signaling Code®, 2022 Edition (NFPA 72)
- National Fire Protection Association Standard for Smoke Control Systems, 2021 Edition (NFPA 92)

As documented in the TAG discussion summary, the allowable exit travel distance, common path of travel and width of egress components were of interest. For a fully-sprinklered building, the Minnesota Building Code allows multi-exit MFDs to have a maximum exit travel distance of 250 feet (MBC Table 1017.2), a maximum common path of exit travel distance of 125 feet (MBC Table 1006.2.1), and a maximum dead-end corridor length of 50 feet (MBC 1020.4 Exception 2). The dead-end distance was of particular interest during the TAG meetings as a dead-end configuration effectively acts as a single exit for occupants limited to traveling in that dead end.

Egress widths were also a large part of the TAG discussions. Stairways serving at least 50 occupants are required to have widths not less than 44 inches. Stairways serving fewer than 50 occupants are allowed to have widths not less than 36 inches (MBC, IBC, SBC Sections 1005.3.1 and 1011.2, NFPA 101: 7.2.2.2.1.2 and 7.3.3.1).

The following paragraphs are a summary of the major criteria affecting single-exit stairway MFDs containing dwelling units (not sleeping units).

Single-Exit Stairway Building Criteria

A summary table of selected single-exit stairway building code provisions is provided in Appendix E.

Minnesota Building Code and International Building Code

Both the Minnesota Building Code and the International Building Code (MBC 1006.3.3 and IBC 1006.3.4) currently allow a single exit from a story of a MFD building with *dwelling units* where the story:

- Is the basement, or the first, second, or third story above grade plane;
- Has a maximum of four dwelling units; and,
- Has a maximum exit access travel distance of 125 feet.

The building is also required to be protected by an automatic sprinkler system (MBC 903.2.8 and IBC 903.2.8).

The corridor walls of MFDs are currently required to be 1-hour fire resistance-rated unless they meet requirements of MBC Table 1020.1 where they are allowed to be 1/2-hour fire resistance-rated when the building is protected with an automatic sprinkler system (MBC 708.3). Dwelling unit separations are required to have a 1-hour fire resistance rating unless the building construction Type is Type IIB, IIIB, or VB construction where they can be 1/2-hour fire resistance rating when protected with an automatic sprinkler system (MBC 708.3).

Prior to the completion of this study, Minnesota adopted additional amendments for single-exit MFD (Group R-2) buildings to be adopted into the 2026 edition of the MBC. These provisional requirements will be adopted by rule consistent with a code change proposal.

The amendment allows a maximum of 4 stories served by a single exit, when meeting the following criteria:

- Each story not exceeding 4,000 square feet
- Four or fewer dwelling units per story
- The interior exit stairway is minimum 48-inches in width, serves only dwelling units and does not serve a basement
- The exit travel distance does not exceed 125 feet, with a maximum of 35 feet from a dwelling unit door to an exit
- Exit access corridor wall construction is a minimum one hour fire resistance rating with no reductions allowed
- The sprinkler system is designed in accordance with NFPA 13
- Each sleeping room has an emergency escape and rescue opening

NFPA Life Safety Code

The NFPA Life Safety Code (NFPA 101) has similar requirements to the IBC regarding single exits from buildings (NFPA 101: 30.2.4.6). NFPA has requirements specific to apartment buildings; a single exit is allowed where:

- The total number of stories does not exceed four;
- There are not more than four dwelling units per story;
- The building is equipped throughout with a sprinkler system designed in accordance with NFPA 13 or NFPA 13R;
- The exit travel distance from an apartment entrance door to an exit door does not exceed 35 feet;
- The exit travel distance within the apartment does not exceed 125 feet;
- The exit stairway (including opening protectives) and corridors are required to be 1-hour fire resistance rated; and,
- Dwelling units are required to be separated by 1/2-hour fire resistance-rated construction.

Seattle Building Code

The Seattle Building Code (SBC) was recently amended to allow taller of single-exit MFD buildings (SBC 1006.3.4). Accordingly, the SBC has similar single-exit stairway criteria as the IBC but includes some additional requirements specific to MFD buildings, as follows:

- Not more than a six-story building where the single exit stairway serves not more than five stories;
- Not more than four dwelling units per floor;
- Minimum 1-hour fire resistive rated construction;
- Equipped throughout with an NFPA 13 sprinkler system using *residential sprinklers* in all habitable spaces in each dwelling unit;

- The exit travel distance does not exceed 125 feet, with a maximum of 20 feet from a dwelling unit door to an exit; and,
- Interior exit stairways must be pressurized. If an elevator is provided, the elevator hoistway is also to be pressurized unless it opens into a rated elevator lobby enclosure.

Proposed Building Code Changes

International Building Code

A change was proposed for the 2027 edition of the model IBC (IBC Code Change E24-24) that would allow MFD buildings up to *six stories* in height to have a single-exit stairway. This proposed change to the IBC is currently being processed through the ICC code development process.

The proposed change would require the building to meet the following criteria:

- Types I, IIA, or IV construction;
- A maximum exit travel distance of 125 feet from anywhere on the floor, and 25 feet between a dwelling unit door and the exit; and,
- A 2-hour fire resistance-rated exit stairway enclosure. Interior stairways must be a smokeproof enclosure.

Other Jurisdictions

A number of other jurisdictions are considering amendments to their building codes to include additional allowances for single-exit stairway MFD buildings. Proposed changes were also considered by the local authorities in Dallas, Texas, and in the State of Colorado.

The Colorado General Assembly recently passed HB24-1239 which requires municipalities to adopt a building code by December 1, 2026, that allows MFD buildings up to five stories to be served by a single-exit stairway.

Minnesota Fire Code

Adoption and enforcement of periodic inspection, testing and maintenance of building fire protection features and systems is necessary to assure a high degree of function and effectiveness of passive features and active fire protection systems. Minnesota has a state-wide fire code, the Minnesota State Fire Code, 2020 Edition (MFC), that is based on the 2018 International Fire Code. The purpose of the MFC is to establish minimum requirements to provide a reasonable level of life safety and property protection in new and existing buildings, and a reasonable level of safety to firefighters and emergency responders during emergency operations.

In general, the MFC does not allow the existing fire protection features of a building to be diminished. Moreover, Section 108.1 of the MFC requires fire protection features of a building to be “continuously maintained” in accordance with the MFC and its referenced standards. This includes both passive and active features.

The MFC addresses requirements for the periodic inspection, testing and maintenance of a building's fire protection features and systems. This includes wall and floor penetrations (Section 703), and door openings (Section 705), specifically by mandating periodic inspections in accordance with NFPA 80, *Standard for Fire Doors and Other Opening Protectives*, and NFPA 105, *Standard for Smoke Door Assemblies and Other Opening Protectives*. Section 901.6 of the MFC also requires periodic inspection, testing and maintenance of sprinkler and standpipe systems by adoption of NFPA 25, *Standard for the Inspection, Testing and Maintenance of Water-based Fire Protection Systems*, and fire detection and notification systems by adoption of NFPA 72, the *National Fire Alarm and Signaling Code*.

The operational effectiveness of fire protection features and systems evaluated in this report have been assigned probabilities of success based upon available data where available and professional judgment where no data are available.

Automatic Sprinkler Systems

Sprinkler systems installed in commercial buildings are required to be designed in accordance with NFPA Standard 13, *Standard for the Installation of Sprinkler Systems*, and are intended to provide a reasonable level of fire protection regarding both life safety and property protection. Systems designed in accordance with NFPA 13 will have robust water supplies and installation criteria and have limited non-sprinklered areas. When first considered for application in MFDs, the cost of these systems was viewed as a barrier to the goal of installing automatic sprinklers in residential occupancies, the occupancy with the greatest number of fire fatalities each year.

NFPA Standard 13R, *Standard for the Installation of Sprinkler Systems in Low-Rise Residential Occupancies,* first published in 1989, was developed to encourage more sprinkler installations in multi-family residential buildings and was specifically aimed at prioritizing life safety over property protection. The criteria for NFPA 13R systems were also selected to reduce the cost of installation and maintenance of residential sprinkler systems through, among other things, the omission of sprinklers in certain low-hazard, non-living spaces.

The MBC, SBC and NFPA 101 allow the installation of NFPA 13R systems where the building is not more than four stories and 60 feet in height (MBC 903.3.1.2, SBC 9.3.3.1.3.2, NFPA 101: 30.3.5.1.2). The model IBC requires MFDs to be sprinklered, but allows the installation of NFPA 13R sprinkler systems rather than the NFPA 13 sprinkler systems used in commercial buildings, where the building does not exceed four stories above grade plane and the roof assembly is less than 45 feet above the lowest level of fire department access (IBC 903.3.1.2).

Fire and Smoke Detection

The MBC requires automatic fire detection in common areas of MFD buildings and automatic smoke detection in the common areas and interior corridors of MFD buildings serving as the means of egress. However, in fully sprinklered MFD buildings, the MBC allows the omission of fire and smoke detectors in these spaces (MBC 907.2.9.1.1).

Fire Department Access

A presumption in the IBC is that a newly-constructed building will have as much as 25 percent of its perimeter on a street or public way. That is demonstrated by the IBC section allowing building area increases when the building's frontage on a street or public way exceeds more than 25 percent. The area increases are allowed recognizing the reduced potential for building-to-building fire spread from exterior fire exposure and aided from fire department intervention. However, this is not a code requirement and the actual building perimeter accessible to the fire department can be much lower than 25 percent for high-density urban parcels. This also can affect exterior fire department rescue and firefighting, should automatic sprinklers not operate effectively.

Separately, each reviewed ICC-based code and NFPA 1 require fire apparatus access roads to extend to within 150 feet of all portions of a building. Increases to this distance are allowed where the building is equipped throughout with an NFPA 13 or NFPA 13R sprinkler system. The IFC does not prescribe a specific increase and leaves that decision to the local fire official. The MFC, SFC, and NFPA 1 allow fire apparatus access road distance to be increased to 600 feet, 375 feet, and 450 feet, respectively, where the building is equipped throughout with an automatic sprinkler system (IFC 503.1.1, MFC 5003.1.1 and 503.1.1.1, SFC 503.1.1, and NFPA 1: 18.2.3.2.2 and 18.2.3.2.2.1). NFPA 1 also requires the fire apparatus access road to extend to within 50 feet of an exterior door providing access to the building's interior.

Additionally, each reviewed ICC-based code and NFPA 1 require fire apparatus access roads to have a minimum, unobstructed width of 20 feet. The MBC allows a reduction of the road width to 16 feet where the building is Group R and is equipped throughout with an NFPA 13 or NFPA 13R sprinkler system (IFC 503.2.1, MBC 503.2.1, SFC 503.2.1, NFPA 1: 18.2.3.5.1.1).

Factors Not Considered by Codes and Standards

It should be noted that building codes and standards do not address other key factors that affect the overall level of fire protection provided by a specific building. These factors include, but are not limited to variations in the quantity and flammability of contents within dwelling units, behavioral characteristics of residential occupants, fire department response times, and fire department response activities. Factors such as contents within dwelling units and human behavior will vary depending on the physical location of the building within a state, but can also vary among dwelling units within the same building.

Fire department response requirements, including response time, will depend on the municipality and will be based on factors such as rural versus urban areas, volunteer versus professional fire service, and the specific location of the building relative to the nearest fire station.

FIRE SCENARIOS

Fire Scenario / Fire Characteristics

The fire scenarios were selected based on review of the data on actual fire events and the consequences of those incidents along with larger scale fire tests. The data indicated that although there are more kitchen fires in dwelling units, the more severe consequences of injuries and deaths occur from fires originating in living rooms and bedrooms. The Minnesota fire incident data identified the most severe consequences also occurring in non-sprinklered buildings [28]. Two design fires with distinct fuel loads were considered in the fire modeling analysis as supported by the data and TAG input as discussed earlier. The dwelling unit fire scenario selected for fire modeling was an uncontrolled living room fire which is described below and in Appendix F. Additionally, in reviewing news articles [29]. about other fires in the United States and resulting from discussions with TAG, a corridor fire involving an electric-powered micromobility vehicle, such as an e-scooter or e-bike, was also selected to be modeled.

Dwelling Unit Fire

The heat release rate (HRR) for the uncontrolled living room fire within the dwelling unit was developed based on a series of full-scale room fire tests conducted by NIST [30]. The rooms contained standard furniture items that would be provided in a typical living room such as a couch, tables, and chairs. These tests indicate that the peak heat release rate was between approximately 8,000 and 10,000 kW [31]. The HRR curve for the modeling analysis was developed to represent the results of the three room fire tests.

Corridor Fire

The corridor fire scenario represented an e-bike fire, as requested by TAG. The HRR for the e-bike fire was developed based on fire testing of micromobility devices conducted by the Institute of Applied Fire Safety Research [32]. This research focused specifically on e-bikes and their fire behavior. This test indicates that the peak heat release rate was approximately 900 kW [33].

Consequences

The objective of the consequence analysis is to understand the number of occupants at risk from the selected fire scenarios in different MFD building configurations. When defining the consequence, the Consultants started with the following understandings:

- No building can be designed to be completely risk-free. For example, building codes and standards in the United States generally recognize that occupants intimate with first materials burning cannot be protected, even in sprinklered buildings. This was also agreed upon by the TAG. As such, occupants in the dwelling unit of fire origin who are intimate with the fire are outside of the scope of this analysis.
- Human behavior during a fire event is highly complex and uncertain. Actions taken by humans during stressful events can be difficult to predict. Whether an occupant attempts to evacuate through a smoke-filled corridor, looks for alternative routes, shelters in place, or is ultimately rescued by the fire service is beyond the scope of this study, as confirmed with TAG.

- Given that only local fire alarms are provided in each MFD unit, and the building-wide fire alarm system only sounds when the sprinkler system activates, the baseline assessment considers that occupants outside of the unit of fire origin are only notified when the sprinkler system operates. This means that if the sprinkler system fails to operate, no queue from a building system for evacuation is provided outside the dwelling unit of fire origin.
- Regulatory decision-making for buildings is focused on societal risk – not individual risk. As such, the comparative assessment is based on comparing metrics of building performance of different building geometries to one another, not the individual risk of occupants within a building.

For these reasons, the Consultants define the "consequence" as the number of occupants outside the area of fire origin that are projected to have not evacuated the building when either of the two following criteria occur:

1. The tenability limits have been reached in the paths of egress. This occurs in three stages:
    a. When a sprinkler activates, the building-wide fire alarm system notification signal is activated, and occupants receive a cue to begin the evacuation process;
    b. If the door to the unit of fire origin is open, evacuation is no longer assumed practicable when smoke fills the corridor in sufficient quantity to reach tenability limits and prevent egress from other units on the level of fire origin; and,
    c. If a door to an exit stairway from the corridor on the level of fire origin is opened and smoke enters the exit stairway in sufficient quantity to reach tenability limits, that stairway is rendered unusable.
2. The building-wide fire alarm system does not activate and occupants outside the unit of fire origin have no indication of a fire / cue via a building system to begin evacuation.

It was further acknowledged in meetings with TAG that, although this analysis identifies building occupants who may be impacted by the event due to the above definition, it does not mean that those building occupants would perish in a fire as other strategies remain viable and are available. However, that evaluation, as agreed upon with TAG, is outside the scope of this study.

Fire And Egress Modeling

Fire Dynamics Simulator (FDS) was used for the fire modeling analysis. FDS is a computational fluid dynamics (CFD) software developed by NIST that models fire-driven fluid flow [34]. FDS has the ability to simulate fire conditions where the smoke layer naturally varies in height as it moves away from the fire plume. Egress modeling was conducted with Pathfinder, a modeling software that simulates egress of people from buildings [35].

The fire modeling followed the description of consequence. Therefore, the fire scenarios evaluated with modeling were limited; the egress model was used to identify impacted occupants for those various scenarios. See Appendix F for details of the fire and egress modeling.

When evaluating the total egress time from either a floor or from the building as a whole, the time for an occupant to egress includes multiple steps that are more than just the Travel Time determined by the egress modeling, as identified in the SFPE *Handbook of Fire Protection Engineering*. See Appendix G for a more detailed discussion of egress [36]. In summary, the major components in egress time are Detection Time, Warning Time, Pre-Evacuation time and Travel Time.

For this analysis, Detection Time and Warning Time combine to be the time between fire ignition and the time that the notification alarm signal is activated, including the time to detect the fire by an initiating device. Pre-Evacuation Time is the time from the time of activation of the notification signal to the time an occupant deliberately begins to egress. For this report, Detection Time, Warning Time and Pre-Evacuation time are aggregated into the term "Pre-Movement Time" presented within this analysis.

Also for this analysis, Movement Time is synonymous with "Travel Time," the time it takes to actually travel to a defined exit or a place of refuge as provided by the egress model. This analysis considered egress time from an individual floor, level, and the time to discharge from the building, as discussed with TAG.

The fire and egress modeling was conducted using the floor plans of the four building geometries to identify tenable conditions in the corridors and stairways; and Movement Time as one of the components of the egress time. The four building geometries each include an exit access corridor between the dwelling units and the exit stairway, as discussed with TAG. The results of the fire and egress modeling scenarios are shown in Appendix H.

Figure 1 and Figure 2 are representative of the fire and egress modeling results for a typical fire floor where the Pre-Movement and Movement Times are those for a single floor. Figure 1 identifies egress times and tenability times on a typical fire floor for the four building geometries for a dwelling unit fire with the dwelling unit door open and stairway door closed (Scenarios 1-1, 2-1 and 3-1). Figure 2 identifies egress times and tenability times on a typical fire floor for the four building geometries for a corridor fire (Scenarios 1-4, 2-3 and 3-3). In each case, it is acknowledged that some occupants may take longer or may not be able to egress on their own, depending on multiple variables.

The identification of the consequences for this comparative assessment was simplified for a majority of the scenarios to be those occupants who would be impacted by untenable corridor and/or stairway conditions per the fire modeling analysis, if the Pre-Movement Time was greater than the estimated time for the corridor to become untenable. For the few scenarios where the corridor remained tenable beyond the identified Pre-Movement Time, a further review of the egress model and fire model was conducted to identify occupants who may be able to egress prior to the corridor becoming untenable.

As such, a significant value of the fire modeling was to identify the relatively short time for the corridor on the fire floor to become untenable if the sprinkler system fails to control the fire, or fails to operate, and the door to the dwelling unit of fire origin is open. This is especially apparent when reviewed in conjunction with the varying and potentially lengthy pre-movement times. This is the case regardless of whether the building has one or two exit stairways.

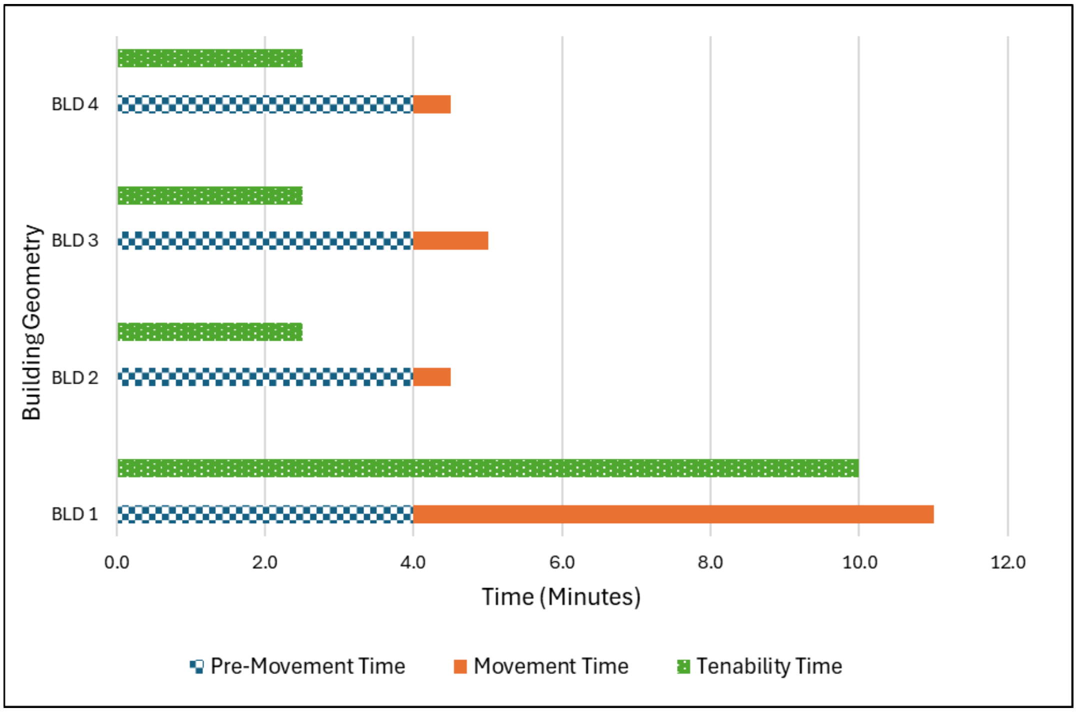

Figure 1. Fire floor egress and tenability times in the corridor for a dwelling unit fire with the dwelling unit door open for the four building geometries

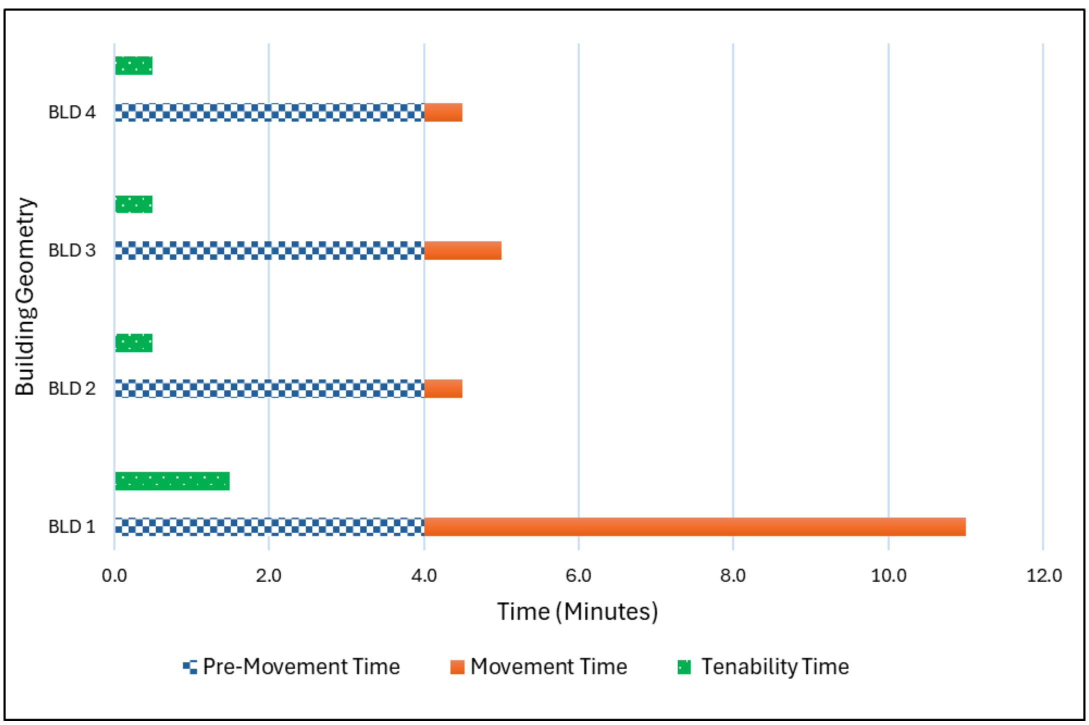

Figure 2. Fire floor egress and tenability times in the corridor for a corridor fire for the four building geometries

Egress modeling was also used to consider the effect on Movement Time for occupants of a wider, 48-inch stairway in the single-exit stairway prototype buildings compared to a 44-inch-wide stairway. Counter-flow, i.e., occupants egressing at the same time firefighters are using the stairway to access the fire floor for rescue and firefighting, was also reviewed.

The egress modeling indicates that increasing the minimum stairway width from 44 inches to 48 inches does not have an effect on reducing the egress time for a single-exit stairway building geometry reviewed under normal conditions because of the low occupant load of a typical floor. For context, the total occupant load of prototype Building 4 is less than that of a single floor of the benchmark two-exit building, Building 1.

Counter-flow does impact the egress time from the single-exit stairway building geometries, adding between 1.5 to 2.5 minutes to the Movement Time from the building. However, when evaluating the wider stairway's effect on counter-flow within a single-exit stairway building, the increased width does not have an impact, assuming that all building occupants begin using the stairway to exit the building at the same time firefighters begin using the stairway to reach the fire floor, the most conservative approach. The egress model for counter-flow does not consider obstructions on the stairways such as hoses and other conditions that may exist in a stairway while firefighters are conducting operations.

COMPARATIVE RISK-INFORMED ASSESSMENT

In this assessment, the aim is to understand the probability of consequence occurrence given the availability (or not) of fire protection features and systems, mandated by code, based on available data and expert judgment. An event tree is used to identify event sequences and calculate the probability of different outcomes occurring based on system reliability estimates.

Event Tree

An event tree shows the likelihood of different outcomes occurring. The event tree starts with an initiating event and then logically progresses through different top events that contain branches which either succeed (horizontal branch) or fail (vertical branch). The probability of success or failure from each branch is propagated until an end state is reached.

The fire protection industry uses event trees to support performance-based designs and quantitative risk assessments to understand potential outcomes of one or more failures occurring in a system [37]. Assigning a consequence to each end state allows a user to calculate the risk of that sequence of events occurring. Summing the individual end state risks yield the total building risk. This allows a user to better understand the risk-significant scenarios and consider measures to mitigate the building risk.

The Consultants developed an event tree to estimate the likelihood of different end states of a fire event in an MFD using mean probabilities (Figure 3). The event tree logic is applicable to fire scenarios within the dwelling unit or in the corridor for both single-exit stairway MFD and multi-exit stairway MFD buildings.

Conditional Fire Event

The Consultants defined the resultant risk as a combination of the probability of an event occurrence and the consequence of the event should it occur. The probability of an event can consider an entire event sequence or can consider conditional states, that is, the probability of an event given that a precursor event has occurred. Since research for this project revealed that ignition frequency data are not readily available for public use, the Consultants and the TAG agreed to apply a conditional probability approach to evaluate the comparative building risk assuming that a credible fire has occurred. This approach is appropriate given: (1) the lack of data available to include an ignition frequency calculation; (2) the ignition frequency is expected to be similar among MFD buildings; and (3) the same comparative approach was used to benchmark the code-compliant MFD buildings and the prototype MFD buildings. This approach is also appropriate to compare the efficacy of select fire protection features identified in the MBC.

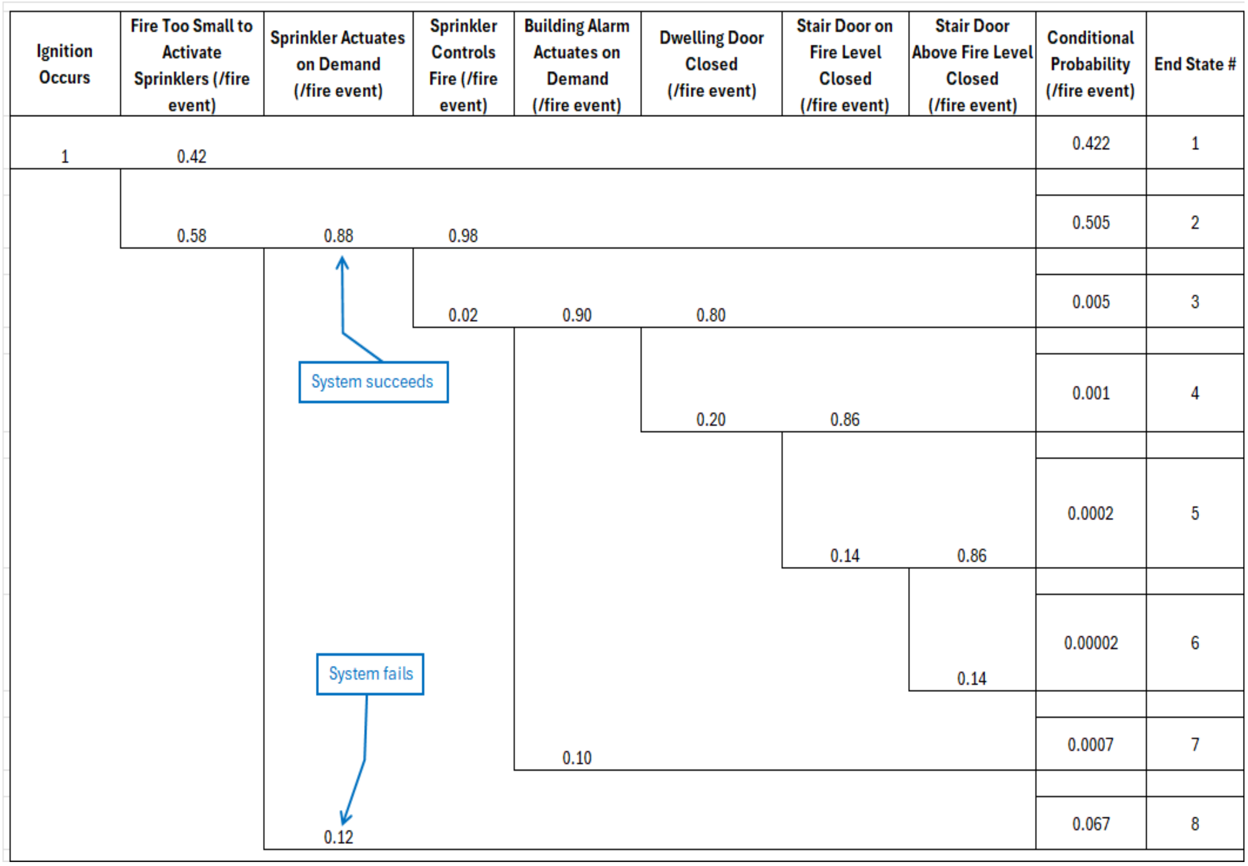

Figure 3. Example event tree (horizontal branch indicates success; vertical branch indicates failure)

The following sections summarize each end state of the Event Tree. The consequences for each end state are supported by the Consultant's review of the MFIRS fire event database, simplified engineering assessments, and/or fire and egress modeling to estimate the tenability of the corridors and exit stairways.

End State 1

The fire is too small to activate the sprinkler system and does not pose a significant hazard to occupants outside the area of origin. Based on a review of Minnesota data of such events, there is a negligible impact to occupants outside the area of fire origin.

End State 2

The fire is large enough to activate the sprinkler system, which activates on demand. The sprinkler system successfully controls the fire. Based on a review of Minnesota data of such events, there is a negligible impact to occupants outside the area of fire origin.

End State 3

The fire is large enough to activate the sprinkler system, which activates on demand. The sprinkler system fails to control the fire. The building fire alarm system actuates; the door to the dwelling unit where the fire originated is closed. Based on a review of Minnesota data of such events, there is a negligible impact to occupants outside the area of fire origin.

End State 4

The fire is large enough to activate the sprinkler system, which activates on demand. The sprinkler system fails to control the fire. The building fire alarm system actuates; the door to the dwelling unit where the fire originated is open. Smoke propagates into the corridor on the floor where the fire originated. The exit stairway door is closed, confining the smoke to the corridor.

In a single-exit stairway configuration, the smoke accumulates quickly in the corridor, making it untenable before occupants begin their egress. The occupants on the floor where the fire originated fail to egress.

In a multi-exit stairway configuration, the smoke spreads into the corridor. Fire/egress modeling is used to estimate the number of occupants on the floor where the fire occurred who can egress before the corridor becomes untenable.

End State 5

The fire is large enough to activate the sprinkler system, which activates on demand. The sprinkler system fails to control the fire. The building fire alarm system actuates; the door to the dwelling unit where the fire originated is open. Smoke propagates into the corridor on the floor where the fire originated. One exit stairway door is also open on the fire floor, allowing smoke to propagate into the stairway.

In a single-exit stairway configuration, the smoke accumulates quickly in the corridor and the exit stairway, making the corridor and the exit stairway untenable before occupants can begin their Movement Time. The occupants in the single-exit stairway building on and above the fire floor fail to egress.

In a multi-exit stairway configuration, the smoke spreads into the corridor and one of the exit stairways. Fire/egress modeling is used to estimate the number of occupants on the floor where the fire occurred who can egress before the corridor becomes untenable. Occupants on other floors egress using the unaffected exit stairway.

End State 6

The fire is large enough to activate the sprinkler system, which activates on demand. The sprinkler system fails to control the fire. The building fire alarm system actuates; the door to the dwelling unit where the fire originated is open. Smoke propagates into the corridor on the floor where the fire originated. The exit stairway door is also open on the fire floor, allowing smoke to propagate into the stairway. The exit stairway door on the floor directly above the fire is also open, allowing smoke to accumulate in the corridor of the floor above the fire floor.

In a single-exit stairway configuration, the smoke accumulates quickly in the corridor and the exit stairway, making the corridor and the exit stairway untenable before occupants begin their movement time. The occupants in the single-exit stairway building on and above the fire floor fail to evacuate.

In a multi-exit stairway configuration, the smoke spreads into the corridor and one of the exit stairways. Fire/egress modeling is used to estimate the number of occupants on the floor where the fire occurred and the floor above where the fire occurred who egress before the corridors become untenable. Occupants on other floors egress using the unaffected stairway.

End State 7

The fire is large enough to activate the sprinkler system, which activates on demand. The sprinkler system fails to control the fire. The building fire alarm system fails to actuate. No occupants evacuate since they do not receive a notification signal from the building's fire alarm system.

End State 8

The fire is large enough to activate the sprinkler system, which fails to activate on demand. The building fire alarm system does not actuate since there is no waterflow through the sprinkler system. No occupants evacuate since they do not receive the notification from the building's fire alarm system.

Comparative Risk-Informed Approach Results

This section reports the comparative results on a building level for the dwelling unit and corridor fire scenarios in each of the four MFD building geometries. Table 2 provides the estimated building performance, or building risk, based on the number of impacted occupants per fire event for each building geometry, as defined within this report. Figure 4 and Figure 5 depict this information from fires that start in the dwelling unit and the corridor, respectively. The building risk is framed as conditional upon a fire occurring and is, therefore, not based on a unit of time.

Table 2. Building Performance from Comparative Risk-Informed Approach

Building Geometry (Bld No.)	No. of Exit Stairways	No. of Levels	Floor Area per Level (ft^2)	Occupant Load Per Level	Fire Location	Impacted Occupants (occupants/fire event)
1	2	8	40,625	204	Dwelling Unit	110
1	2	8	40,625	204	Corridor	110
2	1	4	4,000	20	Dwelling Unit	5.1
2	1	4	4,000	20	Corridor	5.6
3	1	8	6,000	30	Dwelling Unit	15.9
3	1	8	6,000	30	Corridor	16.5
4	1	8	4,000	20	Dwelling Unit	10.5
4	1	8	4,000	20	Corridor	11.0

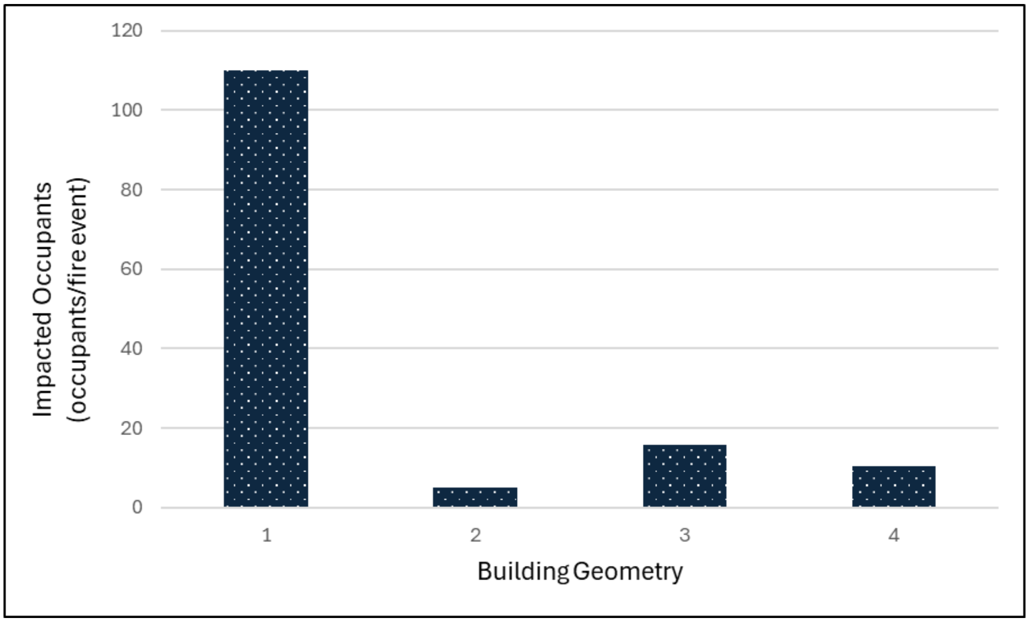

Figure 4. Building performance of code-compliant vs. prototype MFDs for dwelling unit fires, by building geometry number

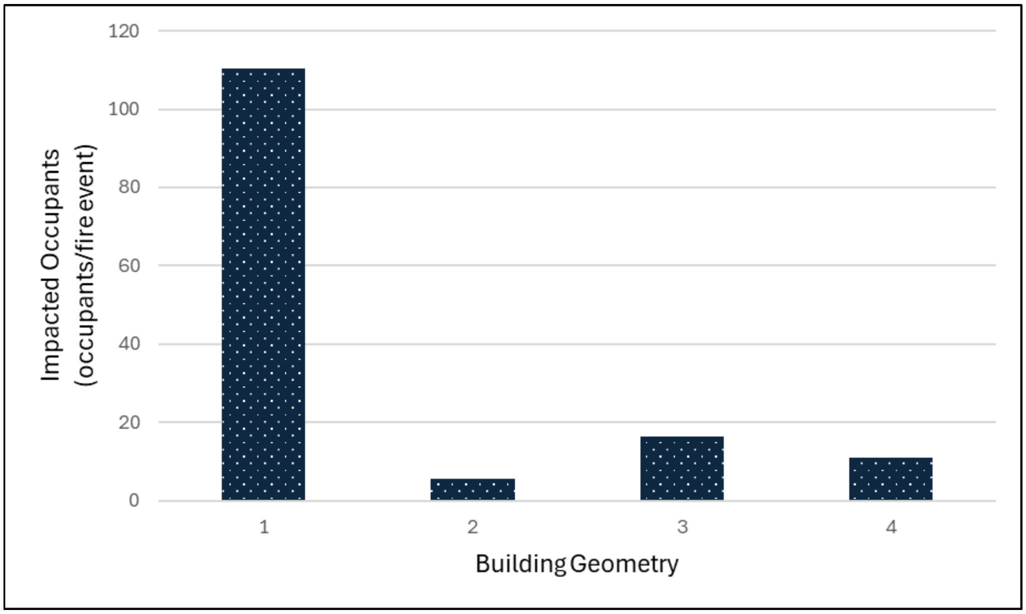

Figure 5. Building performance of code-compliant and prototype MFDs for corridor fires, by building geometry number

These results indicate that the building performance, or building risk, of prototype Buildings 3 and 4 is significantly lower than the building risk of Building 1. The higher building risk of Building 1 is attributed to the larger number of occupants in Building 1 who do not receive the cue to evacuate from the sprinkler system failing to flow on demand.

The building risk of Building 3 and Building 4 is a factor of 3 and a factor of 2 higher, respectively, compared to that of Building 2. This is also due to prototype Building 3 and Building 4 having a higher number of occupants who do not receive the cue to evacuate from the failure of the sprinkler system to flow on demand. This data provides critical insight into the value of the sprinkler system to both (1) suppress and control the fire, and, (2) activate the building-wide fire alarm system to cue occupant evacuation.

Uncertainty

Uncertainty is an important metric in risk studies in general as it reports the confidence of the results. For this comparative RIA, the uncertainty analysis indicated that the reported results are considered reliable based on the data used in this study. Appendix I reports the uncertainty associated with these results based on the system reliability distributions calculated in the Event Tree.

POTENTIAL ENHANCEMENTS

An analysis of potential mitigating measures was conducted to reduce the building risk of the prototype single-exit stairway MFDs so that it is comparable to or lower than the building risk of a code-compliant single-exit stairway MFD.

Common Corridor / Egress Path Smoke Detection

The primary risk driver for each scenario is the sprinkler system failing to flow because no water is applied to the fire and the building fire alarm not activating since there is no waterflow through the sprinkler piping. MBC Section 907.2.9.1.1 requires automatic smoke detectors to be provided in interior corridors serving as part of the required means of egress in MFD buildings *unless* the building is provided throughout with an automatic fire extinguishing system. Therefore, it is currently possible to comply with the MBC with the automatic sprinkler system as the sole means of activating the building's fire alarm system. A potential mitigating measure for the prototype single-stairway MFD buildings is to provide smoke detectors in common means of egress areas in addition to the sprinkler system as a diverse method of activating the building's fire alarm system.

To determine smoke detector reliability, the Consultants reviewed the National Fire Sprinkler Association fire event data in multi-family residential dwellings from 2014–2023 and selected the Minnesota fire events. Using the same approach as in Comparative Risk Assessment section, the Consultants calculated the reliability of a spot-type smoke detector to successfully activate. The Consultants then modified the Event Tree to incorporate the logic for the common means of egress smoke detectors.

Figure 6 and Figure 7 compare the building risk of fires that originate in the dwelling unit and the corridor, respectively, by adding the common area smoke detection system to the prototype MFDs.

The cost of adding smoke detectors in the common means of egress of single-exit stairway buildings is not expected to be significant given that: (1) the buildings may already be equipped with fire alarm systems for the elevator lobby smoke detectors and/or monitoring of the automatic sprinkler system; and, (2) the area of the common means of egress is generally small, typically requiring only a single additional smoke detector within each corridor. The estimated construction cost for adding system smoke detectors in the corridors of the common means of egress in prototype Building 3 is $12,000.

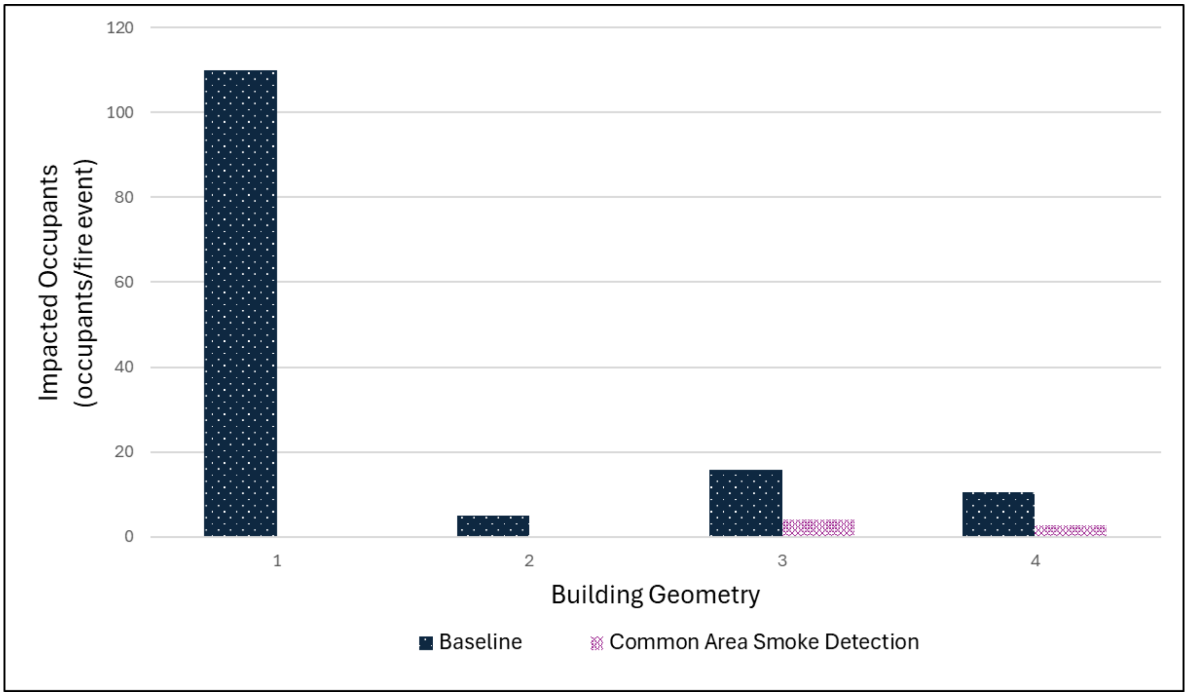

Figure 6. Change in building performance for prototype MFD dwelling unit fires with common area smoke detection, by building geometry number

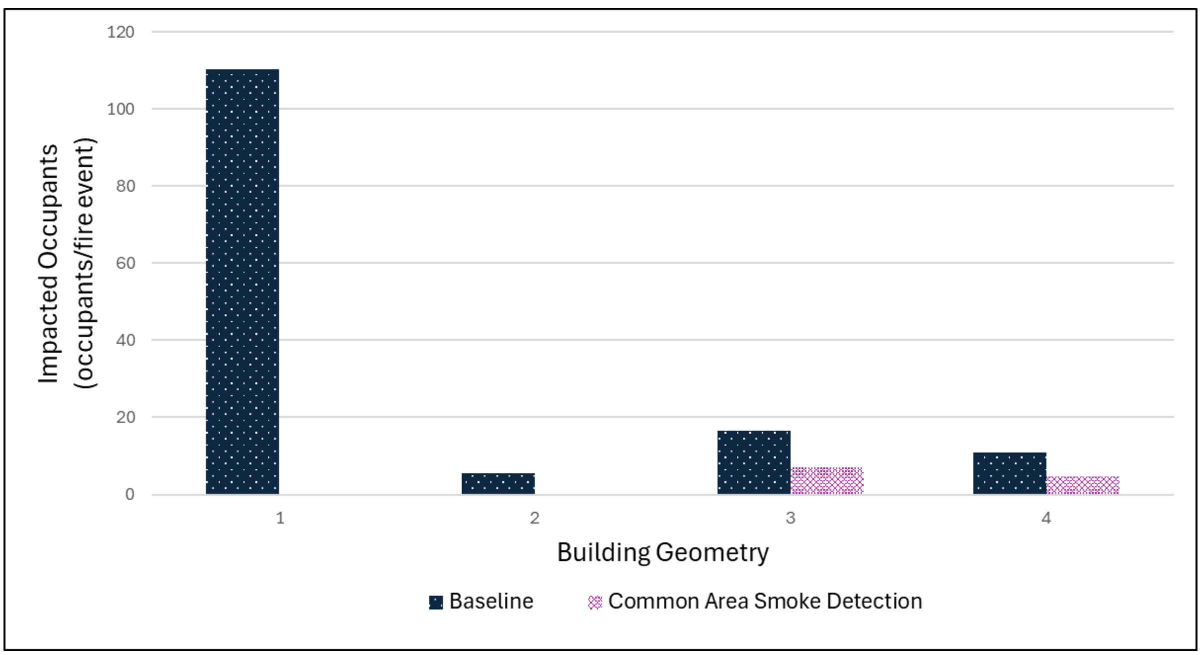

Figure 7. Change in building performance for prototype MFD corridor fires with common area smoke detection, by building geometry number

Inspection, Testing, and Maintenance

The reliability of different mitigating systems is directly tied to the level of service the system receives during its lifetime. Systems that are maintained according to their required inspection, testing, and maintenance intervals have a higher likelihood of success compared to systems that are neglected. The purpose of this section is to demonstrate the increases in reliability for different systems required in the prototype buildings to generate a similar building risk to that of the code-compliant single-exit stairway building based on the reliability data from the MFIRS database.

The analysis demonstrates that a sprinkler system failing to operate is the largest risk-driver for MFD fire events. If the probability of a sprinkler system successfully flowing increases from 88 percent (the average reliability calculated based on the MFIRS data) to 96 percent through more rigorous inspection, testing and maintenance programs, the building risk of the prototype single-exit stairway MFDs can be reduced to a building risk similar of the currently code-compliant single-exit stairway MFD, as shown in Figure 8.

Therefore, rigorous enforcement of sprinkler system inspection, testing and maintenance as required by the Minnesota State Fire Code and referenced Standard NFPA 25, *Standard for the Inspection, Testing and Maintenance of Water-based Fire Protection Systems*, and NFPA 72, *National Fire Alarm and Signaling Code* is recommended.

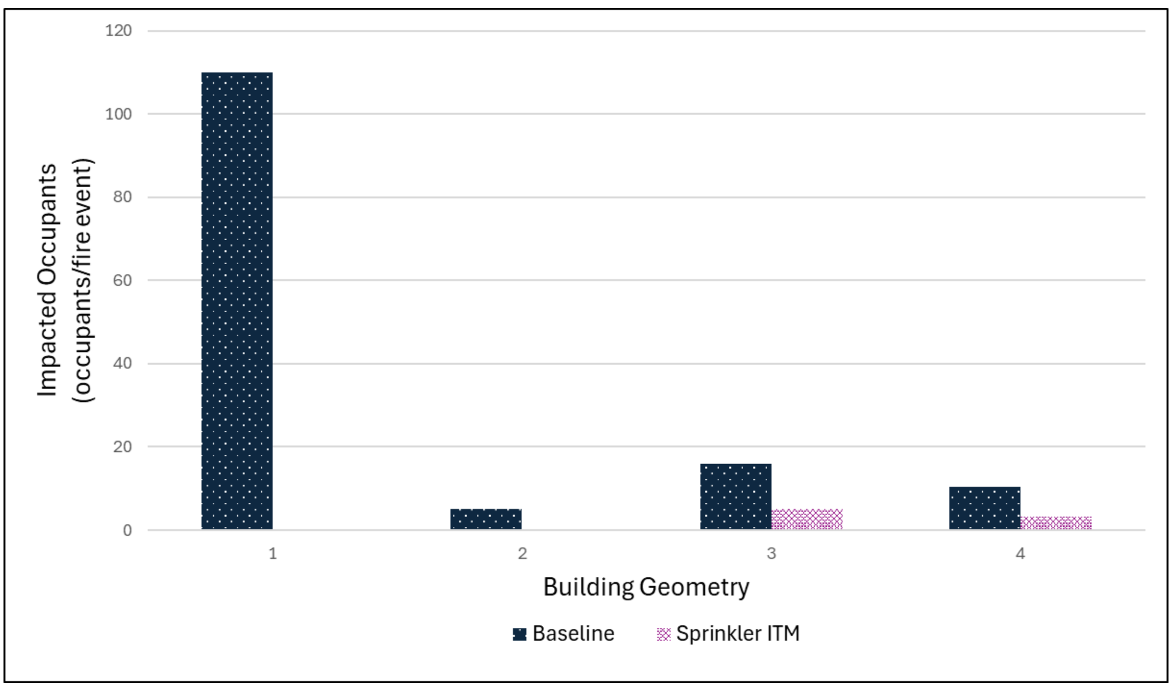

Figure 8. Change in building performance for dwelling unit fires with improved reliability of the sprinkler system, by building geometry number

Additional Considerations

The Consultants considered various other enhanced building features for potentially reducing the building risk of the single-exit stairway prototype buildings. These features were either suggested by TAG, included in other codes' requirements for single-exit stairway buildings, or identified as a result of the Consultants' experience.

Considerations associated with each of these potential protection enhancements as mitigation strategies are presented below. These are listed as potential considerations as sufficient data were unavailable for a quantitative assessment.

1. **Voice Alarm System.** To provide building occupants with increased situational awareness, an occupant notification system with live voice capability would allow the fire service to communicate with occupants who have not yet evacuated the building. The research on human behavior indicates that alarm system type and performance have an impact on Pre-Movement Time. By providing live voice messages, occupants can be notified and given timely, credible information and instructions about egressing or remaining in their units. The estimated additional construction cost for upgrading to a voice occupant notification system from the standard fire alarm system occupant notification system in prototype Building 3 is $47,000.

   The Consultants could not quantitatively evaluate the impact of voice alarm system performance in MFDs, but note that some TAG members recommended its consideration for implementation into a single-exit stairway MFD where the allowable height has been increased.

2. **Building Construction Type.** The construction type of a building determines whether the building's structural elements are combustible or noncombustible, and the level of the elements' fire resistance—the ability of the elements to withstand the effects of a fire exposure. The minimum required construction type is determined from the MBC based upon the building's intended use (in this case, Group R-2), and its size in terms of its height and floor area. In general, taller buildings are required to be of noncombustible construction with the required fire resistance rating of the building's structural fire resistance increasing from 0 hours for some low-rise buildings to as much as 3 hours for very tall and/or very large buildings. This is intended to prevent the collapse of tall buildings subjected to a fire, and to allow occupants adequate time to either escape or reach an area of refuge where they can be "defended-in-place" during a fire and be rescued, if necessary.

   Multi-family residential buildings are currently allowed to be constructed per the MBC up to five stories in height using combustible construction with the structural elements having a zero fire resistance rating. Buildings greater than five stories are required to be of noncombustible construction and have a structural frame with a minimum fire resistance rating of 2 hours. Buildings greater than twelve stories in height must be of noncombustible construction and have a structural frame with a minimum fire resistance rating of 3 hours. Although the MBC allows a zero-rated structural frame in some types of construction, other MBC criteria require a degree of fire resistance for dwelling unit separations and corridor walls. (The above fire resistance ratings are based upon fully-sprinklered buildings.)

The required fire resistance rating of a building's structural elements is also related to the anticipated fuel load of the occupancy. Residential occupancies such as the MFDs in this study are generally considered as having a relatively low fuel load.

The MBC allows a reduction in fire resistance ratings for dwelling unit separations, corridor walls and floor construction in sprinklered buildings, recognizing their record in limiting life loss and property damage. Corridor wall construction and dwelling unit separations in sprinklered MFDs are required to have a minimum rating of 1/2-hour (MBC Sections 1020.1 and 708.3). The estimated additional construction cost for a single 3/4-hour rated dwelling unit corridor door in lieu of the 1/3-hour rated door in prototype Building 3 is $1,150.

The building's structural elements and fire resistive assemblies (FRA) are used for a defend-in-place strategy. Fire resistance ratings specified for the FRAs in the various types of construction for low-rise MFDs is considered adequate to serve as compartmentation for the defend-in-place strategy given: the low probability of simultaneous failure of both automatic sprinkler protection and the compartmentation of the dwelling unit; the relatively short Movement Time for occupants to evacuate a low-rise building under normal circumstances; and the enhanced features recommended in this report.

In conclusion, based upon available data, the Consultants do not have a specific recommendation beyond complying with the existing height limits in MBC Table 504.3 and Table 504.4 for construction type requirements for Group R-2 occupancies for single-exit stairway MFD buildings. Similarly, the Consultants could not quantitatively evaluate the impact of increased fire resistance ratings or material specifications for corridor walls, the dwelling unit doors to the corridor, dwelling unit separations and stairway enclosures.

3. **Scissor Stairways.** The Consultants considered the use of "scissor" stairways as a means of providing two exit stairways while minimizing the required floor area and construction cost for a second stairway enclosure. Scissor stairways are effectively two exit stairways in a single shaft that has a marginal increase in the required floor area and construction cost of the building. While not an uncommon design in high-rise buildings designed decades ago, this stairway arrangement has been specifically prohibited in recent version of the building codes. (See MBC Section 1007.1.1.)

Minnesota reported a multiple-life loss fire in November 2019 involving a scissor stairway exit arrangement in a high-rise multi-family residential building. The report on this fire stated that the building was not protected with an automatic sprinkler system and the apartment door to the corridor failed to close, resulting in an uncontrolled fire that generated heat and smoke that spread to multiple floors within the building [38]. In contrast, New York City allows scissor stairways to be considered as two exits under limited conditions: In Group R-2 occupancies, the enclosing stairway walls must have a minimum rating of 2 hours and be constructed of masonry; the common walls separating the two stairways must have a minimum rating of 2 hours and be constructed of masonry; and the entry doors to the two stairways must be separated by a minimum of 15 feet.

The Consultants believe that scissor stairways could provide an acceptable alternative to constructing two separate stairway enclosures, provided the construction integrity is maintained such that the two stairways have independent environments and that the exit discharges from the two stairways are reasonably remote from one another, preferably both discharging directly to the exterior.

The estimated additional construction cost for a scissor stairway in lieu of the single-exit stairway in prototype Building 3 is $98,000. This compares with the estimated construction cost of an independent second exit stairway in Building 3 of $350,000. In addition, the use of a scissor stairway in lieu of a second exit stairway would increase the usable area on each floor by about 200 square feet. In the case of rental buildings, this additional usable area would have an economic benefit over the life of the building that could be quantified as a present value depending upon local rental rates.

However, the Consultants noted that the comparative building risk benefit will be relatively small (up to an approximately two percent reduction) because: (1) the single-exit stairway corridor is sufficiently small such that it will quickly fill up with smoke and obscure the access to both exits; and, (2) the failure of the sprinkler system is the risk-dominant event.

4. **Smoke Control.** The Consultants reviewed providing smoke control as a potential building enhancement. Smoke control can be an important element in a building's fire safety strategy, particularly in very tall buildings where the stack effect is a significant influence on the movement of smoke within the buildings. Older editions of the model codes mandated smoke control for high-rise buildings with prescriptive criteria for exhausting smoke from the fire floor and pressurization of the stairways. Smoke control design has evolved substantially as the science of fire growth and smoke movement have become better understood.

   The current edition of the MBC requires the interior exit stairways in a *high-rise building* either be designed as smokeproof enclosures or be pressurized to limit smoke spread into the enclosures, and that the building also has a method for the post-fire removal of smoke. The estimated additional construction cost for including a stairway pressurization system for the single-exit stairway in prototype Building 3 is $75,000. This cost estimate is based upon the system being supplied from non-standby power circuits as allowed for low-rise buildings.

Stairway pressurization systems are complex systems and rely heavily upon inspection, testing and maintenance for their proper operation over the life of the building. The efficacy of smoke control provided by stairway pressurization systems is dependent on balancing the number of doors assumed to be open with minimum and maximum stairway pressure criteria. The efficacy of such systems can decrease markedly if more doors are open than designed for, which can result in rapid environmental changes. With most of the design considerations in the model codes based upon sprinkler-controlled fires, the data indicate that the more significant consequence mitigation is when the sprinkler system does not control a fire. If the sprinkler system is functional, the data indicates that the building performance does not require additional mitigation. If the sprinkler system is not functional, it is unlikely that the design of a stairway pressurization system would be effective in limiting smoke quantity and spread from an uncontrolled fire. Therefore, the Consultants do not expect that adding a stairway pressurization system would have a significant building risk reduction impact on these low-rise MFD buildings. Similarly, the Consultants could not quantitatively evaluate the impact of such a system within the limits of this evaluation.

5. **48-inch Wide Stairway**. TAG asked the Consultants to evaluate the effect of increasing the minimum stairway width to 48-inches for the single-exit stairway MFD. The egress modeling indicates that increasing the minimum stairway width from 44 inches to 48 inches does not have a significant impact on reducing the egress time for a single-exit building primarily because of the low occupant load of the building.

   The wider stairway's effect on counter-flow, when occupants are egressing and firefighters are simultaneously using the same stairway, also does not have a material impact in the modeled case, even when assuming that all building occupants begin using the stairway to exit at the same time firefighters begin using the stairway to reach the fire floor, the most conservative approach. The model for counter-flow does not consider obstructions on the stairs such as hoses or fire service staging. In summary, the Consultants did not find adequate data for increasing the minimum stairway width to 48 inches as a means to reduce the building risk in these low-rise MFD buildings.

Risk Achievement Worth (RAW)

Risk achievement worth (RAW) calculates the impact of different mitigation systems assumed to be unavailable [46]. Modifying the system availability results in a recalculation of the Event Tree's end state probabilities for each building geometry. The same consequence is then applied to each end state to calculate the new risk with that selected system unavailable. The ratio of the risk values indicates the relative importance of that system (Equation 1). This helps identify the systems having large impacts on the risk.

$$RAW_{System} = \frac{Risk_{system\ always\ failed}}{Risk_{system\ available}}$$

(Equation 1)

RAW values equal to 1.0 have little to no effect on the results, whereas RAW values exceeding 1.0 show the features' importance to risk, providing a helpful tool to identify those that have an appreciable impact on risk when pursuing risk mitigation strategies. The larger the RAW value, the more critical that system is to risk mitigation.

Table 3 provides the RAW factors for each scenario for which reliable data are available on fire safety system performance. The table shows that the sprinkler system failure generates a risk increase of over 8 times the base for the building geometries evaluated, making it the single-most risk-significant feature. This is expected because it provides fire suppression / control and activation of the building-wide fire alarm system occupant notification to cue egress.

The dwelling unit and exit stairway doors have an almost negligible impact on the risk because they are only involved in the Event Tree sequence where the sprinkler system is flowing but fails to control the fire, and the building-wide fire alarm system has successfully activated. For the corridor fire, the combustion products fill the corridor and obstructs egress as such the impact of the dwelling unit door position on the condition of the corridor is minimized.

Table 3. System RAW Importance Factors

System	Dwelling Unit Fire				Corridor Fire			
	Bldg. 1	Bldg. 2	Bldg. 3	Bldg. 4	Bldg. 1	Bldg. 2	Bldg. 3	Bldg. 4
Sprinkler Protection	8.6	8.6	8.6	8.6	8.6	8.3	8.4	8.4
Fire Alarm System Notification	1.11	1.10	1.09	1.10	1.09	1.05	1.07	1.07
Dwelling Unit Door	1.001	1.05	1.02	1.02	1	1	1	1
Stairway Door and Dwelling Unit Door	1.004	1.10	1.09	1.10	–	–	–	–
Stairway Door	–	–	–	–	1.002	1.05	1.07	1.07

SUMMARY AND CONCLUSIONS

The Consultants were tasked with reviewing data to provide information to the Minnesota policy makers such that they can make a more informed decision on potential changes to the MBC allowing taller and/or larger floor plan area single-stairway MFDs. This report does not identify an acceptable level of risk or safety and does not propose rule changes to the MBC. Those tasks are left to the policy makers in the State of Minnesota.

The conclusions within are based upon an analysis of data of MFD fires, input from project stakeholders, and the application of established fire protection principles. The comparative RIA evaluates two example code-complying MFDs to define a benchmark level of building performance, a "building risk" as defined within. That same RIA is then applied to calculate the building risk of two prototype single-exit stairway MFD buildings up to 75 feet in height. Where the results of the comparative RIA for the prototypes are greater than those of the benchmark MFDs allowed by the Minnesota Building Code, mitigation measures are considered to reduce the comparative RIA results to be equal to or less than that of the benchmark MFDs.

The outcomes from this comparative assessment do not reflect absolute metrics for estimating building risk or the individual risk to an occupant within the building and should not be used for such. Regulatory decision-making for buildings is focused on societal risk—not individual risk. As such, the risk in this report is based on comparing the different building geometries to one another and the associated features and systems within.

The process that was used included:

- Literature and data review of multi-family residential buildings currently allowed by the MBC, fire loss history, and fire safety system reliability data.
- Engagement with the TAG stakeholders to confirm the RIA, along with the benchmark and prototype MFD configurations to review, and the evaluation process for the consequence analysis.
- Defining the fire and egress model scenarios based on the data review and input from TAG, and conducting the fire and egress modeling.
- Using the RIA to quantify and compare the building performance, or building risk, associated with different MFD geometries and fire protection features. Evaluation of various mitigation options for the prototype buildings to understand the building risk impact.
- Quantifying the risk achievement worth (RAW) for systems where sufficient data are available to identify the critical systems and uncertainty to understand the risk distribution of the identified systems.
- Develop construction cost estimates for potential protection enhancements to achieve outcomes in the RIA equivalent to or better than those required by the current Minnesota Building Code.
- Presentation of outcomes of analysis in a report to inform decision making by the Minnesota policy makers.

After reviewing the data and conducting the analysis, the Consultants have the following conclusions.

1. The MBC permits smoke detectors to be removed from common means of egress within MFDs if the MFDs are protected throughout by an automatic sprinkler system. Providing smoke detectors in common egress areas of fully-sprinklered MFDs, such as corridors, would provide a means of activating the building fire alarm system that is independent from the sprinkler system. The addition of the common area smoke detectors would reduce the comparative building risk of the prototype single-exit stairway MFDs (Building 4) and for a dwelling unit fire in Building 3 to be less than or equal to that of a code-compliant single-exit stairway MFD.
2. The most risk-significant failure is the sprinkler system failing to flow. Creating a more robust inspection, testing and maintenance program consistent with NFPA standards will increase the reliability of a sprinkler system to flow on demand and for building occupants to be notified. Based on the MFIRS data, the current observed mean reliability of a sprinkler system flowing on demand is approximately 88 percent. If this reliability can be increased to approximately 96 percent, the estimated risk of both prototype single-exit stairway MFDs (Building 3 and Building 4) would be less than or equal to that of a single-exit stairway, code-compliant MFD having the observed sprinkler system reliability. This is not intended to imply an increased frequency of ITM beyond that included in the NFPA standards but, rather, a greater assurance that the required ITM is being conducted.
3. A properly operating automatic sprinkler system provides the most significant comparative building risk reduction impact.
4. The number of exit stairways factors into the comparative building risk evaluation only when the sprinkler system has failed to control the fire, AND when the door to the dwelling unit of fire origin is open, AND when the exit stairway door on the floor of fire origin is also open.
    a. When this occurs in single-exit stairway MFDs, the exit stairway is no longer tenable for the building occupants. For multi-exit stairway buildings, the occupants have the ability to use the unaffected exit stairway.
    b. The risk of this scenario has a small contribution to the overall building risk profile (estimated to be 0.02 percent for fires that start in dwelling units, and 0.09 percent for fires that start in the corridors) given the multiple failures (sprinkler system, dwelling unit door, stairway door) that need to occur.
5. Almost 97 percent of the building risk for each analyzed scenario can be attributed to the sprinkler system failing to flow on demand (End State 8 in the Event Tree) due to:
    a. No water to control or suppress the fire;
    b. No flow in the sprinkler system to activate the waterflow switch that activates the building's fire alarm system to notify occupants to evacuate; and,
    c. No activation of fire alarm panel also results in no signal being sent to initiate the fire department response.

Taken in combination, if occupants do not receive a building system cue to evacuate, the analysis assumes that they remain in their dwelling units where they are either defended-in-place or rescued by firefighters. This makes the consequence within the building and associated risk-informed comparative results strongly tied to the performance of the sprinkler system and the total number of occupants in the building potentially exposed to untenable conditions. Thus, reliable fire sprinkler systems are important fire risk mitigation measures.

6. When the sprinkler system fails to control the fire and the door to the dwelling unit of fire origin is left open, the combustion products freely flow into the corridor. The corridor volumes in the single-exit stairway buildings are expected to be sufficiently small such that the corridor becomes untenable before an occupant is anticipated to begin to evacuate, affecting the occupants on the floor where the fire occurred. Thus, reliable door closers are important fire risk mitigation measures if the sprinkler system fails.
7. When the sprinkler system fails to control the fire and the door to the dwelling unit of fire origin in a single-exit stairway MFD is left open AND the exit stairway door is open, the combustion products freely flow into the stairway. Given that the corridor volume is expected to be sufficiently small, the exit stairway quickly fills with smoke and becomes untenable before occupants are anticipated to make the decision to evacuate. In this scenario, the occupants in the single-exit stairway building fail to evacuate. However, occupants in multiple-exit stairway MFD buildings on floors other than where the fire originated can use the unaffected exit stairway to egress.
8. This report focuses on limited fire protection features and systems identified within the Minnesota Building Code based on available data. The Consultants defer to the MBC where data could not support quantitative conclusions. Examples include construction type requirements based on height and area, fire resistance ratings of structural elements and fire resistance ratings of various other assemblies.
9. The Consultants reviewed mitigation measures via the RIA where the comparative building risk of the prototype MFD exceeded the benchmark building risk using the Event Tree. While several concepts were evaluated, it was not an exhaustive evaluation of all possible mitigation measures. Instead, the focus was on items where the available data could support quantitative evaluations to compare the building risk of the various prototype building geometries as documented in the Recommendations. These options and others not included in this report are ultimately up to policy makers. If other options are considered, a similar evaluation should be conducted.
10. The lack of available data on fire service operations in single-exit stairway buildings and comments from TAG reinforced that tactical response questions remain for effectively fighting fires in single-exit stairway buildings more than four stories in height.
11. Egress modeling demonstrates that the issue of counter-flow within the prototype single-exit stairway MFD building is not a significant factor due in part to the limited building height and limited number of occupants in the prototype buildings.

LIMITATIONS

The Consultants noted the following limitations with the data requested and/or reviewed as part of this study, including areas where additional information could be collected to aid future analysis.

1. The MFIRS database did not have information related to the buildings' year of construction or the number of exit stairways in the building. The Consultants could use such data to better understand the fire protection systems and features required by the applicable code at the time the building was constructed, and the potential impact of the number of exit stairways during a fire event.
2. There was limited or no data available for the reliability of building-wide fire alarm notification systems, stairway pressurization systems, dwelling unit door position, or exit stairway door position. This data could be obtained by additional research studies. For the purposes of this study, the Consultants relied on engineering judgment to estimate these failure probabilities and associated distributions.
3. The MFIRS database did not include data on why the sprinkler system failed to flow. Given the importance of a sprinkler system, it is recommended that the MFIRS database add a field documenting why the sprinkler system failed to flow or review inspection, testing, and maintenance (ITM) records to understand the non-compliance findings related to sprinkler systems.
4. Ignition frequency data were not available for MFDs. Calculating definitive frequencies of ignition per year is unlikely to yield reliable data given the variability in reporting, the significant number of fire events to review, and the large number of fires that go unreported. Future studies could investigate relative correlations between the ignition frequency and the building area or the number of bedrooms and kitchens.
5. The MFIRS database did not document the actions taken by the fire department during the fire event, or how rescue operations were performed. Considering TAG member input and consensus, this analysis acknowledges the positive fire service impact but does not factor fire department response in this RIA.
6. The MFIRS database did not include a detailed cause of death for reported civilian fatalities in the specific event reports. This information would help analysts better understand the circumstances that lead to civilian deaths in MFDs, how the MFDs failed to protect the occupants, or if the event was beyond the design basis.
7. Data entry into MFIRS is subjective and relies on fire departments to interpret the fields and document a response. Firefighters may interpret fields differently or submit incomplete forms, leading to variability in the reported data. This is a known problem in data reporting and is one reason that the UL FSRI has developed the new National Emergency Response Information System (NERIS) system for fire data reporting [39]. This study does not address non-fire related events that may result in occupants either needing to evacuate or remain in place. Examples of such events outside the scope of this study are active-shooter or earthquake events.
8. Limited potential fire building risk mitigation measures are included in the Potential Enhancements section of this report but, as noted, sufficient data to quantify their efficacy in fire risk reduction are not available. Data collection on performance of these and other systems would enhance future RIAs of this type.

RECOMMENDATIONS

Consistent with the stated purpose of this study, recommendations have been developed to reduce the building risk of the prototype MFD single-exit stairway buildings to be less than or equal to that of a code-compliant single-exit stairway MFD building. The recommendations are based upon the RIA to identify features that significantly impact the comparative building risk. The recommendations were developed for the Minnesota policy makers to consider on an individual basis and are not required to be taken together.

1. Provide smoke detectors in the common means of egress in single-exit MFDs more than four stories tall.

Providing smoke detectors in common egress areas, such as corridors, in MFDs that are sprinklered throughout provides a means of activating the building fire alarm system that is independent from the sprinkler system. The addition of the common area smoke detectors would reduce the comparative building risk of the prototype single-exit stairway MFDs in Building 4, and in dwelling unit fires for Building 3 to be less than or equal to that of a code-compliant single-exit stairway MFD.

2. Increase enforcement of NFPA 25 and NFPA 72 inspection, testing, and maintenance (ITM) requirements in single-exit MFDs more than four stories tall.

Implement a more robust ITM program to increase the reliability of a sprinkler system flowing on demand. Based on the MFIRS data, the current observed mean reliability of a sprinkler system flowing on demand is approximately 88 percent. If this reliability can be increased to approximately 96 percent, the estimated comparative building risk of both prototype single-exit stairway MFDs (Building 3 and Building 4) would be less than or equal to that of a single-exit stairway MFD compliant with the MBC having the observed sprinkler system reliability.

The ITM program should also include periodically inspecting that dwelling unit and exit stairway door closers function properly, that doors can fully close and latch automatically, and that doors are not propped open, in accordance with NFPA 80. The RIA risk-significance of the dwelling unit doors and exit stairway doors will rise as the sprinkler system reliability increases.

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APPENDIX A – STATE OF MINNESOTA LEGISLATION

Minnesota Legislature, Office of the Revisor of Statutes

HF 5247, 4th Engrossment – 93rd Legislature (2023-2024). Posted on 6/5/2025; 8:54 AM

Article 15, Section 46.

Single-Egress Stairway Apartment Building Report

The commissioner of labor and industry must evaluate conditions under which apartment buildings with a single means of egress above three stories up to seventy-five feet would achieve life safety outcomes equal to or superior to currently adopted codes. The commissioner must use research techniques that include smoke modeling, egress modeling, an analysis of fire loss history in jurisdictions that have already adopted similar provisions, and interviews with fire services regarding fire suppression and rescue techniques in such buildings. The commissioner shall consult with relevant stakeholders, including but not limited to the Minnesota State Fire Chiefs Association, Minnesota Professional Fire Fighters Association, Fire Marshals Association of Minnesota, Association of Minnesota Building Officials, Housing First Minnesota, Center for Building in North America, and faculty from the relevant department of a university which grants degrees in fire protection engineering. In addition, the commissioner must also contextualize the life safety outcomes from the single-egress evaluation to life safety outcomes in other types of housing. The commissioner may contract with external experts or an independent third party to develop the report and perform other functions required of the commissioner under this section. The report must include recommendations for code updates for the single-egress buildings evaluated in this section. By December 31, 2025, the commissioner must report on the findings to the chairs and ranking minority members of the legislative committees with jurisdiction over housing and state building codes.

APPENDIX B – THE SYSTEMS APPROACH

Having a minimum of two means of egress from a building has been viewed as a fundamental fire safety principle for many years based upon a presumption that a second exit would be available to building occupants in the event the first exit was not usable for egress. Yet, U.S. building codes have allowed limited circumstances where a single exit is permissible based upon factors such as building height and the number of building occupants exposed to the condition. Such determinations have been made on a consensus basis over many years by the fire safety community based upon subjective determinations.

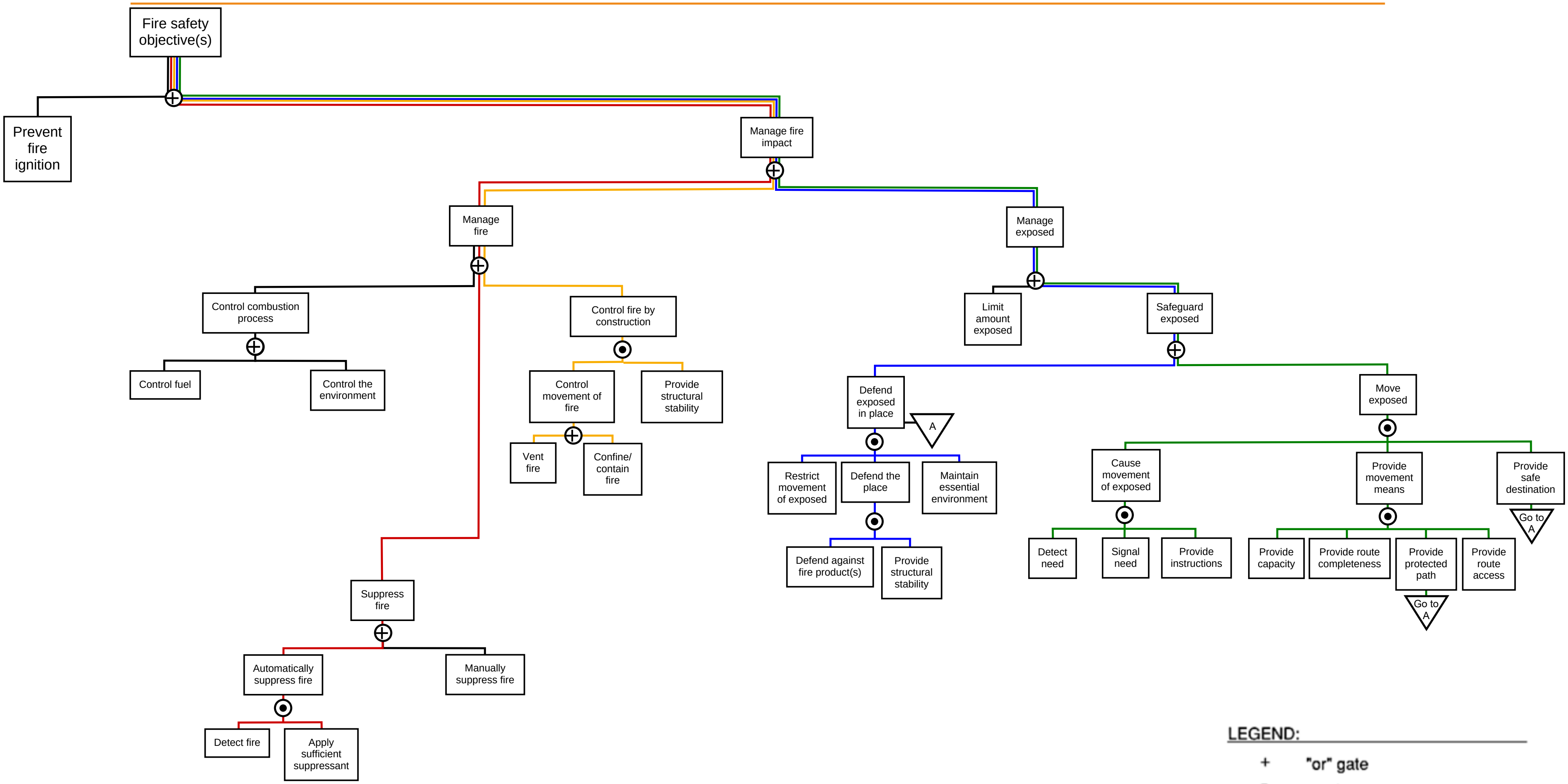
It should be noted that even providing a minimum of two means of egress from a space cannot assure that all building occupants will be able to escape in all cases. For example, building designs with a common exit access corridor leading to multiple exit stairways expose building occupants to a common atmosphere to access the exits. The viability of building exits may be affected by building geometry, fuel load, occupant density, the presence of operational automatic sprinklers, the integrity of the compartmentation, and other factors.

Unlike the vast majority of structures in the U.S., the property of the federal government does not fall under the jurisdiction of state and local building codes. Consequently, the U.S. General Services Administration (GSA), owner-operator of the federal government facilities, was able to deviate from the common practice of simple code compliance and formulate the “Goal Oriented Systems Approach” to fire safety in the 1970s. Classic performance-based design in fire protection engineering dates to this era when it was first applied to the General Services Administration (GSA) Federal Office Building in Seattle, Washington. Harold E. (Bud) Nelson, a fire protection engineer with GSA (later to become President of the Society of Fire Protection Engineers), developed this approach in the era of emerging fire safety demands for high-rise buildings while the model building codes of the time were greatly lacking in providing adequate fire protection requirements for these buildings. This method has since evolved and has become known as the "Systems Approach" to fire safety analysis.

NFPA 550 Fire Safety Concepts Tree

The National Fire Protection Association "Committee on Systems Concepts" developed a similar version of the GSA systems approach now documented in NFPA 550, Guide to the Fire Safety Concepts Tree. The systems approach provides an organized way to characterize and evaluate a building's fire protection strategy with respect to established goals for life safety, property protection and/or business continuity – goals that are often poorly related, or even unrelated, to many of the U.S. building code’s prescriptive requirements. The use of the Fire Safety Concepts Tree also allows for the evaluation of a particular building component, a manual fire alarm system for example, with respect to the established fire protection goals for the building.

There are two primary ways to use the Fire Safety Concepts Tree (Figure B-1).



SUPPRESS FIRE
• Fully-sprinklered building • Quick response sprinklers • Automatic sprinkler waterflow detection with automatic occupant and fire dept. notification • Fully-supervised sprinkler system with off-site monitoring for enhanced reliability • Class 1 standpipe system for fire department use

CONTROL FIRE BY CONSTRUCTION
• Rated dwelling unit separations • Rated corridors • Rated stairwell enclosures • Rated shafts • Rated enclosures for hazardous rooms

DEFEND IN PLACE
• Rated dwelling unit separations • Rated corridors • Rated stairwell enclosures • Rated shafts • Occupant notification system

MOVE EXPOSED
• Egress system: number, capacity, travel distance • Occupant notification system • Protected paths via rated construction • Emergency lighting • Egress signage

LEGEND:

- + "or" gate
- ● "and" gate
- Red: Suppress fire
- Yellow: Control fire by construction
- Blue: Defend in place
- Green: Move exposed

Figure B-1. Guide to the Fire Safety Concept Tree with Notes Applicable to the Typical Single-Exit Stairway Building Configuration.

The objective approach involves developing a mathematical probability of success in reaching agreed upon numerical probability goals. For example, it could be decided that the goal was 99.7 percent probability of success in having not more than one fire death per 100,000,000 hours of personnel exposure, or a 99.6 percent probability of success in preventing any fire from exceeding $100,000 in property damage, or a maximum of $250,000 in business interruption loss. The GSA used this approach in some of its building designs, establishing parameters such as a 99.999 percent probability of success in confining a fire to a workstation, a room, a floor, or a building.

The objective use of the systems approach requires development of success probabilities related to all components of a building's fire protection strategy. In some cases, statistical data are available to develop these probabilities with a good degree of confidence. In other cases, fire test data make it possible to accept basic assumptions. Where data are not available, probabilities are typically based on professional judgment.

For the second approach, the Fire Safety Concepts Tree can also be used in a subjective manner. In this approach, the Fire Safety Concepts Tree is used as a method of organizing thoughts regarding the design or evaluation of a building's fire protection strategy. It encourages the evaluator to investigate alternate approaches, and to consider the interaction of various elements of the overall fire protection system. The subjective use of the Tree provides an excellent tool for facilitating communications among interested parties.

In the case of the single-exit stairway building, the Fire Safety Concepts Tree clearly demonstrates that the fire protection strategy of a building does not depend upon a single feature, such as its means of egress. A successful fire protection strategy depends upon several building features and human elements working together, a principle evident in modern building codes.

This can be seen graphically in the Fire Safety Concepts Tree, annotated for application to this single-exit stairway building analysis, that identifies the various fire protection features of the building and their relationship to one another, showing how various fire protection features and combinations of features can work to achieve an objective. Overall, the Systems Concept provides a powerful method and an organized approach to evaluating a building's level of fire protection against established performance objectives. This approach helped establish the comparative assessment used in this study.

As stated in NFPA 550, one of the most important uses of NFPA 550 is for communication with the stakeholders involved in building design and, in this case, building code development:

> *Codes and standards are not intended to be tutorial; they presume a significant level of comprehension of the principles of fire protection engineering. The Fire Safety Concepts Tree is a simple visual representation of the total concept of fire safety incorporated in codes and standards. It can be used as a means of communication between fire safety specialists and others to help identify the role of specific requirements. The tree should be considered as a first level of education in fire protection engineering (i.e., as an introduction to the full breadth of the subject).*

Figure B-1 shows that fire safety objectives can be achieved by alternative methods. The Fire Safety Concepts Tree can also be used to identify redundancies as well as missing fire protection features in a building. It also shows how all building features work together as a system that provides for the successful fire protection strategy of a structure. Theoretically, if 100 percent success can be achieved by one path, less reliance can be placed on the others. This “systems concept” is discussed in greater detail in the literature and in NFPA 550.

In reviewing the Fire Safety Concepts Tree, it should be noted that two types of "gates" are provided below the various levels of decision. These include "or" gates (+) which indicate that either solution below a particular gate will satisfy the objective above it if they are totally successful or that proportions of each combined will totally satisfy the objective. The "and" gates (·) indicate that, in order to satisfy the goal immediately above the "and" gate, all items in the level immediately below it must be satisfied.

An overall view of the Fire Safety Concepts Tree would indicate that the left side, "Prevent Fire Ignition," refers primarily to those items which would be normally contained within a fire prevention code. The right side of the Tree, under "Manage Fire Impact," deals primarily with those items which would be included within a building code. The Fire Safety Concepts Tree indicates that it is possible to achieve a fire protection objective by either making fire ignition extremely unlikely, or by appropriately managing the fire impact. Of course, a combination of both is the most common approach.

Although the Fire Safety Concepts Tree recognizes various ignition prevention strategies, for the purpose of this analysis, we have presumed that an ignition has occurred and will, therefore, focus on the building’s fire protection features related to “Managing Fire Impact.” This involves Managing the Fire and Managing the Exposed. The relationship of the means of egress to other major fire protection features can be clearly seen in Figure B-1 from the roles of fire suppression, compartmentation/defend-in-place and the means of egress. The different protection strategies are represented by the colored lines. The figure has been further annotated in the colored boxes at the bottom of the figure to identify the fire protection features typically required in a multi-family dwelling (MFD) building under consideration in this study. It should be clear that achieving success with one or more strategies depicted by the various colored paths can lead to meeting the fire protection objective for the project. For example, it shows the relationship of the automatic sprinkler system as an alternative means to providing rated construction.

When considering managing the fire impact, one can either "Manage the Fire" or "Manage (the) Exposed." In order to Manage (the) Fire by construction (yellow line on Figure B-1), not only does the movement of the fire need to be addressed, but it is also necessary to provide for sustained structural integrity in heat-affected areas. The building code provides for the necessary structural integrity by invoking requirements for the protection of structural elements exposed to fire that vary based upon the building’s use, height and area.

A “Manage-by-Construction” issue relates for this analysis relates to the walls and floors between the dwelling units and walls and doors between the dwelling units and the corridors. The Minnesota Building Code (MBC) presently requires a minimum one-half hour construction between dwelling units and common corridors serving more than ten occupants in new, sprinklered multi-family residential construction. Such separations can be compromised if doors are left open. When speaking of "fire," we are actually referring to all of its components: heat, light, smoke and gases. Therefore, effective fire barriers must protect against passage of these elements.

Of greatest concern with respect to life safety are smoke and gases resulting from a fire. The Consultants believe the protection afforded by the minimum construction types included in the MBC is sufficient and have not proposed modifications or additional enhancements.

The above discussion identifies some critical aspects regarding the management of fire by construction. Even with significant improvements to building construction materials and methods, reasonable fire management goals would be difficult to achieve without the assistance of automatic fire suppression, required in multi-family residential buildings over two stories in height in Minnesota since March 1995, and in all multi-family buildings since the State's adoption of the IBC-based code in July 2007.

Within the Fire Safety Concepts Tree, fire suppression may be either manual or automatic. In the case of manual suppression, the human element must be considered. Opportunities for undermining fire protection goals exist in each of the following steps for manual suppression:

- Detection of the fire;
- Communication of a fire signal to responsible persons;
- Decision to act;
- Response to the affected area;
- Application of the suppressant in sufficient quantity;
- Achievement of fire control.

Considerable time can elapse between the origin of a fire and its detection. Areas of the building that are normally unoccupied or not typically visible to occupants present the possibility of a delay in detection. In some instances, the delay could have significant fire protection ramifications, particularly if the areas contain a large number of combustibles. Numerous large-loss fires have occurred due to "delay in detection" and/or "delay in alarm." Even with automatic fire detection systems, the elapsed time between fire detection and the application of suppressant can jeopardize the fire protection of a much larger area.

There are also significant time components to many of the steps that follow detection in a manual suppression scenario. That is why the immediate application of suppressant by automatic means, e.g., automatic sprinklers, during the early stages of a fire offers a much higher degree of reliability in controlling or extinguishing fires when compared to manual methods.

The most widely used method of automatic suppression is the automatic sprinkler system. In recent years, most major U.S. building codes have required the installation of automatic sprinkler protection in an ever-increasing number of buildings, including multi-family residential buildings. The installation cost of such systems in new construction is often partially or fully offset by a reduction in the construction costs associated with providing other features of fire protection, as well as various other design benefits.

If the fire is controlled by automatic suppression, the red line on Figure B-1 indicates that lesser degrees of attention may be afforded in other areas in order to achieve a particular fire safety objective. For example, structural protection and fire control via construction can be less important relative to a situation in which no suppression system was installed. The degree of reduction would depend rather heavily upon the reliability of the suppression system. In the case of automatic sprinklers, system reliability depends on many factors such as system design and maintenance.

The effectiveness of automatic sprinklers in controlling or extinguishing fires is generally excellent. If reasons for unsatisfactory performance related to controllable factors such as impaired water supplies and partial protection are eliminated, records of past performance in many types of occupancies have shown that sprinklers either extinguish or effectively control fires more than 99.0 percent of the time. In addition, there have been no reported multiple loss of life fires reported in fully-sprinklered Group R-2 buildings where occupants were not intimate with the fire.

The high degree of reliable performance is partially due to the electrical supervision (monitoring) of the systems. Electrical supervision of sprinkler systems generally includes the transmission of an alarm signal to a constantly attended location indicating sprinkler operation or a sprinkler system impairment, such as a closed valve. Improperly closed valves account for the largest portion of the unsatisfactory sprinkler performance. (See “Sprinkler System Reliability” below.)

A sprinkler waterflow alarm results from the operation of a sprinkler system which is indicative of a fire and is typically arranged to automatically activate the building fire alarm system and notify the fire department. A valve supervisory alarm indicates tampering with the sprinkler control valve such that the water supply to the sprinkler system has been impaired. Responsible persons receiving these alarms can contact building personnel for corrective action. Additional related equipment, such as fire pumps, water storage tanks, can also be electrically monitored to further ensure the operability of the sprinkler system. An analysis of the reliance placed upon the sprinkler system to accomplish fire protection goals will dictate the relative degree of reliability necessary for the sprinkler system.

The Consultants also note that listed *residential sprinklers* were developed in the early 1980s, designed to limit room temperature and carbon monoxide in a residential environment to improve the survivability of occupants in the room of fire origin. While these sprinklers have been installed in numerous buildings, their use is not mandated, and we cannot reasonably assume the survivability of occupants intimate with the fire in all cases.

In terms of the "Manage Fire Impact" side of the Fire Safety Concepts Tree, the fire protection strategy can be accomplished by taking measures to "Manage the Exposed" rather than to "Manage the Fire." This refers to the protection of people and/or valuable contents. Again, a number of choices are involved including the limiting of the amount exposed (e.g., limit of the number of occupants) or by safeguarding them.

The "Safeguard Exposed" concept allows an individual to be either defended-in-place or moved out of the affected area. The "Defend in Place" concept relates to areas of refuge and compartmentation, concepts included in current building codes, typically via requirements related to fire resistance-rated construction. (See the blue line on Figure B-1). If we have already managed the fire through an automatic suppression system, an area of refuge may be viewed as a secondary means of protection. However, secondary means of protection can be of considerable value and is not to be minimized. A basic principle is included in the Fundamental provisions of the NFPA Life Safety Code, as follows:

> *The design of every building or structure intended for human occupancy shall be such that reliance for safety to life does not depend solely on any single safeguard. An additional safeguard(s) shall be provided for life safety in case any single safeguard is rendered ineffective. . .*

The alternative to “Defend Exposed in Place” is to “Move (the) Exposed.” (See the green line on Figure B-1.) If individuals are to be moved from a potentially dangerous area to an area of safety, it is necessary that the fire be detected, that movement be caused, and that appropriate means of movement be provided. In causing movement, a building alarm system normally is provided for this purpose. Detection can be accomplished either visually, by an automatic detection system, or by an automatic sprinkler system. After the fire is detected, it is necessary that a signal be given to indicate need for action/movement. An automatic fire alarm system with occupant notification appliances is the typical means of causing movement.

The means of movement relates to the egress systems normally required by building codes, which lead occupants to the outdoors or an alternative safe area. The movement means must have adequate exit facilities for each floor of the building. The number and size of exits is based upon three basic principles: exit capacity, travel distance to an exit and redundancy. Exit capacity relates to having adequate width of doors and stairways for the population, or occupant load, of the building; requirements are dependent upon the anticipated use of the building. Exit travel distance is the maximum allowable distance for occupants to reach an exit from any point in the area being evaluated, and it must be within prescribed limits. Also, depending upon the occupant load and use, building codes have required a minimum number of exits for each space or for each floor (with some exceptions) and the physical separation of the exits to address a potential scenario where a single incident could affect multiple egress paths. Aside from providing adequate capacity and meeting exit travel distance requirements, multiple exits have been viewed to provide redundancy should one of the exits become unusable, as previously stated.

Many codes allow an increase in the allowable exit travel distance and a reduction in required exit widths for buildings having automatic sprinklers. This is in recognition of their ability to limit the size and the spread of building fires, allowing more time for occupants of a building to exit the building or reach an area of safety.

It is not the intent of this discussion to provide a detailed analysis of the systems concept. It is intended to identify a tool which provided an element of this fire safety analysis and an outline for the thought process that was involved in the analysis.

Sprinkler System Reliability

The data analysis associated with this study identified a sprinkler system reliability as described in the Data Summary Section. Various other studies of sprinkler system reliability have been published.

Walter Maybee of the U.S. Department of Energy reported reliability approaching 100 percent over a period of 35 years in its highly-maintained facilities [1]. The DOE data is based upon a concentrated effort at including all fire incidents involving sprinklers, not just those involving multiple sprinklers and large losses. Maybee also noted that the DOE sprinkler reliability has been approaching that reported by Marryatt in his study of sprinkler performance in Australia and New Zealand where all systems were required to be electronically supervised and monitored off-site by third parties and the overall record for successful sprinkler operation was 99.76 percent [2].

John Hall of the Fire Analysis and Research Division of NFPA reported in his study of fires from 2003–2006 that automatic sprinklers installed in the area of fire origin (and where fires were considered large enough) operated 95 percent of the time and were 96 percent effective, resulting in a combined operational performance of 91 percent [3].

NFPA (Ahrens) provides statistical data that, at first glance, look less promising [4]. According to this study of sprinkler system effectiveness over several years, systems were effective 88 percent of the time (Figure B-2). As reported in that document, sprinkler systems either failed to operate or they operated ineffectively 12 percent of the time.

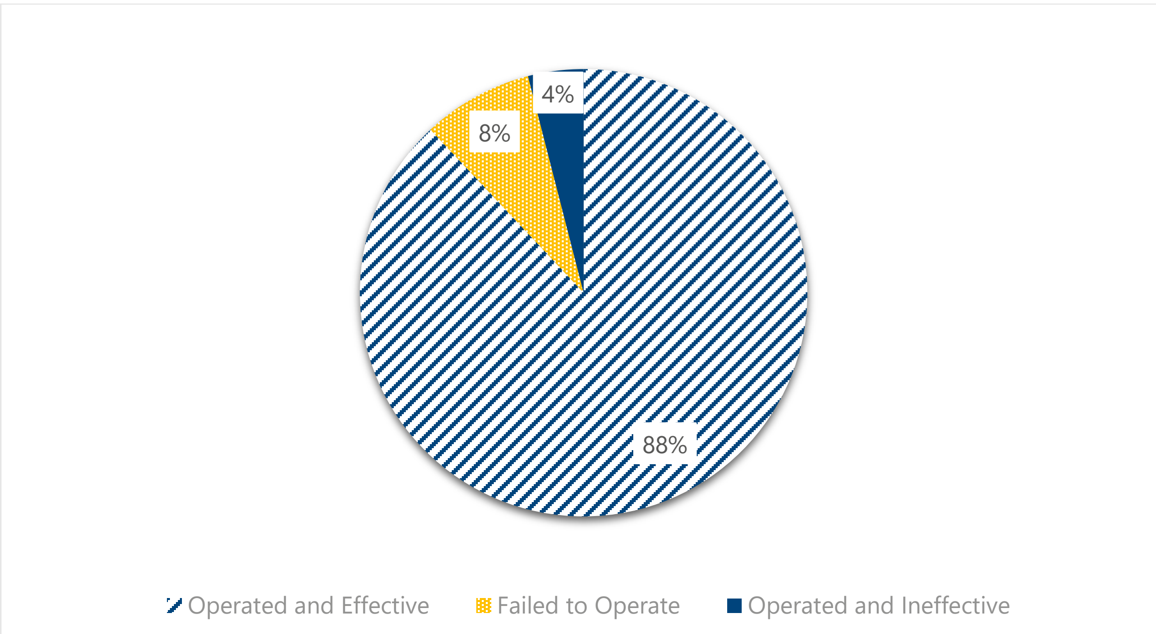


Figure B-2. Sprinkler system operation and effectiveness (Ahrens).

The NFPA report identified the seven major reasons why sprinkler systems evaluated in the study failed to operate or were ineffective as discussed below. These failure mechanisms may not properly represent the expectation in multi-family residential buildings as described below, beginning with comments addressing several of the "Reasons" documented by Ahrens.

Reason 1: System shut-off (40 percent). Electronic supervision of the sprinkler system components (e.g., control valves, pump power, water tank level) is intended to prevent inadvertent shut-offs and other impairments, and to notify responsible personnel in such an event. In the rare instances where a system will be shut off for system maintenance, fire safety issues can be addressed by implementing measures such as fire watches. Furthermore, the MFC (Section 901.7) requires the local authorities to be notified of system impairments, providing an additional degree of management of such conditions.

Reason 2: Water did not reach fire (17 percent). Obstructions to sprinkler water reaching the fire can be minimized by proper system design and regular system inspections.

Reason 3: Manual intervention (13 percent). The sprinkler system in residential applications will be automatic, not requiring manual operation. As for manual interruption of an activated system, protocols by employees and responding fire fighters can be implemented.

Reason 4: Not enough water discharged (10 percent). The sprinkler system density and site water supply are to be designed for the hazard; if the hazard were to change, the required design density may change. However, in a residential occupancy it is unlikely that the nature of the combustibles in a residential environment will materially change over time.

Reason 5: Lack of maintenance (8 percent). The Minnesota State Fire Code (MFC) requires system inspections, testing and maintenance of fire sprinkler systems per NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*, and the associated fire alarm systems are required to be inspected, tested and maintained per NFPA 72, *National Fire Alarm and Signaling Code*. Rigorous enforcement of these requirements is recommended.

Reason 7: Inappropriate system for type of fire (6 percent). Specific to this project, the systems will be designed for the specific hazards associated with multi-family residential buildings and are, therefore, expected to function effectively.

This leaves Reason 6 (system component damage) which accounts for 6 percent of the total and 7 percent of the 12 percent of ineffective cases, representing a failure percentage of 0.9 percent [0.07 x 0.12 = 0.0084]. The resulting reliability is 99.1 percent. An appropriate evaluation of the NFPA data and reliability data cited in several other references consistently support the assumption that a properly designed and maintained sprinkler system would be able to suppress or control a fire at least 98 percent of the time, which means failure to do so 2 percent of the time [5].

Nevertheless, the reliability used for this analysis is based on Minnesota-specific data discussed in the Data Summary Section.

Endnotes

[1] Walter W. Maybee, "Sprinkler Performance Update—1952–1986," *SFPE Bulletin* (May/June 1988), U.S. Department of Energy.

[2] H. W. Marryatt, *Automatic Sprinkler Performance in Australia and New Zealand, 1886–1968* (Australian Fire Protection Association).

[3] National Fire Protection Association, *U.S. Experience with Sprinklers and Other Automatic Fire Extinguishing Equipment* (Quincy, MA: National Fire Protection Association, January 2009).

[4] Marty Ahrens, *U.S. Experience with Sprinklers* (Quincy, MA: National Fire Protection Association, July 2017).

[5] Marty Ahrens, *U.S. Experience with Sprinklers*.

APPENDIX C – TECHNICAL ADVISORY GROUP AND SUMMARY OF COMMENTS

As part of this project, the State of Minnesota Department of Labor and Industry (DLI) created a Technical Advisory Group (TAG) to advise the Consultants on the project. This input included three formal meetings and individual stakeholder interviews. The three formal meetings occurred on April 10, 2025; June 26, 2025; and December 12, 2025. Individual TAG member interviews and communications occurred between April 10, 2025, and December 16, 2025, the date that DLI ended the comment period.

Technical Advisory Group Members

Name	Role	Organization
Mary Barnett	Multi-family Housing Architect	Minnesota Construction Codes Advisory Council
Tom Brace	Fire Sprinkler System Expert	National Fire Sprinkler Association
Nathan Bruhn	Large Municipality Building Official	Association of Minnesota Building Officials, St. Paul
Adam Casillas	Professional Firefighter	Minnesota Professional Fire Fighters Association
Nick Erickson	Housing Development Advocate	Housing First Minnesota
Patrick Farrens	Fire Chief/Tactical Analysis	Minnesota State Fire Chiefs Association
Jim Fisher	Fire Prevention Advocate	Governor's Council on Fire Prevention and Control
Stephen Kartak	Local Government Representative	Minnesota Construction Codes Advisory Council
Jerry Norman	Large Municipality Building Official	City of Rochester
Tom Pitschneider	Municipal Fire Marshal	Fire Marshals Association of Minnesota
Melisa Rodgiguez	Fire Protection Engineer	Governor's Council on Fire Prevention and Control
David Selinsky	Licensed Professional Architect	Minnesota Chapter, American Institute of Architects
Stephen Smith	Advocate for Single-Exit Stairways	Center for Building in North America
Amanda Swanson	Chief Deputy State Fire Marshal	Minnesota Department of Public Safety/State Fire Marshal Division

DLI Staff

Name	Role	Organization
Greg Metz	Building Codes Coordinator	Minnesota DLI Construction Codes and Licensing
Ryan Rehn	Building Codes Coordinator	Minnesota DLI Construction Codes and Licensing

Consultants

Name	Role	Organization
Carl Baldassarra	Senior Principal, Fire Protection	Wiss, Janney, Elstner Associates, Inc.
Kyle Christiansen	Senior Fire & Life Safety Consultant	Crux Consulting
Brian Meacham	Director, Risk & Regulatory Consulting/Adjunct Professor	Crux Consulting/Lund University
Nicholas Ozog	Associate Principal, Fire Protection	Wiss, Janney, Elstner Associates, Inc.

TAG Comment Summary

A summary of the comments discussed at the TAG meetings and in the individual interviews with TAG members is provided below, in no particular order.

Key Factors

- Data provided by TAG members and other outside data, along with commentary from TAG, identified sprinkler reliability, door closer effectiveness, and stairway integrity as key factors that impact occupants' ability to egress unassisted through the building exits.
- For single-exit stairway buildings, the concepts of educating building occupants and realistic expectations for defend-in-place strategies should be discussed.
- Human behavior related to egress during a fire event should be discussed, although it is acknowledged that it is part of a larger human behavior discussion and that the building code does not explicitly address human behavior.
- Building construction type and fire resistance ratings of compartmentation walls were acknowledged as being considered but were viewed as being adequately addressed by the current building code and are acceptable at this time.
- Passive systems such as structural fire resistance ratings, compartmentation and associated fire resistance ratings of floor and wall assemblies of dwelling units, common corridors, and exit stairways can support a defend-in-place strategy and contribute to limiting smoke spread.
- Both passive and active fire-protection-system integrity and reliability are of concern. Potentially, this can be addressed via regular inspection, testing, and maintenance programs and regulatory reporting.
- In a single-exit stairway design, compartmentation integrity should have increasing importance.
- The inclusion of an elevator in the subject buildings is not specifically required. However, practical and market drivers may result in an elevator being included, especially if the building is four stories or more in height. The cost of including an elevator is a factor and increasing the number of units per floor, useable floor area, or stories assists in making an elevator economically viable.
- Well-documented frequency data of fire occurrence in residential occupancies is not available for Minnesota. TAG indicated that at some point the fire service will need to respond to a fire in a single-exit stairway building. Therefore, assuming a fire ignition in this assessment was selected.
- Building geometries and conditions to be used in the analysis and modeling were discussed and agreed upon as discussed in detail elsewhere in this report.
- Egress width for stretcher maneuverability and potential elevator access should be considered in potential rule-making efforts.
- The use of emergency escape and rescue openings and other means of rescue by the fire service were discussed. Ultimately, TAG identified additional egress options, including fire service rescue, to be minimized due to the large variation in response time resulting from large fire protection districts having large coverage areas.

Data

- Minnesota-specific data on apartment sizes, fire loss history, fire service staffing, and various system reliability were shared. Evaluation of the data is included in the data summary part of this report.
- The characteristics of the general building stock for the jurisdiction were reviewed qualitatively for construction type, number of stories and presence of elevators, including typical violations.
- Data inconsistency and associated reliability were discussed and acknowledged; the Consultants reviewed data provided by TAG along with insights or caveats associated with such data.
- Focus on the data from Minnesota; review sprinkler effectiveness data and how NFPA 13 and NFPA 13R systems are different.
- Review fire incident data from Minnesota and other jurisdictions where single-exit stairway buildings have been allowed. This review should include instances where injuries occur and impacts on the fire service. Ignition sources and fire spread data could be reviewed as well, where available.
- Appropriate context to the data from NFPA, Appendix D, and other sources is important to frame conclusions.
- Inspection, testing, and maintenance records were discussed with common modes of failure addressed.

General

- Minnesota building departments are engaged and active, but some variability exists across the state in working with building owners in reporting, inspection and enforcement.
- Flexibility in unit designs and sizes should not be limited in rulemaking; building design should be driven by market factors. "Garden-type" dwelling units are currently not prohibited.
- Current limitations of single-exit buildings have an impact on options for unit sizing. Market factors on affordability and lot sizes factor into unit sizing, not necessarily code language. There is reported interest in unit sizes that vary from studios to multiple bedrooms, e.g., three plus bedrooms.
- Other jurisdictions have allowed various versions of single exit buildings, including Seattle and New York City.
- Inspection, testing, and maintenance for both active and passive protection systems currently have a large variation in enforcement, but this should be standardized to increase compliance for important systems.
- Accessibility requirements are not part of this study but, given the importance of the issue, these issues should be considered in potential rulemaking efforts.

APPENDIX D – DATA AND FIGURES

National Fire Protection Association

The National Fire Protection Association (NFPA) is an organization that publishes standards, performs fire event research, and provides information to the public regarding fire safety. NFPA Research published findings from data collected on residential home fires, including one– and two–family dwellings as well as apartments (Figure D-1). Fire events are much more common in one– and two–family dwellings compared to multi-family dwellings (MFDs), which is to be expected given the substantially larger housing stock of single-family homes versus MFDs. Additionally, the number of reported fire events in apartment buildings from 2000–2020 has stayed mostly constant while the single-family home fire events have fallen over the same timeframe.

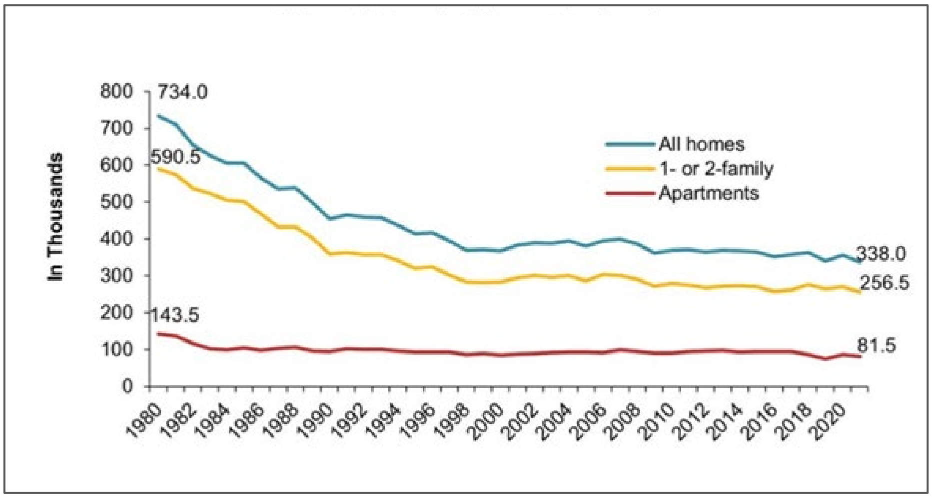


Figure D-1. Reported number of home structure fires by year: 1980–2021 [1]

To supplement this data, a study by The Pew Charitable Trusts titled “Modern Multifamily Buildings Provide the Most Fire Protection” evaluated the fatality rates of single-family homes, MFDs built 1999 or earlier, and MFDs built 2000 or later. Figure D-2 illustrates the significant reduction in annual fatality rates for MFDs constructed in the year 2000 or later, reflecting advancements in the U.S. building codes for multi-family housing.

NFPA also published home fire fatalities by area of fire origin by year (Figure D-3). These data are not identified by residential building type, e.g., single-family, multi-family, etc. Fires that start in the living room and bedroom were responsible for approximately three times as many annual fatalities compared to kitchen fires from 2000–2020.

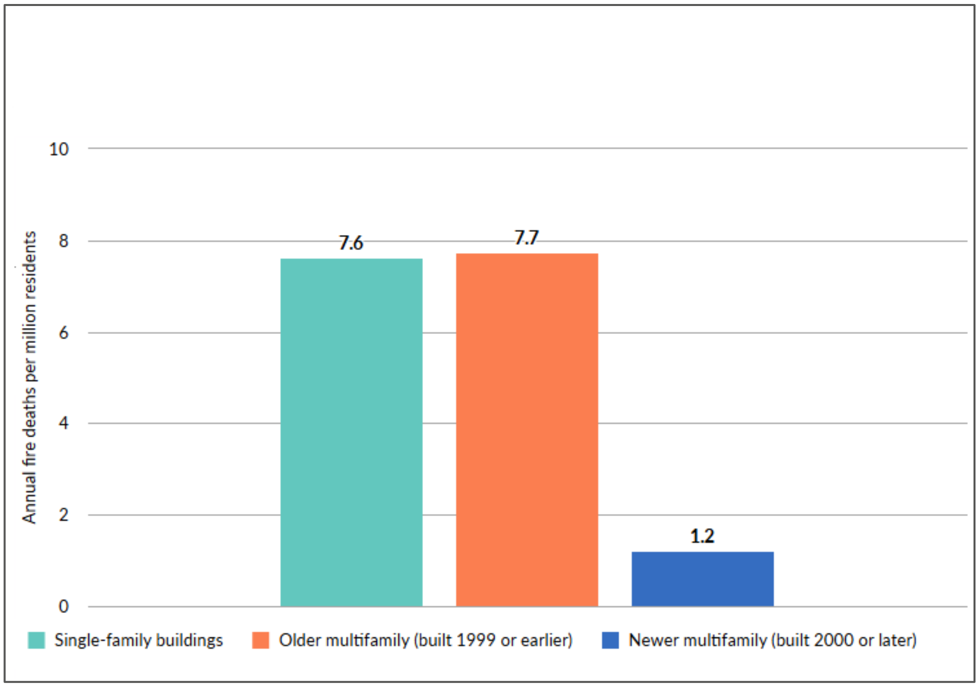


Figure D-2. Annual fatality rates of single-family versus multi-family dwellings [2]

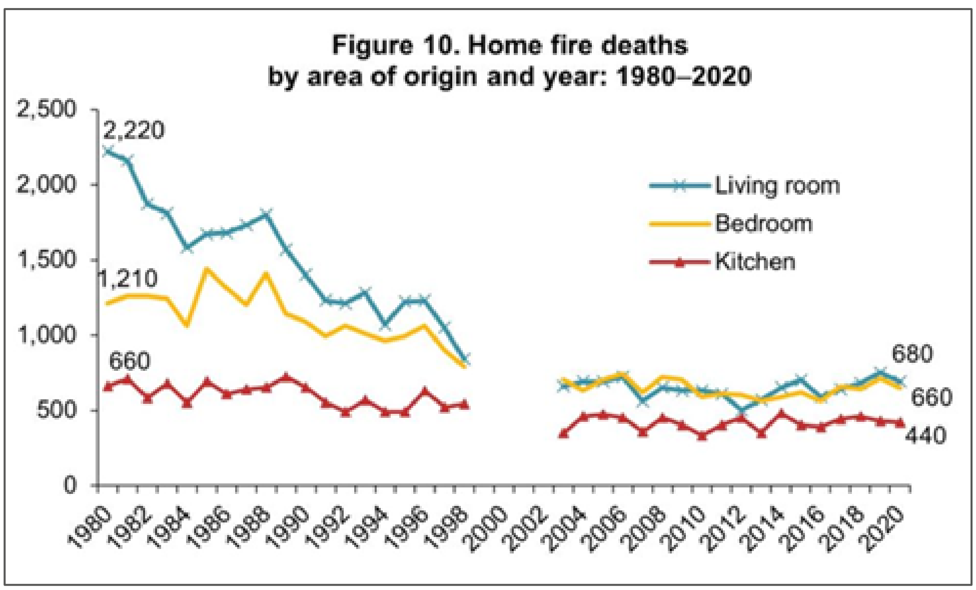


Figure D-3. Home fire fatalities by area of fire origin and year: 1980–2020 [3]

The Consultants contracted NFPA Research to create a custom data set for MFDs from their national database for this report. The data available included the following for MFDs from 1999–2023: number of fires, civilian fatality rates, fires by area of origin, item first ignited, extent of flame spread, civilian fatalities in sprinkler presence, and civilian fatalities by detection presence. Much of this data were categorized by MFDs 1–3 stories, 4–6 stories, and 7 or more stories. The objective of reviewing this data set is to better understand trends causing civilian fatalities in MFDs.

The release of NFIRS version 5.0 in 2003 changed the way that fire event data were collected and reported. To use a more consistent data set that aligns with NFIRS 5.0, the Consultants pared the data set to include events from 2004–2023.

The data produced valuable insights. Figure D-4 shows that most civilian fatalities occur in non-sprinklered buildings up to three stories in height. On average, 88 percent of civilian fatalities occurred in non-sprinklered MFDs up to three stories from 2004–2023. Only two percent of the fatalities occurred for the same period in sprinklered MFDs up to three stories. The Minnesota Building Code (MBC) allows MFD buildings up to three stories to have a single exit stairway. Although the number of exit stairways was not identified in the data set, the impact of sprinklers to reduce civilian fatalities in MFDs where a single exit stairway is permitted is significant.

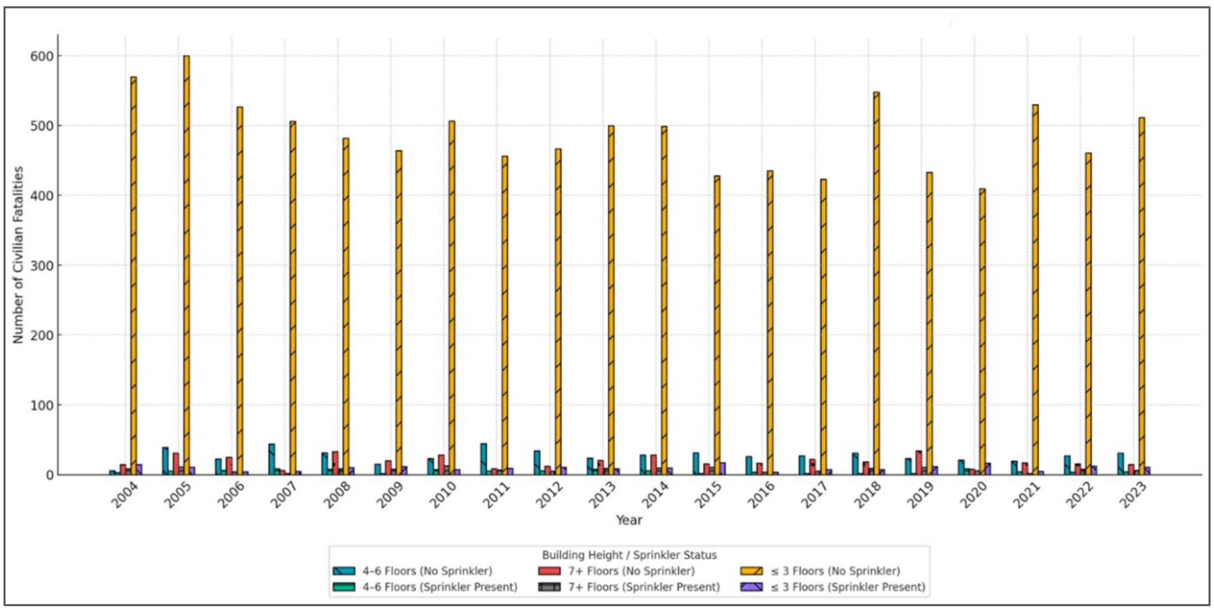


Figure D-4. Civilian fatalities by MFD building height and sprinkler protection status (2004–2023)
(Source: NFPA Research Custom Data Search)

Figure D-5 shows that fatalities in sprinklered buildings are uncommon events. The average number of annual civilian fatalities in the United States in sprinklered 1–3 story, 4–6 story, and 7 or more story MFDs are 9.3, 4.5, and 7.0 fatalities, respectively. Comparatively, the number of annual civilian fatalities in the United States in non-sprinklered 1–3 story, 4–6 story, and 7 or more story MFDs are 483, 23.9, and 18.6 fatalities, respectively.

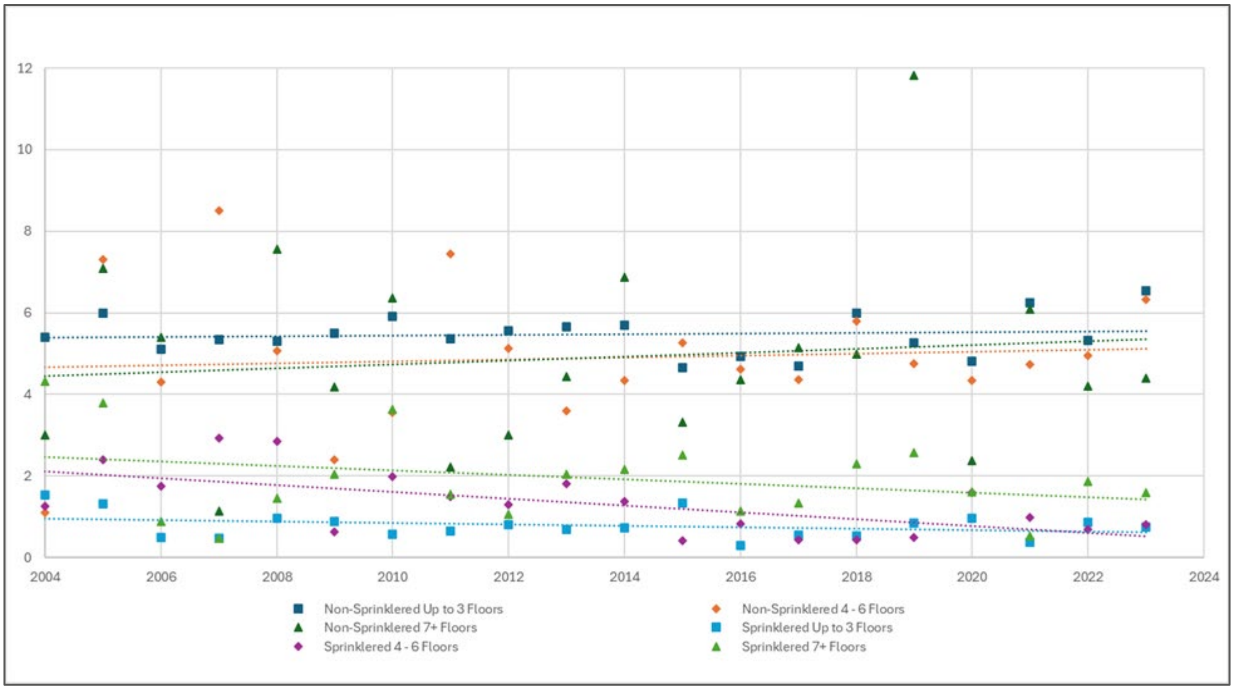


Figure D-5. National civilian fatalities per thousand MFD fires (2004–2024)
(Source: NFPA Research Custom Data Search)

Given that most of the fires occur in 1-3 story MFDs (which are believed to have the largest number of buildings of the three height categories), the Consultants normalized the data to calculate the civilian fatalities per 1,000 fire events based on MFDs at 1–3, 4–6, and 7 or more stories. The non-sprinklered 1–3 story MFD has the highest fatality rate at approximately 5.5 fatalities per 1,000 fire events.

The second and third highest fatality rates were in non-sprinklered 4–6 story and 7 or more story buildings at approximately five fatalities per 1,000 fire events. The presence of an automatic sprinkler system installed throughout the MFD reduced the civilian fatality rate for all three MFD height groups to an average of approximately 1 to 1.5 civilian fatalities per 1,000 fire events. This trend demonstrates the effectiveness of automatic sprinklers to reduce the civilian fatality rate in different MFD building geometries.

State of Minnesota

The Minnesota State Fire Marshal's Office (MSFMO), under the Minnesota Department of Public Safety, is responsible for providing support to local fire departments, educating the public on fire safety, developing and adopting the State's fire code, and reviewing State fire data.

The MSFMO publishes an annual "Fire in Minnesota" report that documents the fire events, trends, and losses that calendar year. The report relies on the fire event data submitted by local fire departments into the Minnesota Fire Incident Reporting System (MFIRS). On average, over 92 percent of fire departments across the State annually report their fire event data.

The Consultants reviewed these annual reports to determine:

- The comparison of Minnesota data to the NFPA national data
- The number of multi-family residential building fires
- The number and nature of civilian and firefighter fatalities

The MSFMO also exported MFIRS data for MFDs from 2002 up to the date the report was run in 2025. The data include the date/time, city, number of floors above grade, presence of smoke detection, area of fire origin, equipment involved in ignition, first item ignited, structure fire spread, presence of automatic extinguishing systems (AES), type of AES, operation of the AES, civilian injury counts, civilian fatality counts, and fire service injury counts. The Consultants pared this data from 2004–2024 (the last full year of data) to align with the adoption of NFIRS Version 5.0. The Consultants also pared the data to only reflect MFD buildings to more closely match the types of structures for this study.

There are similar trends between the national data provided by NFPA and the data provided by the MSFMO. Minnesota data reported the area where a fire is most likely to start (the kitchen) and the areas of origin that cause the largest number of civilian fatalities (the living room/bedroom), similar to the national NFPA data. Approximately 50 percent of the Minnesota MFD fires started in the kitchen (Figure D-6). However, most civilian fatalities occurred as a result of fires starting in a common living room or bedroom (Figure D-7).

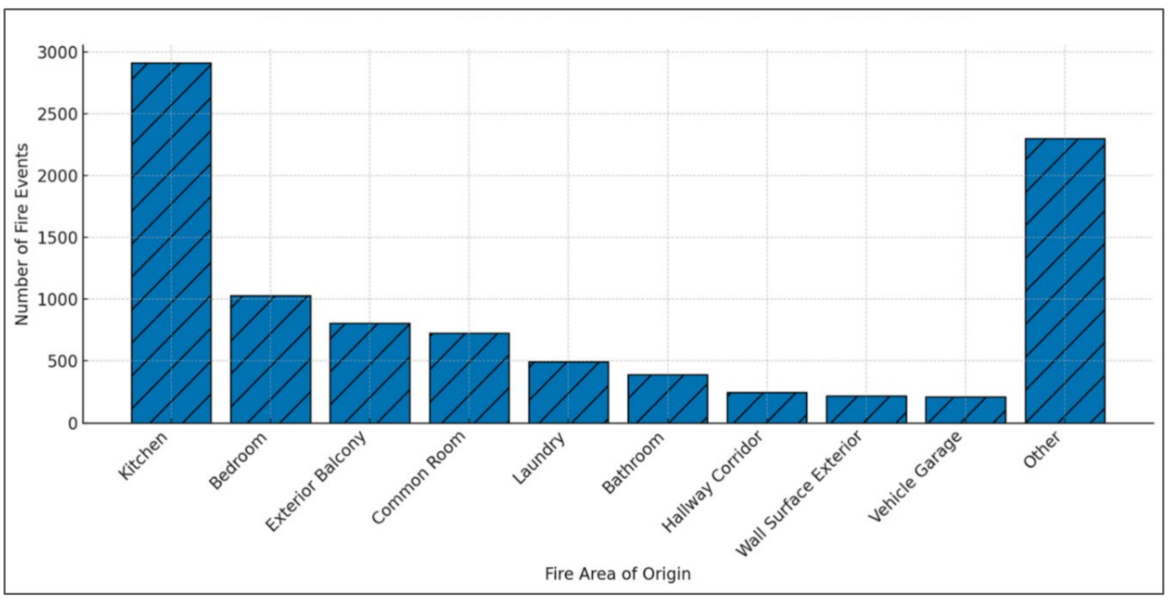


Figure D-6. Areas of fire origin in Minnesota MFDs, 2004-2024
(Source: Minnesota State Fire Marshal's Office)

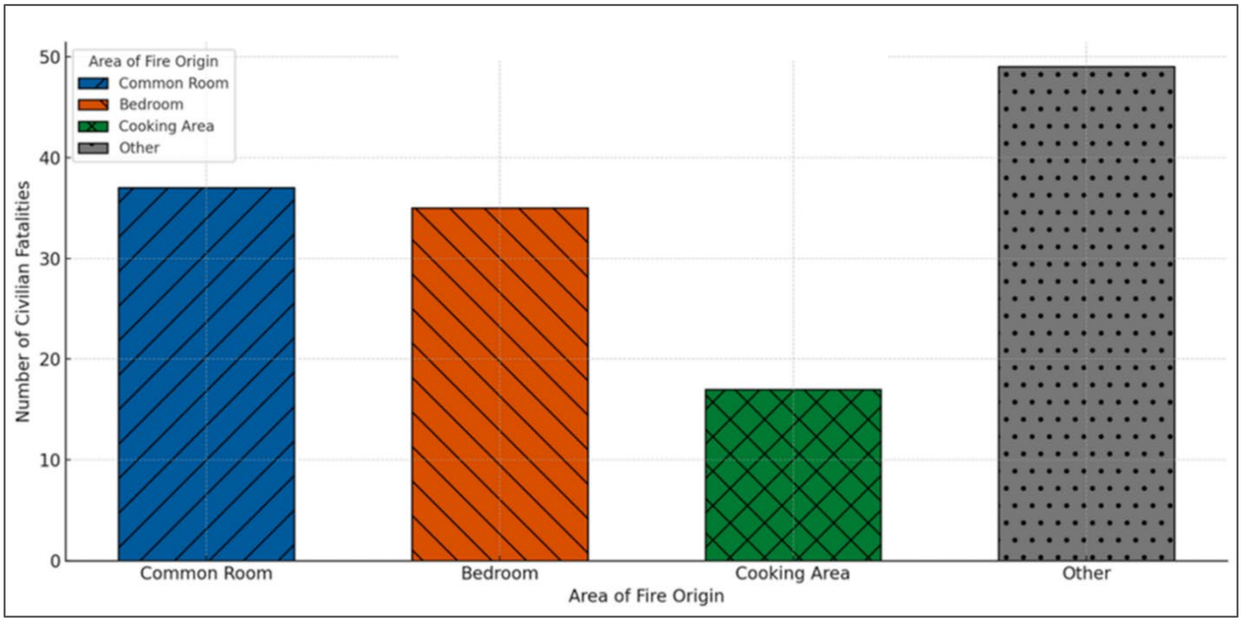


Figure D-7. Civilian fatalities by area of area fire origin in Minnesota MFDs, 2004–2024
(Source: Minnesota State Fire Marshal's Office)

The comparison of the Minnesota civilian fatalities per 1,000 reported fire events in one– and two–family homes versus MFDs matches the national trend of one– and two–family homes having a significantly higher civilian fatality rate compared to MFDs.

The Consultants also focused on fires that originated in the means of egress (corridors, stairwells, or ramps) in MFDs. The data showed:

- 179 fire events started in the interior stairway or ramp which resulted in no civilian fatalities and six firefighter injuries.
- 164 of the fires in interior stairways or ramps occurred in 1–3 story buildings where a single stairway is permitted by the current edition of the MBC.
- 244 fire events started in hallway corridors which resulted in no civilian fatalities and eleven firefighter injuries.
- 188 of these fires in hallway corridors occurred in 1–3 story buildings.

The Consultants reviewed the number of fire events involving civilian fatalities and casualties in Minnesota. Of the 9,812 MFD fires that occurred between 2004 and 2024, 98.8 percent of fire events resulted in no civilian fatalities. The number of fire events and civilian fire fatalities per event are shown in Figure D-8. Of the 138 civilian fatalities that occurred during this period, 100 of the fire events involved a single civilian fatality. The fire events that resulted in multiple civilian fatalities occurred in non-sprinklered buildings. (Sprinkler coverage was undetermined for eight of the fire events where a single fatality occurred.)

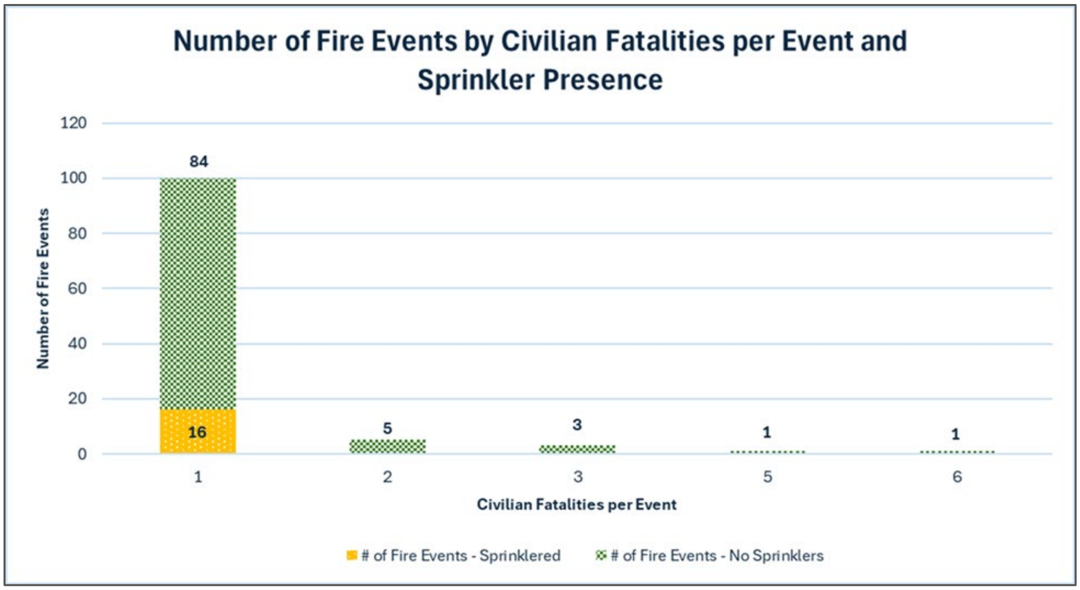


Figure D-8. Number of fire events by civilian fatalities per fire event in MFDs with sprinkler presence, 2004–2024 *(Source: Minnesota State Fire Marshal's Office)*

Figure D-9 shows the general location of civilians at the time of injury, and the presence of sprinkler protection. Evaluating the civilian fatalities by the location where the fatality occurred shows that 75 percent of fatalities occurred in the area where the fire originated. Civilian fatalities outside the area of origin were not as common, especially for sprinklered buildings.

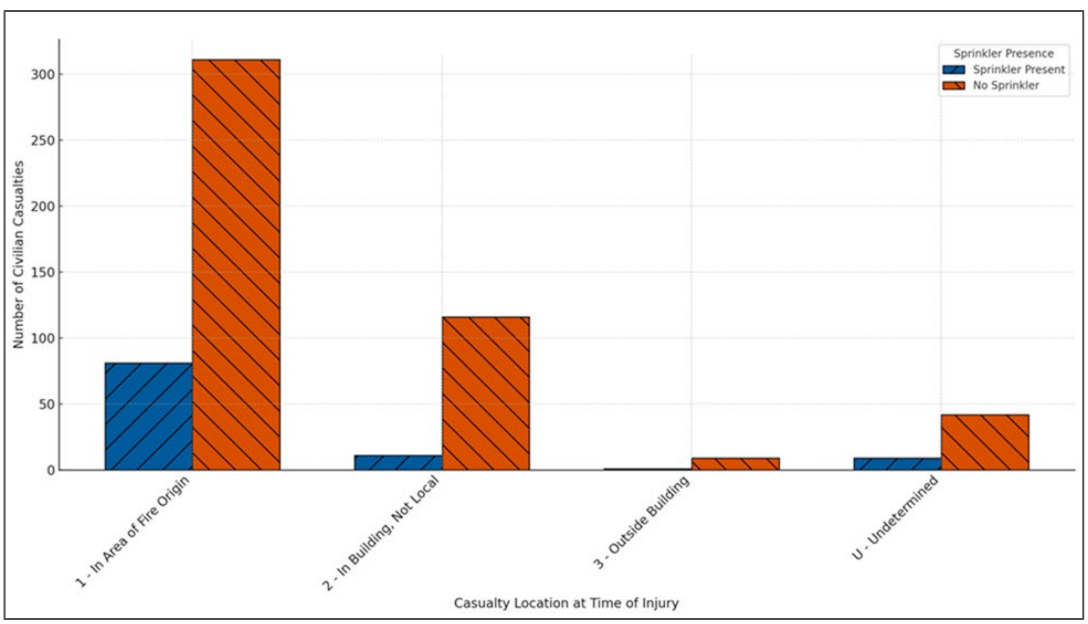


Figure D-9. Casualty location at the time of injury in MFDs, by sprinkler presence, 2004–2024. *(Source: Minnesota State Fire Marshal's Office)*

The Minnesota data also included firefighter injuries per fire event. Figure D-10 identifies firefighter injuries in MFDs in buildings of 1–3 floors in height, 4–6 floors in height, and 7 or more floors in height, for both sprinklered and non-sprinklered buildings.

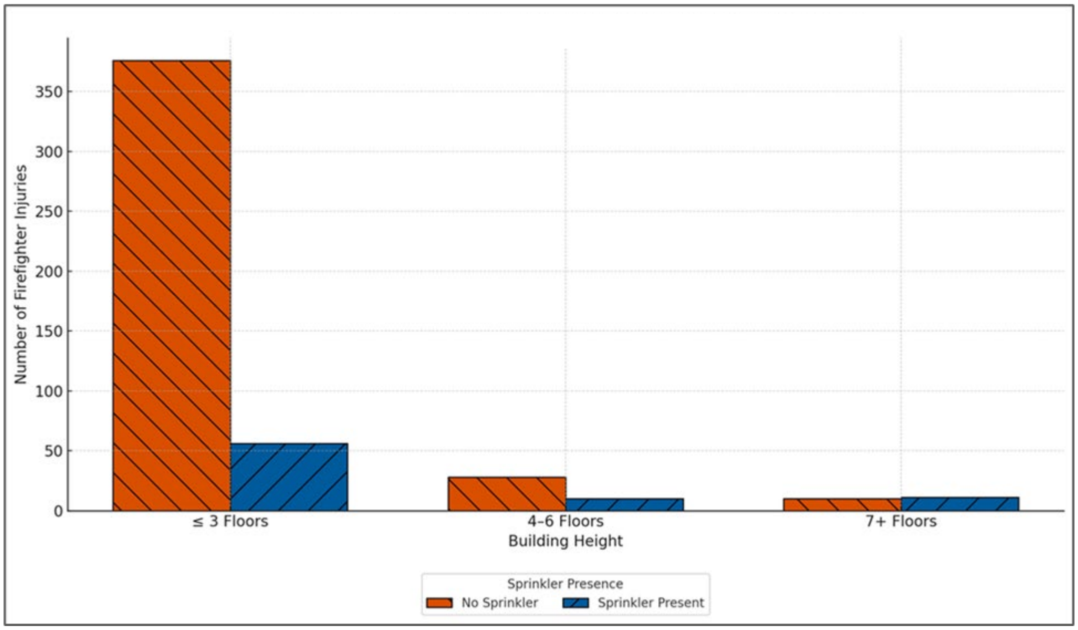


Figure D-10. Firefighter injuries in Minnesota MFDs by building height and sprinkler presence, 2004–2024
(Source: Minnesota State Fire Marshal's Office)

Data Reliability

The Consultants evaluated the reliability of different mitigating systems as beta distributions: a continuous probability distribution that reports values between 0 and 1 based on the shape parameters alpha (α) and beta (β), which represent the success count and failure count, respectively. Larger alpha and betas represent a larger sample size and reduce the distribution's variance. The purpose of capturing each system's success or failure as beta distributions is to quantify the uncertainty associated with the system's performance and its impact on the overall results. Where possible, the Consultants used data specific to the State of Minnesota. If data were lacking or unavailable, other data sources (national, international) were used.

Fire Size

The MFIRS data reports instances where the fire was too small to activate the sprinkler system. Modeling this parameter addresses the likelihood that the fire is large enough to fuse a sprinkler. Fires that are too small to activate a sprinkler system are generally sufficiently small such that they do not pose a significant adverse impact to building occupants. Of the 569 fire events that occurred in MFDs equipped throughout with an automatic sprinkler system, two fire events each reported a single civilian fatality.

The alpha parameter of the beta distribution is equal to the number of events where the fire was too small to activate the automatic sprinkler system. The beta parameter is equal to the sum of the events in which the fire is large enough to require sprinkler activation.

Sprinkler Systems

The MFIRS and NFIRS fire event databases included information about the sprinkler system during a fire event: whether the building was not protected/partially protected/fully protected by an automatic sprinkler system; if the fire was too small to activate the sprinkler system; if the sprinkler system flowed successfully or failed to flow; or if the sprinkler system flowed, but failed to control the fire. Of the 1,368 fire events that occurred in buildings protected throughout by an automatic sprinkler system and had sprinkler performance data available, 50 percent of sprinklers operated effectively, 42 percent of fires were too small to activate the sprinkler system, 6 percent of sprinklers did not operate, 1 percent of sprinklers operated but not effectively, and 1 percent was unknown or other.

The alpha parameter of the sprinkler system failing to flow on demand is equal to the number of fire events that occurred in MFDs sprinklered throughout where the sprinkler system did not operate. The beta parameter is equal to the sum of the fire events where the sprinkler system discharged water.

The alpha parameter of the sprinkler system failing to control the fire is equal to the number of fire events that occurred in MFDs sprinklered throughout where the sprinkler system operated but was not effective. The beta parameter is equal to the number of fire events where the sprinkler system operated and was effective.

Fire Alarm System

The Consultants could not find published data on the reliability of building-wide fire alarm occupant notification systems to fail on demand. Therefore, the Consultants used engineering judgment for this system's beta distribution to fail on demand. The basis for this engineering judgment is that the MBC requires a fire alarm system to be continuously monitored, and that these systems have historically demonstrated a track record of reliable performance.

Dwelling Unit Door Position

The Consultants could not find any published data on the reliability of dwelling unit doors to be in the "open" or "closed" positions. The MBC requires dwelling unit doors in MFDs to be equipped with self-closers; however, this does not prevent building occupants from propping doors open. The Consultants used engineering judgment for the beta distribution of the dwelling unit door to be in the open position. The basis for this engineering judgment is that the doors are mostly passive systems with self-closers that are generally reliable.

Stairway Door Position

Kevin Frank's thesis for the University of Canterbury performed a study evaluating the position of exit stairway doors with self-closers in six hotels, two apartments/condominiums, two boarding houses, and three rest homes in New Zealand [4]. Logging devices placed in the exit door measured the door position as a function of time for 180 days. The results indicated that exit stairway doors in apartment buildings were closed approximately 86 percent of the time with a standard deviation of 0.30.

The Consultants used this information to create a beta distribution for the stairway door position to be open with a mean of 0.14 to match the data in that report and an assumed distribution based on the relatively large standard deviation.

Table D-1 summarizes the beta distributions for each system or event, including the 5 percent, 50 percent, and 95 percent of the distribution. The purpose of reporting these values is to provide the 90 percent confidence range of the system failure and to conduct a holistic uncertainty analysis of the systems for their impact on risk.

Table D-1. Beta Distribution Parameters for System Reliability

Description	Parameter – Alpha[1]	Parameter - Beta[1]	Values
Fire is too small to activate the automatic sprinkler system	569	780	5% ~ 0.40 50% ~ 0.42 95% ~ 0.44
Sprinkler system fails to flow on demand	90	690	5% ~ 0.10 50% ~ 0.12 95% ~ 0.13
Sprinkler system fails to control the fire	10	680	5% ~ 0.008 50% ~ 0.014 95% ~ 0.023
Building-wide fire alarm fails to operate on demand[2]	16	144	5% ~ 0.06 50% ~ 0.10 95% ~ 0.14
Dwelling unit door fails to close[2]	16	64	5% ~ 0.13 50% ~ 0.20 95% ~ 0.28
Exit stairway door fails to close[3]	14	86	5% ~ 0.09 50% ~ 0.14 95% ~ 0.20

Table Notes:

[1] The alpha and beta shape parameters of the beta distribution represent success (behavior near 0) and failure (behavior near 1.0), respectively.

[2] Beta distribution parameters assumed based on engineering judgment.

[3] Beta distribution parameters based on Mr. Frank's thesis.

Endnotes

[1] Shelby Hall and Tucker McGree, "Home Structure Fires," NFPA, published July 31, 2025, https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/home-structure-fires.

[2] The Pew Charitable Trusts, "Modern Multifamily Buildings Provide the Most Fire Protection," Issue Brief, September 30, 2025. https://www.pew.org/en/research-and-analysis/issue-briefs/2025/09/modern-multifamily-buildings-provide-the-most-fire-protection.

[3] Shelby Hall and Tucker McGree, "Home Structure Fires," NFPA, published July 31, 2025, https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/home-structure-fires.

[4] Kevin Michael Frank, *Fire Safety System Effectiveness for a Risk-Informed Design Tool* (University of Canterbury, October 2013), 231.

APPENDIX E – SINGLE-EXIT MFD BUILDING CODE SUMMARY

Table E-1 summarizes the criteria allowing single-exit MFD buildings in the current Minnesota State Building Code (MBC) and other selected codes.

The information below is not intended to provide a comprehensive description of all requirements in each code and standard as they relate to the subject topic; the codes and standards should be reviewed for detailed requirements.

Table E-1. Summary of Single-Exit MFD Criteria in Selected Building Codes[1]

Building Code	Max. No. of Stories Above Grade Plane	Max. Dwelling Units/Floor	Max. Floor Area (sq. ft.)	Max. Exit Travel Distance [D.U. Door/Total] (ft.)	Construction Type	Stairway Requirements	Corridor Rating	Other[2]
Minnesota Building Code, 2020	3	4	—	-/125	—	—	—	—
Minnesota Building Code, 2026 Amendment	4	4	4,000	35/125	—	1. Min. 48-inch width	1 hour	1. NFPA 13 design 2. Emergency escape/rescue windows
International Building Code, 2024	3	4	—	-/125	—	—	—	—
Seattle Building Code, 2021	6[3]	4	—	20/125	Types IA, IB, IIA, IIIA, IV, or VA	1. 1 hour encl. 2. Pressurization for interior stairways 3. Discharge direct to exterior	—	1. NFPA 13 design; residential sprinklers 2. Smoke detection required in common areas 3. Emergency escape/rescue windows 4. Allowed only for dwelling units of R-2 5. D.U. door cannot open directly into an exit stairway
New York City Building Code, 2023	4/6[4]	3	2,500/2,000[4]	-/50	Type I or II	2 hour encl.	—	1. D.U. emergency escape/rescue windows on street or having street access
NFPA Life Safety Code, 2024	4	4	—	35/160	—	1 hour encl.	1 hour	1. Min. 1/2 hr. D.U. separation

Table Notes:

[1] Unless otherwise stated, minimum code requirements for dwelling units apply. All buildings require automatic sprinkler protection per NFPA 13 or NFPA 13R, except as noted otherwise.
[2] See the individual codes for more information.
[3] Single-exit allowed to serve up to 5 stories of a 6-story building.
[4] Criteria for 4-story and 6-story buildings, respectively.

APPENDIX F – MODEL DESCRIPTION

Building Geometries

Four model building geometries were developed based on the input of the TAG members for inclusion in the fire modeling analysis and agreed upon at the June 26, 2025, TAG meeting. The overall goal of the analysis was to compare the relative differences related to select fire scenarios between buildings with varying geometries/layouts to determine the appropriate consequence used within the risk informed approach (RIA). The four building geometries used in the fire and egress modeling analysis are all under 75 feet in building height; specific details are described below.

1. **Building 1 (40,625 square feet):** Building 1 serves as a baseline benchmark in the analysis and represents a Minnesota Building Code (MBC) multi-family residential (MFD) building with two exit stairways that is MBC code-compliant. This building is eight levels tall. Each level of the building measures 625 feet long by 65 feet wide (approximately 40,625 square feet in area per level). For the purposes of the modeling analysis each level is 10 feet in height, measured floor to floor. Each of the building's two interior exit stairway shafts are 18 feet by 8 feet with stairways that are 44 inches wide. Each residential unit is served by a single corridor that is approximately 535 feet long and 5 feet wide. The building contains a single elevator with shaft dimensions of 9 feet by 9 feet. A sketch of this building geometry is provided in Figure F-1 below.
2. **Building 2 (4,000 square feet):** Building 2 represents a baseline MBC code-compliant single-exit stairway MFD building. The building is four levels tall; each floor measures about 67 feet long by 60 feet wide (approximately 4,000 square feet in area per floor). For the purposes of the modeling analysis, each level is 10 feet in height, measured floor to floor. The building's single interior exit stairway shaft is 18 feet by 8 feet with stairways that are 44 inches wide. The building contains four residential units per level of roughly equal dimensions. Each residential unit is served by a single corridor that is approximately 30 feet long and 5 feet wide. The building contains a single elevator with shaft dimensions of 9 feet by 9 feet. A sketch of this building geometry is provided in Figure F-2 below.
3. **Building 3 (6,000 square feet):** Building 3 represents a prototype design for a single-exit stairway MFD residential building. This building is eight levels tall; each floor of the building measures 100 feet long by 60 feet wide (approximately 6,000 square feet in area per floor). For the purposes of the modeling analysis, each level is 10 feet in height, measured floor to floor. The building's single interior exit stairway shaft is 18 feet by 8 feet with stairways that are 44 inches wide. The building contains eight dwelling units per level of roughly equal dimensions. Each residential unit is served by a single corridor that is approximately 65 feet long and 5 feet wide. The building contains a single elevator with shaft dimensions of 9 feet by 9 feet. A sketch of this building geometry is provided in Figure F-3 below.

4. **Building 4 (4,000 square feet):** Building 4 represents a second prototype design for a single-exit stairway MFD residential building. The building's floorplan is identical to that of Building 2, however Building 4 includes eight levels rather than four. For the purposes of the modeling analysis, each level is 10 feet in height, measured floor to floor. A sketch of the geometry for Building 4 is provided in Figure F-2 below.

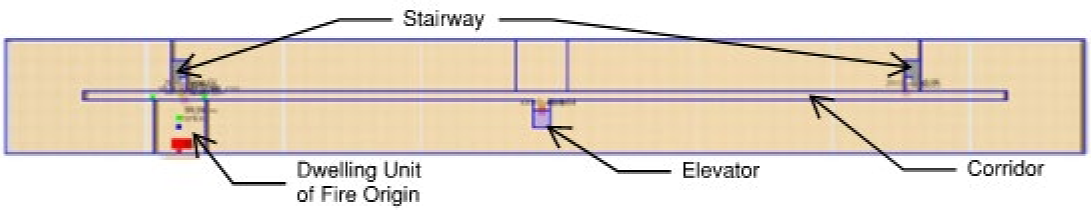


Figure F-1. FDS model of Building 1

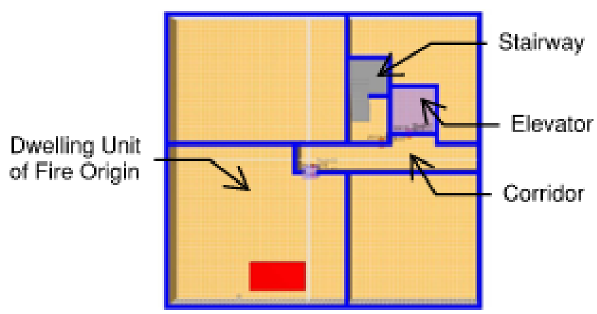


Figure F-2. FDS model of Buildings 2 and 4

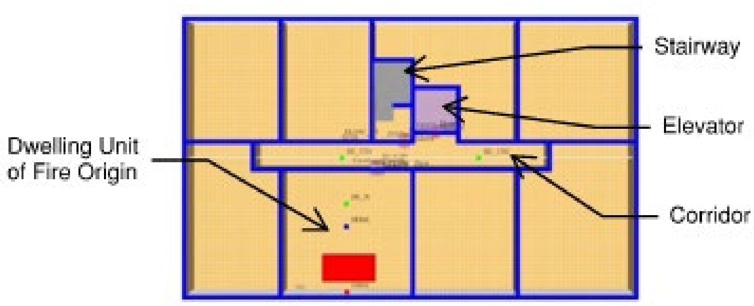


Figure F-3. FDS model of Building 3

Fire Model Description

Fire Dynamics Simulator

Fire Dynamics Simulator (FDS) was selected as the software used for the fire modeling analysis. FDS is a computational fluid dynamics (CFD) software that models fire-driven fluid flow. FDS numerically solves a form of the Navier-Stokes equation within each cell of a three-dimensional, gridded system. This model is appropriate for low-speed, thermally driven flow simulating the properties of the smoke and heat transport from a fire. FDS will provide more accurate results than hand calculations presented in NFPA 92 or the use of a two-zone modeling software like CFAST. Of the two, FDS has the ability to more closely simulate actual fire conditions where the smoke layer naturally varies in height as it moves away from the fire plume.

Design Fire Location

The design fires were located within the model on the lowest level of the building as discussed with TAG. This fire location resulted in the potential to impact the most occupants based on the consideration that the occupants would either be on the fire floor or above the fire floor. Occupants would then require use of the stairway(s) to egress the building.

Design Fire Fuel Loads

Two design fires with distinct fuel loads were considered in the fire modeling analysis as supported by the data and TAG input. A dwelling unit fire scenario was selected to simulate an uncontrolled living room fire. Additionally, a corridor fire involving an electric-powered micromobility vehicle, in this case an electric bicycle (e-bike), was also selected for the modeling analysis.

Given that the Minnesota fire incident data identified the most severe consequences occurring in non-sprinklered buildings, the fire modeling analysis assumed that the dwelling unit fire and the e-bike fire were not controlled by the activation of the fire sprinkler system [1]. This condition is intended to simulate a failure of the sprinkler system to activate or an inability of the system to adequately control the fire following activation.

Heat Release Rates Dwelling Unit (Living Room) Fire

As identified in the data review of actual fire events and consequences, dwelling unit fires occurring in living rooms and bedrooms cause more severe consequences of injuries and deaths, even though they occur less often than fires in other areas of the dwelling unit, such as kitchens. Therefore, simulated fires occurring in dwelling units were based on measured heat release rates (HRR) from a series of full-scale residential dwelling room fire tests conducted by NIST [2]. The fires in these tests were allowed to fully develop to flashover and were not suppressed by a sprinkler system. The subject room's nominal dimensions were approximately 12.1 feet by 12.1 feet with a 7.9-foot ceiling, and a 7.9 foot-wide by 6.9-foot-tall opening created in one wall centered at the front of the room. The room contained standard items that would be provided in a typical living room such as a couch, tables, and chairs. The typical layout of the room and the fuel load are depicted in Figure F-4 and Figure F-5.

These NIST tests indicate that the peak heat release rate was between approximately 8,000 and 10,000 kW [3]. The HRR curve developed for the modeling analysis was based on the results of these three-room fire tests (Figure F-6).

Figure F-4. Photo of NIST room fire test

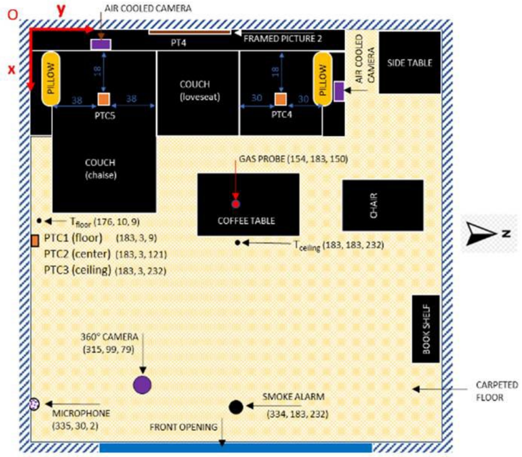


Figure F-5. Plan view of NIST room fire test

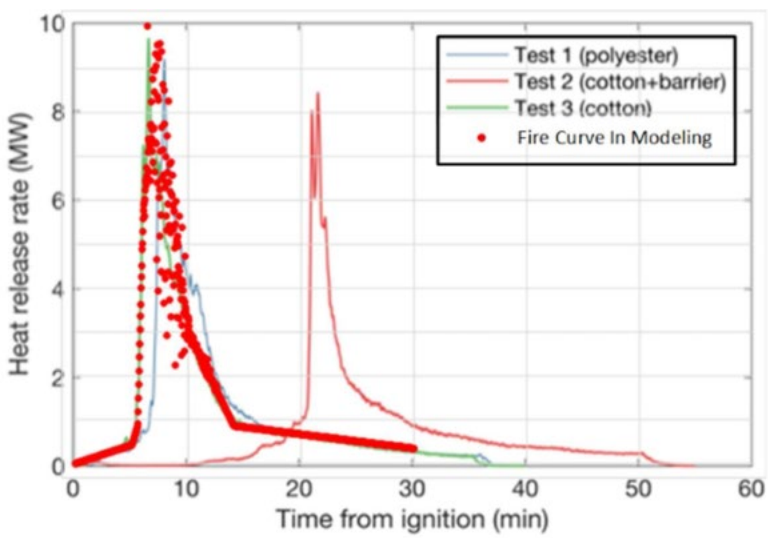


Figure F-6. Dwelling unit fire heat release rate comparison between the NIST fire tests and the fire model used in this analysis

Corridor (E-Bike) Fire

Commentary from TAG indicated that e-bikes are a representative fuel load in corridors of residential buildings given their current popularity and use should be evaluated. The HRR for the e-bike fuel load was developed based on fire testing of micromobility devices conducted by the Institute of Applied Fire Safety Research [4]. The research project focused specifically on e-bikes and their fire behavior. The tested e-bikes contained an aluminum frame, 28-inch tires, hydraulic brakes, plastic components, a 250W motor, and a 660 Wh lithium-ion battery.

One outcome of the research project was the development of a representative design fire curve for lithium-ion powered e-bikes based on realistic “worst-case” scenarios. The resulting design fire curve, which was used by the Consultants in this modeling analysis, is represented in Figure F-7.

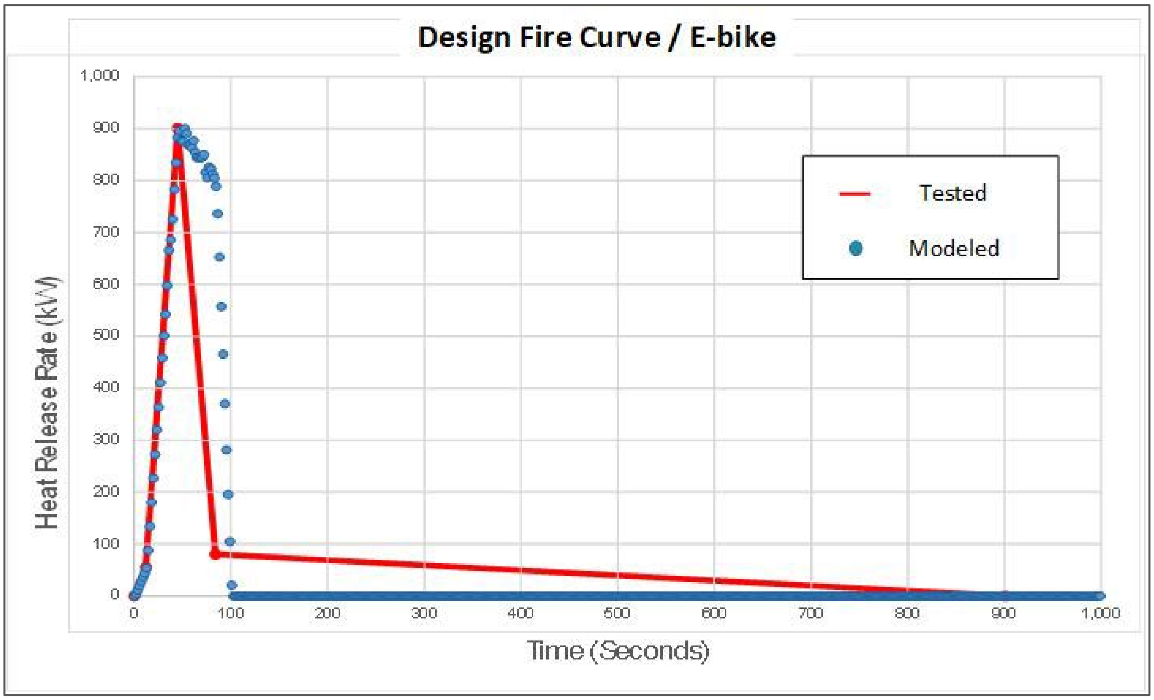


Figure F-7. Comparison between heat release rates of e-bike fire test and the fire model

Fuel Characteristics

Fuel characteristics for both the flashover room fire and the e-bike fire were based on polyurethane foam. This material is expected to comprise a large portion of the interior materials within a typical dwelling unit and is representative of a majority of the combustibles provided within the NIST room fire tests. While other combustible materials will also be present within a typical apartment, polyurethane generally exhibits increased soot production compared to other common combustibles. For this modeling analysis the e-bike fire used the same variables as the room fire. Therefore, assuming the main combustible involved in the fire is polyurethane is expected to provide conservative estimates for smoke filling behavior within the dwelling units, common corridors, and stairway enclosures.

Flexible polyurethane foam GM27 was selected as the representative fuel source. The physical properties of the foam are provided in Table F-1 below.

Table F-1. Properties of Polyurethane Foam GM 27 [5]

Parameter	Value
Chemical formula	$C_{1.0}\,H_{1.7}\,O_{0.3}\,N_{0.08}$
Heat release per unit mass of O_2	13,100 kJ/kg
Yield fraction of CO from fuel (kg/kg)	0.05
Yield fraction of soot from fuel (kg/kg)	0.10
Radiative fraction	0.35

Mesh Size Selection

In FDS, cell sizing must be determined to adequately resolve fluid flow and plume dynamics. The measure of how well a flow field is resolved for simulations involving buoyant flames is given by the non-dimensional expression $D^*/\delta x$. The D^* value represents the characteristic fire diameter and is based on the peak heat release rate and ambient conditions. The value δx represents the nominal size of each mesh cell [6]. Typically, $D^*/\delta x$ values of 4, 10, and 16, are used to represent course, moderate, and fine mesh resolutions, respectively.

The computational domain was required to include the entirety of each building to understand building-wide smoke movement during a fire scenario. Due to the relatively large computational domain, a mesh resolution with a nominal cell size of one foot was selected to simulate fire conditions on the floor of fire origin. This is representative of a moderate mesh with regard to the flashover room fire and a course mesh for the e-bike fire. A more course mesh resolution was selected for all other areas not included on the floor of fire origin. These mesh resolutions were selected to optimized run time given the large domain without compromising simulation results.

Weather Conditions

The building interior temperature in each scenario was defined at 70°F. The fire modeling results presented in this report are each representative of scenarios with an outdoor temperature of -17°F based on review of winter temperatures for cities within the State of Minnesota as documented in the *Handbook of Smoke Control Engineering* (2012 edition) by Klote, Milke, Turnbull, Kashef and Ferreira. A sensitivity analysis was conducted where the outdoor ambient temperature was increased to a more moderate temperature (approximately 70°F) to determine the impact on the movement of smoke and hot gas on the fire floor and through the stairway. The sensitivity analysis revealed that the outdoor ambient temperature had an insignificant impact on the smoke movement and development of untenable conditions within the corridors and stairway.

Wind conditions were not considered for the current fire modeling analysis. Additional analysis would be required to determine the potential effect of variable weather and climate conditions on the modeling results.

Leakage

Due to the relatively small enclosures considered in the fire modeling analysis, leakage from construction was considered within each fire modeling scenario. Defining construction elements with leakage areas, rather than impenetrable boundaries, allows for pressures within the building to regulate as they would be expected during an actual fire scenario. To account for leakage between the building's exterior and interior areas, all dwelling units within each scenario were provided with one small opening to the exterior that measured the size of one model mesh cell.

Leakage within the building's interior was modeled based on the gaps between stairway doors and elevator doors, their frames, and the floor in accordance with information provided in the *Handbook of Smoke Control Engineering* (2012 edition). The stairway doors were assumed to have a total leakage area of 0.25 square feet. The elevator doors were assumed to have a total leakage area of 0.50 square feet. Leakage at doors was modeled using the HVAC features of FDS.

Performance Criteria

A tenability analysis of the hazards associated with the smoke as recommended in NFPA 92 was performed to assess the impacts of the products of combustion and heat exposure from a fire within the building on the ability of building occupants to safely move to the nearest exit [7]. This area was monitored in the CFD model for the following impairments for the full duration of the CFD simulation [8].

1. Impaired vision from smoke obscuration (visibility).
2. Asphyxiation from toxic gases causing confusion and loss of consciousness (asphyxiates).
3. Pain to exposed skin and respiratory tract caused by burns from exposure to radiant and convective heat leading to collapse (heat exposure).

For the purposes of this tenability analysis, it was necessary to identify a toxic species present in fire effluents to provide an accurate prediction of when impairment on physiological and pathological functions will adversely affect the egress of occupants [9]. The species identified for this analysis for asphyxiation in the modeled fire is carbon monoxide (CO).

A summary of the thresholds selected for each tenability criteria is provided in Table F-2 below. Each of the criteria were evaluated at an elevation six feet above the finished floor for the subject floor based on the fire scenario.

Table F-2. Summary of Tenability Criteria and Thresholds (*Source: NFPA 92*)

Tenability Criteria	Tenability Threshold
Visibility	15 Feet
Carbon Monoxide	600 ppm
Temperature	140°F

Visibility

Low visibility caused by smoke obscuration can slow occupant egress or cause occupants to turn back. Familiarity with the egress route and training also contribute to an occupant's willingness to pass through smoke in limited visibility. The SFPE *Handbook of Fire Protection Engineering* recommends a visibility tenability limit of 30 feet for large enclosures and 15 feet for small spaces. In this case, 15 feet of visibility is considered as the tenability limit [10].

Carbon Monoxide

Asphyxiates affect the amount of oxygen delivered to various parts of the body and can cause incapacitation when oxygen levels in the brain are critically affected.

Exposure to toxic gases is a complex issue that may be reasonably approached with a focus on the effects of exposure to carbon monoxide (CO). CO is a toxic and incapacitating gas that is produced in building fires.

The concept of Fractional Effective Dose (FED) has been introduced in different guides and standards and is a measure of the airborne contaminants that are absorbed by an occupant. Typically, FED values correlated to fatalities or incapacitation and depend on how long the occupant is exposed to harmful conditions. For CO exposure, the international standard ISO 13571 evaluates FED,

$$X_{FED} = \sum_{i=1}^{n} \sum_{t_1}^{t_2} \frac{[CO]}{[CO] \cdot t} \Delta t$$

where:

[CO] = average concentration in ppm, of carbon monoxide over the chosen time increment,

Δt = chosen time increment, expressed in minutes,

[CO]·t = exposure dose causing occupants' compromised tenability, expressed in minutes multiplied by average concentration [11].

Also, ISO 13571 states that the human population is assumed to be comprised of healthy, young adults at a moderate level of activity, with allowances then made for variability due to more susceptible subpopulations:

> *An FED criterion of 1.0, corresponding to the median value of a log-normal distribution of human responses, translates to a blood carboxyhemoglobin saturation of approximately 30%. Use of a threshold criterion of 0.3 FED would reduce the blood carboxyhemoglobin saturation to about 10% as an allowable maximum for acute exposure, above which tenability could potentially be compromised* [12].

Purser indicates that since individual susceptibility varies in the population, it is considered that approximately 11.3 percent of the population is considered likely to be susceptible below an FED of 0.3 [13]. Approximately 90 percent of the population is considered susceptible below an FED of 1.3. For this reason, it will be necessary for the user to select an FED value to protect an acceptable proportion of vulnerable subpopulations (for example, an FED of 0.3 or some other value)

When 0.3 FED is considered for an exposure for 20 minutes, the minimum concentration of carbon monoxide could potentially be 600 ppm. In other terms, the tenability limit for an exposure of 20 minutes at a constant concentration is 600 ppm.

Temperature

Heat exposure can cause heat stroke (hyperthermia), skin burns, and respiratory tract burns. Convective heating exposure is expected to cause the most severe heat exposure at the top level of the building where the hot gases rise from the fire source below. Saturated air at a temperature of 140°F is expected to cause burns for exposure times greater than 30 minutes [14]. A temperature of 140°F along any walking surface within the building was used as a conservative tenability limit.

Egress Analysis

The intent of the fire modeling analysis outlined above is to determine the times for building spaces to become untenable following the initiation of a fire event. To fully understand the consequences of these events, an egress model was also used to determine if occupants are expected to be exposed to untenable conditions prior to reaching an exit.

Egress Simulator

The Pathfinder® model was utilized to conduct the egress analysis. Pathfinder is an agent-based egress and human movement simulator developed by Thunderhead Engineering based upon human behavior in fire and is one of the most accepted egress models in use around the world. The program simulates evacuation and general pedestrian movement for each occupant (agent) using a combination of parameters to select their current path to an exit.

Modeling Parameters

The parameters used for the egress analysis include: queue times for each door of the current room, the time to travel to each door of the current room, the estimated time from each door to the exit, and the distance already traveled in the room. Agents respond dynamically to changing queues, door openings/closures, and changes in room speed constraints (simulating smoke and debris). The maximum walking speed of the occupants was defined as 1.2 m/s, according to movement characteristics for the general population when occupants move as individual agents [15]. Pathfinder default values were used to define occupant characteristics such as door choice preference and willingness to move through smaller spaces.

Pathfinder contains two behavior modes which determine how the agents move and interact with one another and the environment. SFPE Mode is based on assumptions and hand-calculations as defined in the SFPE *Engineering Guide to Human Behavior in Fire* [16]. In this mode, occupants make no attempt to avoid one another and may be superimposed on top of one another. Doors impose flow limits and the agent’s movement speed is dependent on the agent density in the space. This mode is expected to provide answers that are similar to the results of the SFPE hand calculations.

The Steering Mode, the second behavior mode option, is more dependent on occupant interaction and collision avoidance. Door queues are not explicitly defined in this mode but occur naturally. Steering Mode is typically used in performance-based analysis as it attempts to emulate actual human behavior and movement as much as possible and often provides results more similar to experimental data. For this reason, each of the egress simulations in this report were conducted using Steering Mode.

The egress analysis in buildings with only one interior exit stairway (Buildings 2, 3 and 4) considered the simultaneous use of the stairway by egressing occupants and firefighters ascending the stairway to access the fire floor for rescue and firefighting operations. This simultaneous use of the stairway is often referred to as counter-flow.

Counter-flow was not modeled for Building 1 because it is expected that a building containing at least two exit stairways will allow the fire service to use one stairway to access the building and occupants to use a different stairway to complete egress. Therefore, counter-flow was not simulated in a building with more than one exit stairway.

Egress Models

The occupant load per floor for each building was determined based on the MBC occupant load factor for residential occupancies of 200 square feet per person (MBC Table 1004.5). The egress model for Building 1 included 204 occupants per floor and approximately 1,630 occupants in the entire building (Figure F-8). The models for Building 2 and Building 4 included approximately 20 occupants per floor, 80 total occupants, and 160 total occupants in Building 4 (Figure F-9). The Building 3 model included approximately 30 occupants per floor and 240 total occupants in the building (Figure F-10).

Each scenario in the fire modeling analysis assumed fires on the lowest level near the stairway discharge. This fire location was selected as it was expected to most significantly impact egress from upper floors of each building.

All occupants in the building simultaneously began egress at the initiation of the simulation. For the single-exit buildings (Buildings 2, 3, and 4), the fire service agents also began to access the building and ascend the stairway at the initiation of the simulation. In each of these simulations, ten fire service agents were assigned to enter the building and ascend the stairway to reach the top level of the building. These counter-flow conditions provided the most conservative egress time by maximizing congestion within the exit stairway enclosure.

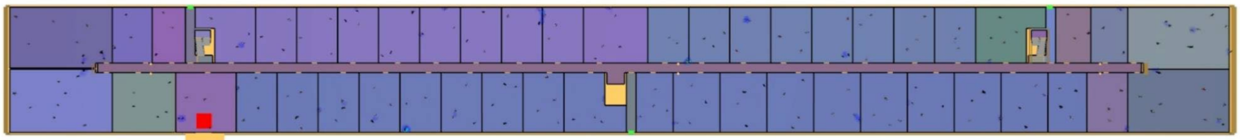


Figure F-8. Egress model of Building 1

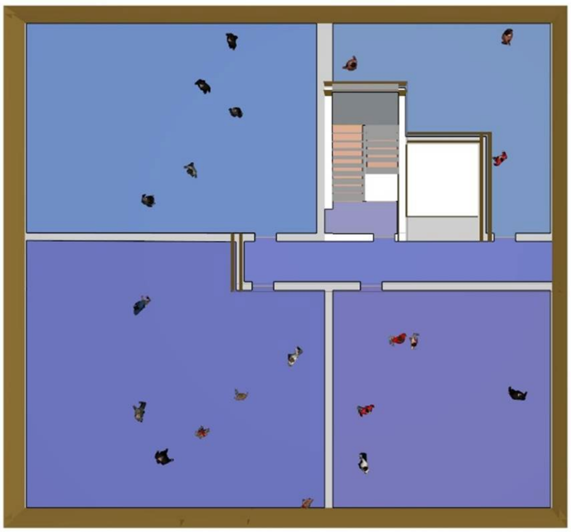


Figure F-9. Egress model of Buildings 2 and 4

Figure F-10. Egress model of Building 3

Endnotes

[1] Minnesota Fire Incident Reporting System (MFIRS) Database, Minnesota State Fire Marshal Division, May 15, 2025.

[2] M. Zammarano, M. Hoehler, J. Shields, A. Thompson, I. Kim, I. Leventon, and M. Bundy, *Full-Scale Experiments to Demonstrate Flammability Risk of Residential Upholstered Furniture and Mitigation Using Barrier Fabric*, Technical Note (NIST TN), (Gaithersburg, MD: National Institute of Standards and Technology, 2020), accessed October 15, 2025, https://doi.org/10.6028/NIST.TN.2129.

[3] *Ibid*.

[4] Max Lakkonen, "Impacts of E-Micromobility on Fire Safety and the New Design Fire Curve for E-Bikes," *International Fire Protection*, March 2024, 45–46.

[5] Society of Fire Protection Engineers (SFPE), *SFPE Handbook of Fire Protection Engineering,* 5th ed. (New York: Springer, 2016), Appendix A, Table A.39, 3469.

[6] Kevin McGrattan, *Fire Dynamics Simulator User's Guide*, 6th ed., NIST Special Publication 1019 (Gaithersburg, MD: National Institute of Standards and Technology, 2020), sec. 6.3.6.

[7] National Fire Protection Association (NFPA), *NFPA 92: Standard for Smoke Control Systems* (Quincy, MA: National Fire Protection Association, 2021), sec. 4.5.1.1.

[8] National Fire Protection Association (NFPA), *NFPA 92: Standard for Smoke Control Systems* (Quincy, MA: National Fire Protection Association, 2021), sec. 1.2.1(2); Society of Fire Protection Engineers (SFPE), *SFPE Guide to Human Behavior in Fire,* 2nd ed. (Cham: Springer International Publishing, 2019), 41.

[9] Morgan J. Hurley, et al. *SFPE Handbook of Fire Protection Engineering (*New York: Springer, 2016), page 2217.

[10] *Ibid*, 2217, Table 63.5.

[11] *ISO 13571:2007, Life-Threatening Components of Fire—Guidelines for the Estimation of Time Available for Escape Using Fire Data* (International Organization for Standardization, 2007).

[12] International Organization for Standardization (ISO), *ISO 13571: Life-Threatening Components of Fire—Guidelines for the Estimation of Time to Compromised Tenability in Fires* (Geneva: International Organization for Standardization, 2012).

[13] D.A. Purser, "Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat," in *SFPE Handbook of Fire Protection Engineering*, 4th ed. (Society of Fire Protection Engineers and National Fire Protection Association, 2008), chap. 2-6.

[14] Morgan J. Hurley et al., *SFPE Handbook of Fire Protection Engineering* (New York: Springer, 2016), 2217, Table 63.20.

[15] Society of Fire Protection Engineers (SFPE), *SFPE Handbook of Fire Protection Engineering,* 5th ed. (New York: Springer, 2016), Figures 59.7 and 59.8; Thunderhead, *Pathfinder User Manual 2025.1* (Thunderhead, 2025), accessed December 29, 2025, https://support.thunderheadeng.com/docs/pathfinder/2025-1/user-manual/.

[16] Society of Fire Protection Engineers (SFPE), *SFPE Handbook of Fire Protection Engineering,* 5th ed. (New York: Springer, 2016), Figures 59.7 and 59.8; Thunderhead, *Pathfinder User Manual 2025.1,* "Simulation - Behavior Parameters." (Thunderhead, 2025), accessed December 29, 2025, https://support.thunderheadeng.com/docs/pathfinder/2025-1/user-manual/#_parameters.

APPENDIX G – EGRESS

This appendix provides a brief description of the egress analysis within this report. As stated in the body of the report, the egress models included in this analysis do not assume specific human actions in a fire environment. Human behavior in fire is a complex subject and is beyond the scope of this analysis. As an introduction, there are several factors affecting human behavior that occur during building fires, including:

- The behavior of the fire, hot gases, and smoke;
- The behavior of the building subjected to the fire ("passive" fire protection);
- The behavior of the devices that detect a fire, notify people, and suppress a fire, e.g., smoke detectors, fire alarm systems, and sprinkler systems;
- The behavior and actions of the occupants within the building; and,
- The behavior and actions of the fire service responding to the incident to protect the lives of occupants, extinguish the fire, and minimize additional damage to the building and adjacent property.

These factors overlap in varying manners with the others and can impact one another. The behavior of fire and smoke within the various building geometries selected for this study is a major part of the analysis associated with the scope of this project. The behavior of the passive and active fire protection systems is not a primary focus of this project but were given consideration appropriate to the scope of this project.

It has been noted that building codes within the United States do not typically address the human factors that can affect the fire risk of buildings. In a given multi-family dwelling (MFD) building fire scenario, occupants may decide to remain in their units as a "defend-in-place" strategy rather than exit the building because they perceive that to be a better alternative. The *SFPE Guide to Human Behavior in Fire* provides additional information about this emerging field of study [1]. This report does not prescribe or assume specific action on the part of building occupants but identifies occupants who may be impacted in the various building geometries and fire scenarios.

Within the United States, when a building is subject to a fire incident and the occupants have been notified of such event, most occupants have been trained since their youth to promptly and fully evacuate the building. There are some exceptions to this, but they do not apply to the MFD building occupancy (MBC Use Group R-2) that is the subject of this study. For example, hospitals and similar institutional facilities are examples of exceptions to the concept of full building evacuation. These occupancies are designed to have two or more fire-rated compartments within the building on each floor. During a fire, this design allows patients and other occupants to promptly relocate from an area affected by a fire to another area on the same floor that is not subject to the fire or its effects and does not require the use of stairways or elevators to do so. Other occupants on the fire floor and elsewhere in the building who are already in the protected areas can remain where they are and need not evacuate the building unless directed otherwise. This is a version of the fire safety strategy known as "defend-in-place" or "protect-in-place." For a major fire, it can be part of the fire safety strategy allowing an orderly and safe phased full evacuation of a building.

The defend-in-place strategy requires special attention to certain elements of building design and construction as well as the training of building managers and occupants, so they understand how and when to utilize this option in lieu of a full evacuation of a building. It also requires awareness of the responding fire department that there may be occupants within the building who might not evacuate unless they are directed to do so by the fire department or by others in a position of authority. Whether a strategy of full evacuation or a defend-in-place strategy is utilized, the goal is the same: to protect the occupants from the hazards of fire and the effects of fire, i.e., heat, smoke, and toxic gases, and structural failure, for such time that the building can be evacuated.

Fire and Egress Models

The computational models used in this study are of two types. One is a “fire model” which utilizes building-specific information and identifies the growth and movement of fire, smoke, and hot gases through the building over time. The fire model utilized for the analyses of this report is the “Fire Dynamics Simulator” as described in Appendix F. The second type of model used in this report is an egress model that identifies the locations and potential movement of building occupants during a fire event to establish the estimated amount of time required for the occupants to move to an area of refuge or egress via exit stairway(s) in the various building geometries. The model utilized for the egress analysis of this report is “Pathfinder” as described in Appendix F.

The data derived from the egress model allowed for a simplified identification of a Required Safe Egress Time (RSET), “Pre-Movement Time” plus “Movement Time” as used in this study. The RSET begins at the time of fire ignition and concludes at the time that occupant evacuation is complete as defined within this study. It is acknowledged that RSET can have great variability for individual occupants based on numerous factors including variability in movement capabilities and individual human behavior. Therefore, this analysis referenced data from available data sets to use as representative conditions.

Evaluating the fire model results allowed for a simplified identification of an Available Safe Egress Time (ASET), “Tenability Time” as used in this study, for various areas within the building geometry. In general, overlaying the results of the egress models onto the fire model results in the identification of the number of occupants that may be impacted in the specific scenario. It is typically the goal to have an ASET that is appropriately greater than the RSET to provide a margin of safety for the occupants to leave the building. For this analysis, the egress model and fire model provides context to the consequence evaluation as defined within this report. A margin of safety was not applied in this analysis.

If the ASET is less than the RSET, a hypothetical occupant must either find an alternative egress route or defend-in-place. Typically for an MFD, the defend in place area is either within their own dwelling unit or elsewhere within the building, such as a fire-resistance-rated stairway enclosure. Under these circumstances, the occupants remain in that location until the fire is extinguished and the smoke has subsided to the point where it is possible for them to exit the building (usually under the guidance of the fire department), or they may remain in the protected location until they are rescued by the fire department. Rescue by the fire department may be through windows, from balconies, or from within their dwelling units or other areas. This analysis was limited to review of the four building geometries and did not include occupants finding alternative means of egress.

For floors above grade, fire department rescue may be accomplished through the use of hand-carried fire department ladders positioned by fire department personnel. Above three floors, the use of a truck-mounted aerial ladder is usually required due to the height limitations of hand-carried ladders. Such vehicles require adequate space to deploy built-in braces that provide lateral stability when the aerial ladder is extended. The positioning of this rescue vehicle must be coordinated with the positioning of other obstructions, including vehicles and may be further complicated by the potential existence of obstructions including but not limited to overhead wires, light poles, and large trees. These and other factors can negatively impact the ability and speed at which rescue operations from an aerial ladder vehicle can occur. The building's geometry, its arrangement on the site and fire service access on an individual site will impact the potential fire service rescue operations.

The significant events, activities, and time frames that are utilized in establishing the RSET and the ASET are organized within a timeline which allows for comparison of the conditions within each scenario. The timeline consists of individual segments that begin with the time of the ignition of a fire, as noted in the "SFPE *Handbook of Fire Protection Engineering*" as follows [2]:

1. **Required Safe Egress Time (RSET):** The time between the ignition of a fire and the time at which all occupants can reach an area of safety. This is the sum of the Detection Time (Item 2), the Warning Time (Item 3), and the Evacuation Time (Item 4).
2. **Detection Time:** The time between the time of fire ignition and the time of the first detection of the fire by a device or an individual.
3. **Warning Time:** The time interval between detection of the fire and the time at which an alarm signal is activated or notification of occupants takes place.
4. **Evacuation Time:** The time from the alarm signal to the time at which the occupants reach a place of safety. This is the sum of the Pre-Evacuation Time (Item 4a) and the Travel Time (Item 4b).
   a. **Pre-Evacuation Time:** The time between the time at which a general alarm signal or warning is given and the time at which the first deliberate evacuation movement is made. This consists of two components: Recognition Time (Item 4.a.i) and Response Time (Item 4.a.ii).
      i. **Recognition Time:** The time between the time at which the alarm signal is perceived and the time at which the occupant interprets this signal as indicating an actual fire/emergency event. This time includes investigation and milling, for example, to determine the situation.
      ii. **Response Time:** The time between Recognition Time and the time at which the first action is taken to evacuate the building. This time includes activities such as firefighting (occasionally attempted by the occupants within the unit of origin), warning others, gathering family members and pets, dressing, retrieving personal belongings, calling the fire department, and similar activities.
   b. **Travel Time:** Once movement toward an exit has begun, the time needed for all occupants to reach a place of safety. In this report, Movement Time is synonymous with "Travel Time," and was determined by the egress model. For this analysis, both the Movement Time from the fire floor and the Movement Time to discharge from the building were identified, as discussed with TAG.

In addition, the following terms are used in this analysis.

Available Safe Egress Time (ASET): The time between the ignition of the fire and the time at which tenability criteria are exceeded in the means of egress. For typical engineering assessments, the ASET should be longer than the RSET by an acceptable Margin of Safety.

Margin of Safety: The time between when the evacuation is complete and the time at which tenability criteria are exceeded in an area. If the tenability limit is reached in an area prior to the evacuation of all occupants needing to use that area to egress, then those occupants do not have a Margin of Safety.

Analysis

For the purpose of this analysis, Detection Time, Warning Time and Pre-Evacuation Time are aggregated into the term "Pre-Movement Time" presented within this analysis. The following items address the Pre-Movement Time component of the analysis for occupants outside the dwelling unit of fire origin.

Considering the various segments of the egress evaluation for this comparative study, the Detection Time segment component is not impacted by the number of stairways in the building.

The Warning Time is not impacted by the number of stairways, but it is highly variable. In units other than the dwelling unit of fire origin, depends on the types and locations of detection devices and occupant notification devices, and by the manner in which the alarm devices are activated in various areas of the building. Delays in the activation of occupant notification devices result in delays in the start of Recognition Time. As agreed upon with the TAG, the occupants in the dwelling unit of fire origin who are intimate with the fire are outside of the scope of this analysis.

Within the Pre-Evacuation Time component, the duration of the Recognition Time can vary significantly due to different characteristics of building occupants. Being in a state of sleep is one of the most important factors, and it is further varied by the depth of sleep at the time of the alarm, and by the individual's physical characteristics that may impact their ability to be awakened by audible or visual alarms. The nature of the audible and visible performance characteristics of the fire alarm devices has been the subject of international research that has impacted the design of the devices and the requirements for them within the building codes. In summary, research has indicated that variations from one-half minute to five minutes are not uncommon, however the extremes can range from as little as a few seconds to hours [3]. This can be a significant issue, with the understanding that humans are sleeping approximately one-third of their time during a typical week, and that sleeping can frequently constitute as much as 50 percent or more of the time that occupants are in their dwelling units, particularly for those who work outside of their homes.

Also, within Pre-Evacuation Time, occupants will have variable amounts of time spent on Response Time prior to leaving their units and initiating Travel Time. The behavior during Response Time includes confirming the conditions, dressing, gathering important items, and assisting others within the unit. It can also include contacting others outside the unit or the building. The assumption is that the amount of time between the Detection Time and the start of Travel Time may be significant and frequently will result in all or nearly all building occupants being in their units prior to the corridor on the fire floor becoming untenable or otherwise not available for egress. This time component is also not impacted by the number of stairways in the building when evaluating the floor, or level, of fire origin.

Because of this, in situations in which building occupants might not be able to exit their units and reach the exterior of the building prior to the means of egress becoming untenable, the strategy of defend-in-place is useful, particularly for those who are on the same level as the dwelling unit of fire origin. For the purpose of this analysis, in reviewing the literature, the variation in Pre-Movement Time for occupants in residential occupancies is mostly due in part to people potentially sleeping when alarm notification occurs, and the potential need to locate others prior to starting evacuation.

As such, in review of data, the Pre-Movement Time for mid-rise residential buildings varies widely from as little as one minute to as long as about nineteen minutes, with the median for the four reported events ranging from 1.4 minutes to 7.7 minutes and the mean for the four reported events ranging from two and one-half minutes to just under ten minutes. A Pre-Movement Time of 4 minutes was selected for this comparative review through evaluation of the identified data sets and averaging the median times [4].

For the purpose of this analysis, Travel Time is addressed as the term "Movement Time" presented within this report. The major variables impacting the Movement Time include the number of occupants, their physical characteristics and abilities to self-evacuate or to evacuate with assistance, the physical characteristics of the egress path (e.g., corridor and stairway widths, and exit travel distance). The environmental conditions within the egress components (including the presence and intensity of fire, hot gases, and smoke) may also impact Movement Time by impacting the occupants' walking speed. For any given building, the individual Movement Time for occupants of each unit varies, with the primary time identified within the analysis of this report as being the maximum for this comparative building analysis. Where appropriate, the specific circumstances for the building configurations examined are discussed in further detail elsewhere within this report. The results of the egress modeling of this report established the Movement Times for each building geometry using different scenarios of fire incident conditions. The criteria used for each scenario are identified elsewhere within this report.

Actions of the Fire Service

As stated previously, the actions of the responding fire service have also been given consideration appropriate to the scope of this project. The building codes used to design buildings in North America are considered minimum standards that are intended to provide a reasonable level of safety for the public. The codes have been developed for national application and do not assume a specific fire department level of staffing, equipment, training or response time. The building code criteria applies in the same manner to buildings in large cities and buildings in rural areas. Nevertheless, building codes have been developed to facilitate fire department actions and interactions with the building in the interest of life safety and property protection. Examples of this include requirements for fire department access to buildings, a minimum size of windows allowing fire department rescue, building standpipe systems for manual firefighting, and fire command centers, etc.

As noted above, the location of physical elements around the perimeter of a building, and the design of windows and balconies for use by occupants to self-egress, or to do so with the assistance of the fire department, are important factors regarding actions of the fire department outside of the building.

Within a building during a firefighting operation, the activities of the fire fighters typically involve the use of at least one exit stairway, also used by occupants for their egress. For the analysis of multi-story residential buildings with a single exit stairway, there are additional considerations. Specifically, it is recognized that the exit stairway could become untenable for occupants due to the presence of fire, smoke, or hot gases because the doors to the stairway are open to facilitate firefighting operations. The other is that the stairway becomes unavailable for egress due to the presence of the fire fighters within the stairway engaged in firefighting operations. The unavailability is nearly always due to the presence of smoke and hot gases entering the stairway as the result of the stairway door on the fire floor being opened, either from occupants exiting the fire floor or from firefighting operations when the door on the fire floor is continuously at least partially open due to the necessity of routing the fire hose from the standpipe outlet within the stairway to location of the fire.

For a building with two or more exit stairways, there are potentially at least two means of self-egress from the building. One is an exit stairway that is available until it is taken out of service for firefighting operations. The second stairway presumably remains available during firefighting operations. However, if the door to this second stairway on the fire floor is opened for egress or firefighting operations, smoke and hot gases may enter this stairway and also compromise its ability to be used as an exit. Generally, building occupants escaping the building from the non-fire floors will not have advance notice of the stairway that is being used by the fire department.

Defend in Place

As noted above, the life safety strategy of defend-in-place is currently used within certain building types and occupancies within the United States. This strategy is also used for high-rise buildings where occupants cannot evacuate the building in a reasonable time and firefighting must be conducted from within the building. Specific to multi-family residential dwelling (MFD) buildings, as the result of significant research several decades ago, researchers had determined that occupants of residential buildings frequently did not begin self-evacuation until after fire department vehicles began arriving in front of their buildings, even when they had received audible and visual alarms, or other clues or information, well in advance of that time [5]. It was only then that many occupants felt that the need to evacuate had been confirmed. Their reluctance prior to the arrival of the fire department was usually driven by uncertainty about the actual existence of a fire (resulting from prior experiences with false alarms) or of the actual severity of the fire.

The use of a defend-in-place strategy often includes the presence of certain physical elements that are not always included within tall residential buildings. Specific to an MFD, these physical elements may include communications systems between the fire department at the building fire alarm control panel and the individual dwelling units; passive fire protection between identified areas such as dwelling units and the corridors and between individual dwelling units; and higher fire resistance-rated construction of the building’s structural frame so that occupants who are defended-in-place can safely do so until the fire burns out or is otherwise extinguished by the fire department.

Defend-in-place strategies in MFDs may also consider training of building occupants so that they understand the strategy and pre-incident planning with the fire service. Studies have indicated that the use of the defend-in-place strategy has a high success rate in buildings that are properly designed, constructed, and maintained, and when both the building occupants and the fire department are familiar with its implementation.

Automatic sprinkler systems are widely considered to be the most effective and reliable fire protection feature for building occupants' life safety. Automatic sprinkler system installations require a building inspection and acceptance test when first installed and periodic inspection, testing and maintenance over the life of the building, mandated by state and local fire prevention codes. (The current fire prevention code is the 2020 Minnesota State Fire Code (MFC), effective March 31, 2020, based upon the model 2018 International Fire Code.)

Yet, as a mechanical system, failures in automatic sprinkler protection are possible, as reflected in the data included in this report. Accordingly, the passive fire protection measures for a defend-in-place strategy are provided based upon a number of factors, fuel load being one of them, and are usually provided without consideration of automatic sprinkler protection.

When sprinkler system outages are known to building managers, alternative plans for safeguarding building occupants should be implemented. Section 901.7 of the MFC requires the fire code official to be notified immediately when a required fire protection system is known to be out of service. The fire code official may impose a fire watch for the building until the fire protection system has been restored to service or, in extreme cases, the fire code official may require the building to be evacuated.

In cases where fires are controlled by the sprinkler system, building occupants may elect to remain in their residential units unless they perceive themselves to be immediately threatened. Occupants who maintain situational awareness during a fire event can be expected to make appropriate decisions concerning evacuation or remaining in their residential units. Situational awareness can be supported through building systems that provide building occupants timely and credible information concerning the status of the event and information allowing them to make decisions concerning their safety. Building voice alarm systems can provide such real-time information to building occupants when staffed by responding firefighters.

Several dwelling unit fire scenarios have been identified where the exit access corridor has been adversely affected by fires that have not been controlled by automatic sprinkler protection and/or failure of the compartmentation, resulting in building occupants outside of the dwelling unit of fire origin being adversely affected. In such cases, affected building occupants may either attempt to egress through the smoke-filled corridor or remain in their residential units. Human behavior studies have shown that approximately 60 percent of people will elect to move through smoke to escape the fire [6].

Nevertheless, the concept of a "defend-in-place" strategy is considered viable. Low-rise and mid-rise buildings have lower total occupant loads than high rise buildings. The low-rise and mid-rise buildings also usually do not have robust fire resistive construction but are of a fire resistance commensurate with the building's fire loading to allow burn-out of the structure without collapse in the unlikely event of sprinkler system failure, sufficient for occupants to evacuate or defend-in-place for rescue.

A series of public comments submitted to the NFPA Life Safety Code Technical Committee for the 1985, 1988 and 1991 Revision Cycles are of interest. James Macdonald, Travelers Insurance Company, was a proponent of a formal defend-in-place strategy for residential buildings and his proposals received considerable attention at that time. Mr. Macdonald was proposing that the Technical Committee recognize a defend-in-place strategy for residential buildings of fire resistance-rated construction, similar to the strategy successfully used for hospitals where patients are defended-in-place for most fire emergencies. Mr. Macdonald cited fatalities where people left the safety of their residential units and attempted to evacuate, including fires at the MGM Grand Hotel (1980), the Las Vegas Hilton (1981). He stated that occupants are more likely to die in the process of evacuation and that self-closers for corridor doors are important to contain a room fire or control spread of a corridor fire.

He also stated residential buildings are constructed with many small compartments that restrict the size of a fire and provide a natural way to limit smoke spread. He noted that buildings having a single exit-access corridor serving two exit stairways effectively lack a second means of egress and that a defend-in-place strategy was necessary.

The Technical Committee took no specific action concerning the proposals but included the following note in the Appendix of the 1985 edition of NFPA 101:

> *It is not always necessary to completely evacuate the building or structure to escape from a fire or other emergency. An area of refuge formed by horizontal exits, smoke barriers, other floors, or like compartmentation often can serve as a place for the occupants to remain in relative safety until the emergency is over. In those occupancies where access to the exits is by way of enclosed corridors, particularly with sleeping occupants, a single fire may block access to all exits, including horizontal exits and smoke barriers. In such cases, the occupants may achieve a greater degree of safety by remaining in their rooms* [7].

The defend-in-place concept has been identified in this report as it constitutes a viable alternative to the traditional MFD building evacuation strategy reflected in the building's means of egress design. While this report identifies MFD building occupants "impacted" under certain scenarios, it is reasonable to expect that occupants can defend-in-place when conditions are such that they cannot readily evacuate the building.

Endnotes

[1] Society of Fire Protection Engineers, *SFPE Guide to Human Behavior in Fire*, 2nd ed. (New York: Springer, 2019.)

[2] Society of Fire Protection Engineers (SFPE), *SFPE Handbook of Fire Protection Engineering*, 5th ed. (New York: Springer, 2016).

[3] Society of Fire Protection Engineers (SFPE), *SFPE Handbook of Fire Protection Engineering*, 5th ed. (New York: Springer, 2016), Table 64-13, "Pre-evacuation Sleep Data."

[4] Society of Fire Protection Engineers (SFPE), *SFPE Handbook of Fire Protection Engineering*, 5th ed. (New York: Springer, 2016), Chapter 64 and PD 7974-6.

[5] G. Proulx, "The Time Delay to Start Evacuating upon Hearing a Fire Alarm," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting 38,* no. 14 (1994).

[6] Society of Fire Protection Engineers, *SFPE Guide to Human Behavior in Fire*, 2nd ed. (New York: Springer, 2019.)

[7] National Fire Protection Association (NFPA), *NFPA 101: Life Safety Code* (Quincy, MA: National Fire Protection Association, 1985), Appendix A.

APPENDIX H – MODELING RESULTS

Summary of Fire Model Scenarios

Fire modeling scenarios were developed to assess smoke migration and the resulting levels of tenability within building corridors and stairways following either a dwelling unit fire or an e-bike fire within the corridor. Modeling scenarios considered the location of fires relative to the interior exit stairway doors and the position of dwelling unit doors and stairway doors. The modeled scenarios are summarized in Table H-1 below.

Modeling Results

Buildings 1, 2, 3, and 4 were evaluated using the identified tenability criteria for visibility, temperature, and carbon monoxide concentration, measured at an elevation six feet above the walking surface of the floor/level being evaluated. The fire modeling results for the scenarios in Buildings 1, 2, 3 and 4 indicated that visibility within occupiable spaces was reduced below fifteen feet (the selected tenability criteria) prior to increased temperatures or carbon monoxide concentrations exceeding their respective tentability thresholds. Therefore, visibility was determined to be the limiting factor for each scenario and is the criterion for the tenability times identified in Table H-2. The fire and egress modeling results for each scenario are summarized in Table H-2.

Representative images of the fire modeling and egress modeling results are provided below for general context. The fire modeling results below only show the locations where the visibility, temperature, or carbon monoxide concentration exceed the relevant tenability criteria. Spaces on the floors where tenability limits are exceeded are shaded in colors corresponding to the scales shown in the figures, while spaces where tenability is maintained appear white (unshaded).

Table H-1. Summary of Fire Modeling Scenarios

Scenario No.	Building No.	Fire Origin	Fire Type	Approximate Peak Heat Release Rate (MW)	Dwelling Unit Door Position[1]	Stairway Door Position[1]
1-1	1	First level dwelling unit adjacent to exit stairway	Room fire	10	Open	Closed
1-2	1	First level dwelling unit adjacent to exit stairway	Room fire	10	Open	Open on fire floor
1-3	1	First level dwelling unit adjacent to exit stairway	Room fire	10	Open	Open on fire floor and floor above fire floor
1-4	1	First level corridor	E-bike	0.9	N/A	Closed
2-1	2 and 4	First level dwelling unit	Room fire	10	Open	Closed
2-2	2 and 4	First level dwelling unit	Room fire	10	Open	Open on fire floor
2-3	2 and 4	First level corridor	E-bike	0.9	N/A	Closed
3-1	3	First level dwelling unit	Room fire	10	Open	Closed
3-2	3	First level dwelling unit	Room fire	10	Open	Open on fire floor
3-3	3	First level corridor	E-bike	0.9	N/A	Closed

Table Notes:

1 Where a dwelling unit door is indicated as "open," the doors were in the closed position at the beginning of the model simulation (t=0s) and were opened after a simulation time of two minutes (t=120s).

Table H-2. Fire and Egress Modeling Summary[1]

Scenario	Building No.	Fire Origin[2]	Corridor Fire Floor Tenability Time (Min.)	Movement Time from Typical Fire Floor (Min.)[3]	Stairway Tenability Time (Min.)[4]	Total Building Movement Time (Min.)[3]	Total Building Movement Time with Counter-Flow (Min.)[5]
1-1	1	Dwelling Unit	10	<7	NA	16	—
1-2	1	Dwelling Unit	10	<7	3	16	—
1-3	1	Dwelling Unit	10	<7	3	16	—
1-4	1	Corridor	1.5	<7	NA	16	—
2-1	2 [4][6]	Dwelling Unit	2.5	0.5	NA	2.5 [3.5]	— [5]
2-2	2 [4][6]	Dwelling Unit	2.5	0.5	3	2.5 [3.5]	— [5]
2-3	2 [4][6]	Corridor	0.5	0.5	NA	2.5 [3.5]	— [5]
3-1	3	Dwelling Unit	2.5	1	NA	5	7.5
3-2	3	Dwelling Unit	2.5	1	3	5	7.5
3-3	3	Corridor	0.5	1	NA	5	7.5

Table Notes:

1 Egress modeling results are a summary of approximate Movement Times for occupants using average occupant movement speeds with 44-inch-wide stairways.

2 For dwelling unit fire location, the door between the corridor and the dwelling unit of fire origin was modeled in the closed position at the beginning of the model simulation (t=0s) and was opened after a simulation time of two minutes (t=120s). For the corridor fire location, the doors between the corridor and the dwelling units were modeled in the closed position.

3 The egress model Movement Time presented in this table does not include Pre-Movement time.

4 "NA" indicates there was no point during the FDS simulation where the tenability limits within the stairway were exceeded due to the stairwell doors remaining closed.

5 "—" indicates that counter-flow was not modeled for the code compliant buildings.

6 Building 4 results are the same as Building 2 results unless otherwise shown with "[ ]".

Building 1

Fire Modeling Results

Scenario 1-1

The visibility results were found to be the criteria that is the first to exceed tenability limits (Figure H-1). In the figures, the areas of the figures in shaded colors show the tenability conditions corresponding to the scale shown in the figures. Figure H-2 and Figure H-3 are provided as representative of temperature and CO concentration results for the Building 1 scenarios only (Scenarios 1-2, 1-3, and 1-4).

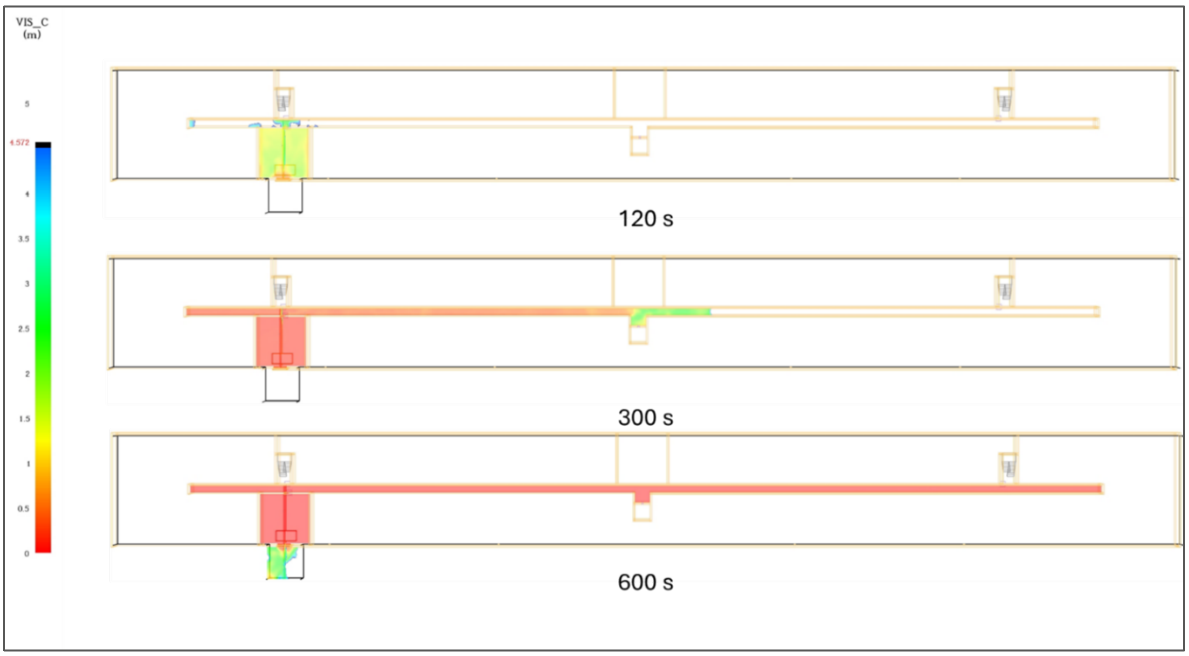


Figure H-1. Building 1, Scenario 1-1. Plan view of fire floor corridor visibility tenability criterion of 15 feet at 150 seconds, 300 seconds and 600 seconds

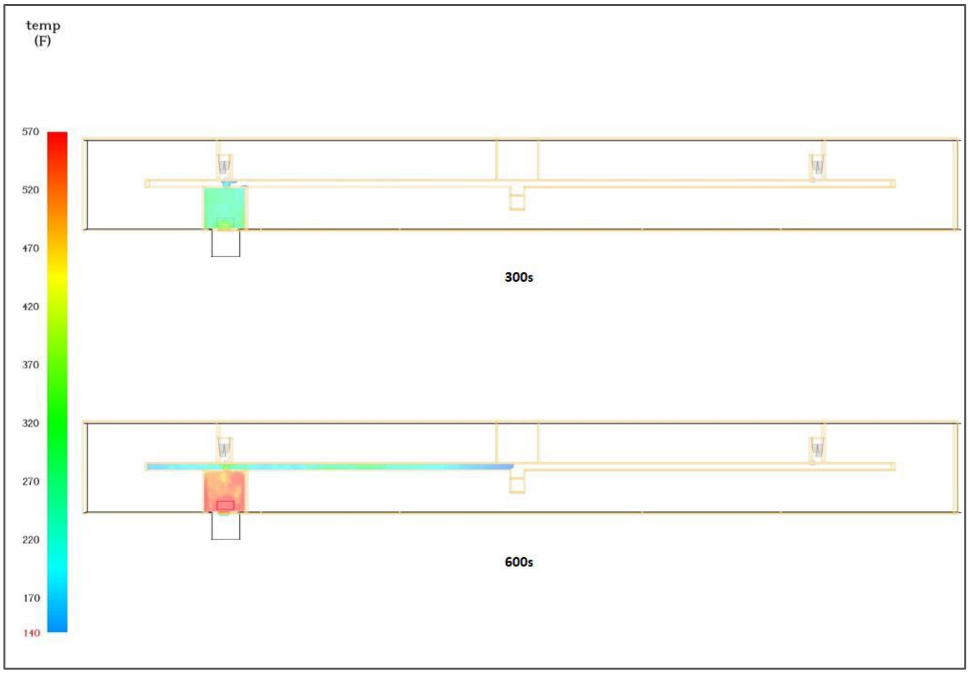


Figure H-2. Building 1, Scenario 1-1. Plan view of fire floor corridor temperature tenability criterion of 140°F at 300 seconds and 600 seconds

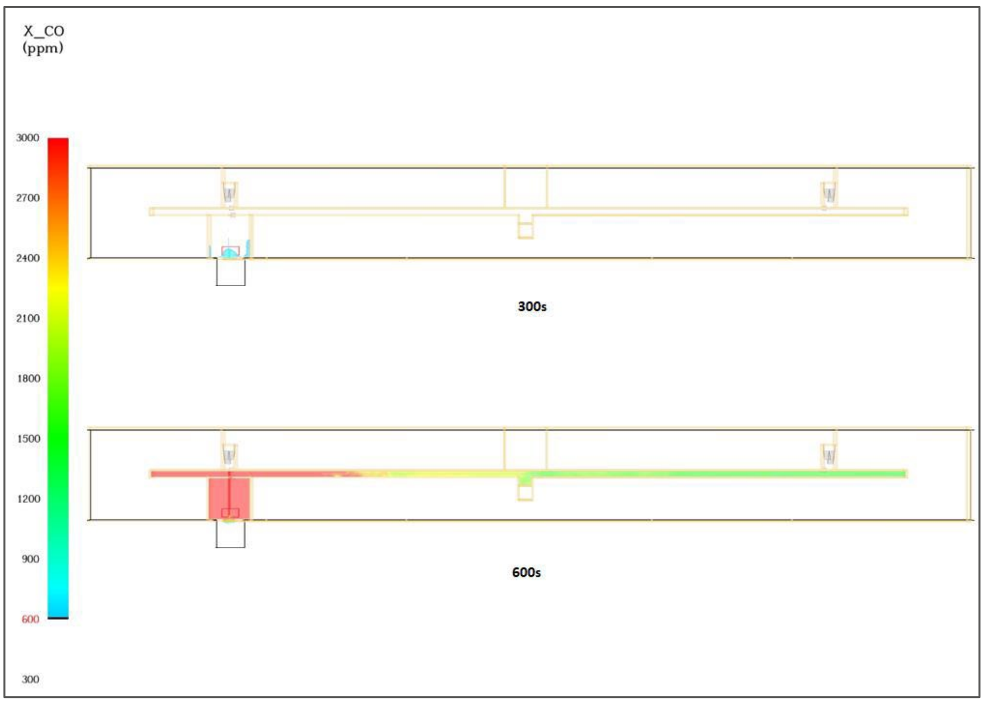


Figure H-3. Building 1, Scenario 1-1. Plan view of fire floor corridor CO concentration tenability criterion of 600 ppm at 300 seconds and 600 seconds

Scenario 1-2 (Figure H-4 and Figure H-5)

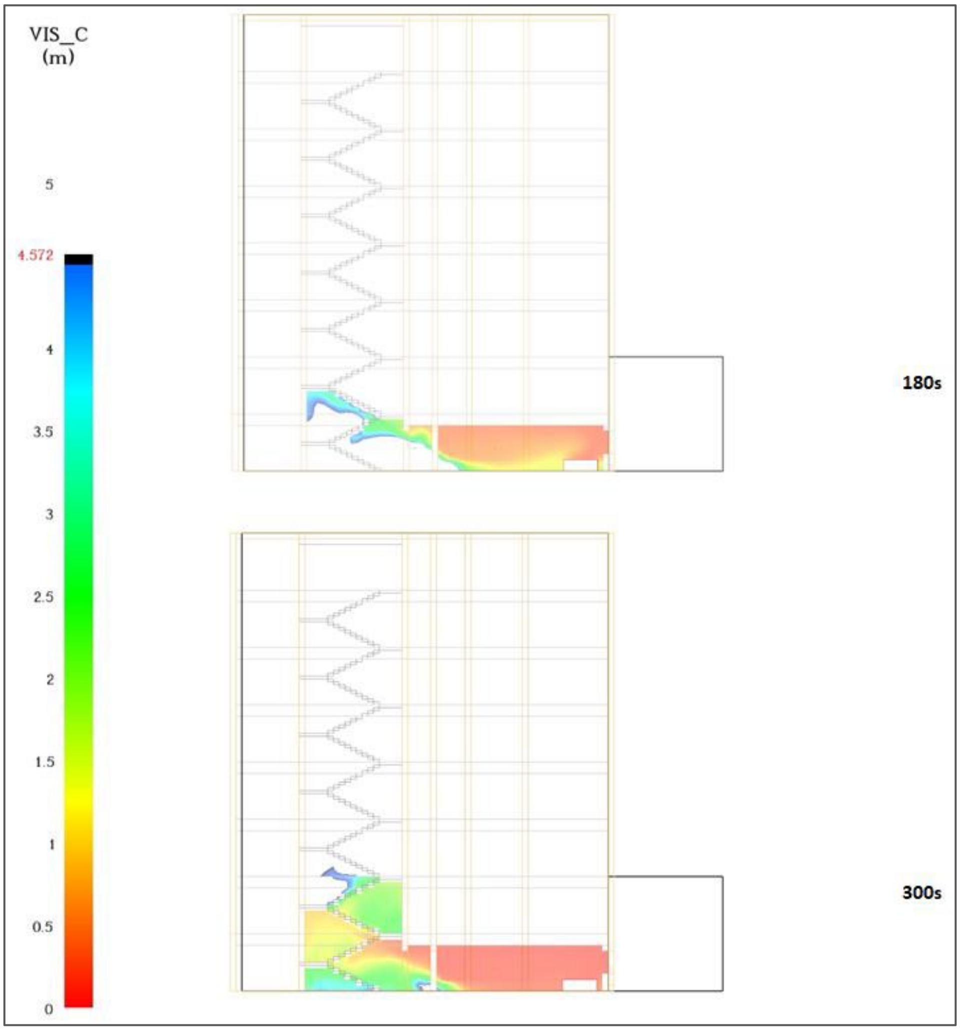


Figure H-4. Building 1, Scenario 1-2. Elevation view of visibility tenability criterion of 15 feet at 180 seconds and 300 seconds

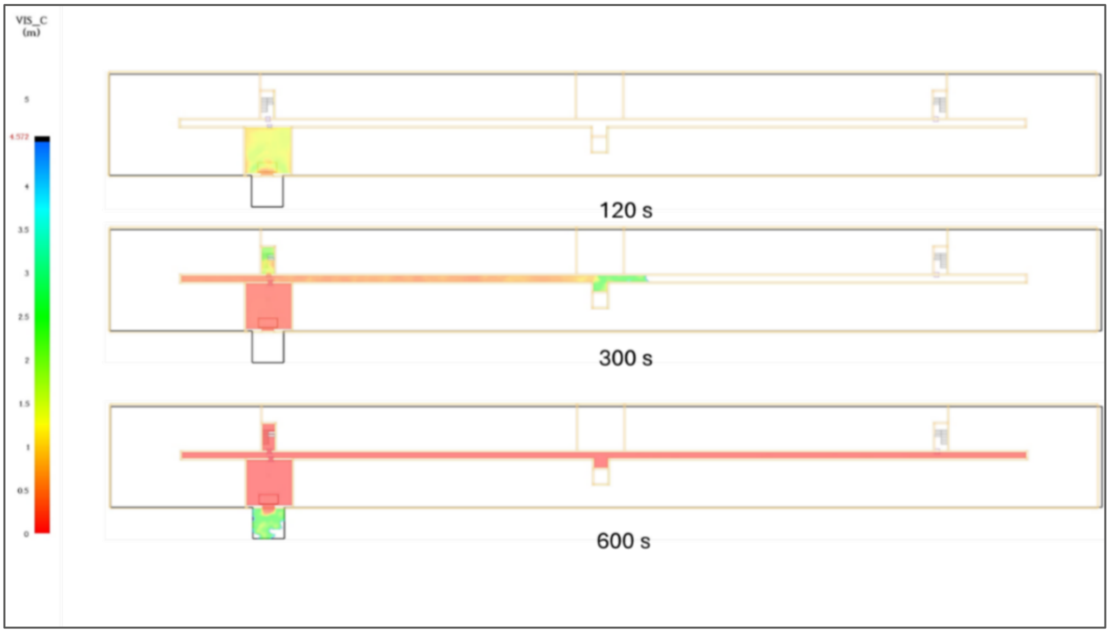


Figure H-5. Building 1, Scenario 1-2. Plan view of fire floor corridor visibility tenability criterion of 15 feet at 120 seconds, 300 seconds and 600 seconds

Scenario 1-3

Scenario 1-3 also considered the corridor on the level directly above the fire floor. Visibility was reduced below the 15 feet tenability criteria in this entire corridor at approximately 960 seconds. (See Figure H-6, Figure H-7 and Figure H-8).

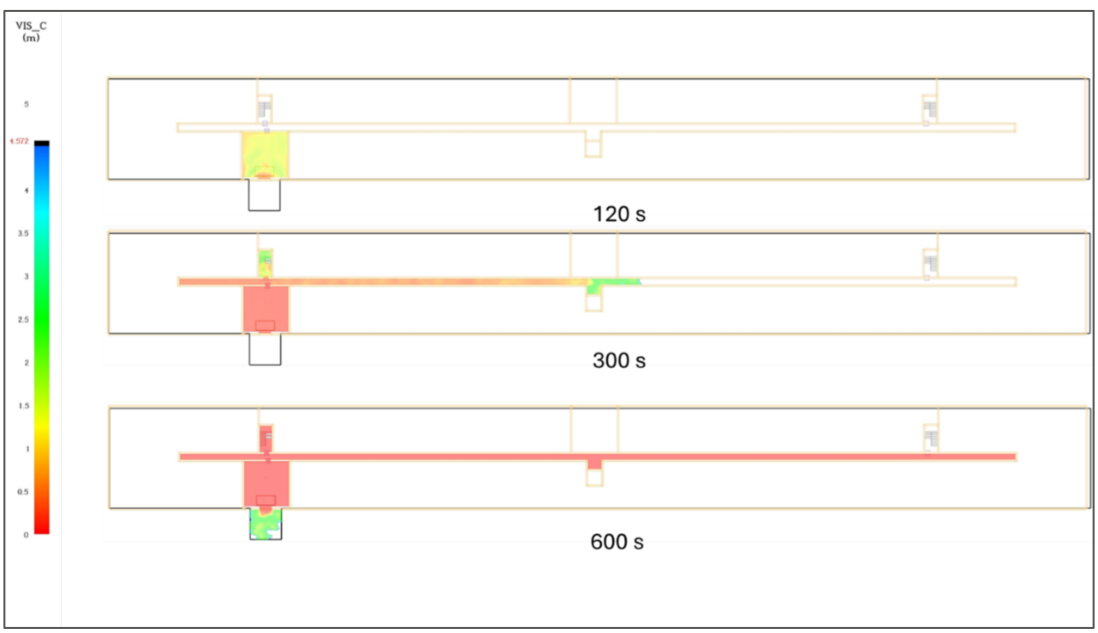


Figure H-6. Building 1, Scenario 1-3. Plan view of fire floor corridor visibility tenability criterion of 15 feet at 120 seconds, 300 seconds and 600 seconds

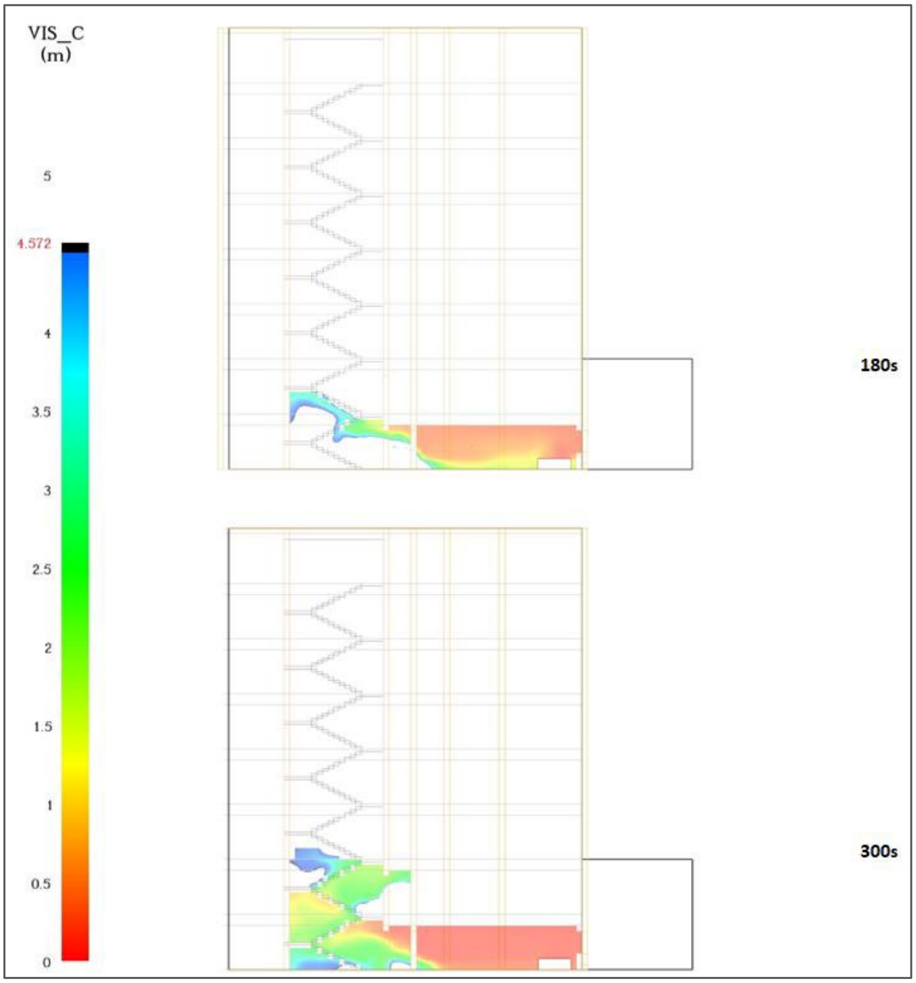


Figure H-7. Building 1, Scenario 1-3. Elevation view of visibility tenability criterion of 15 feet at 180 seconds and 300 seconds

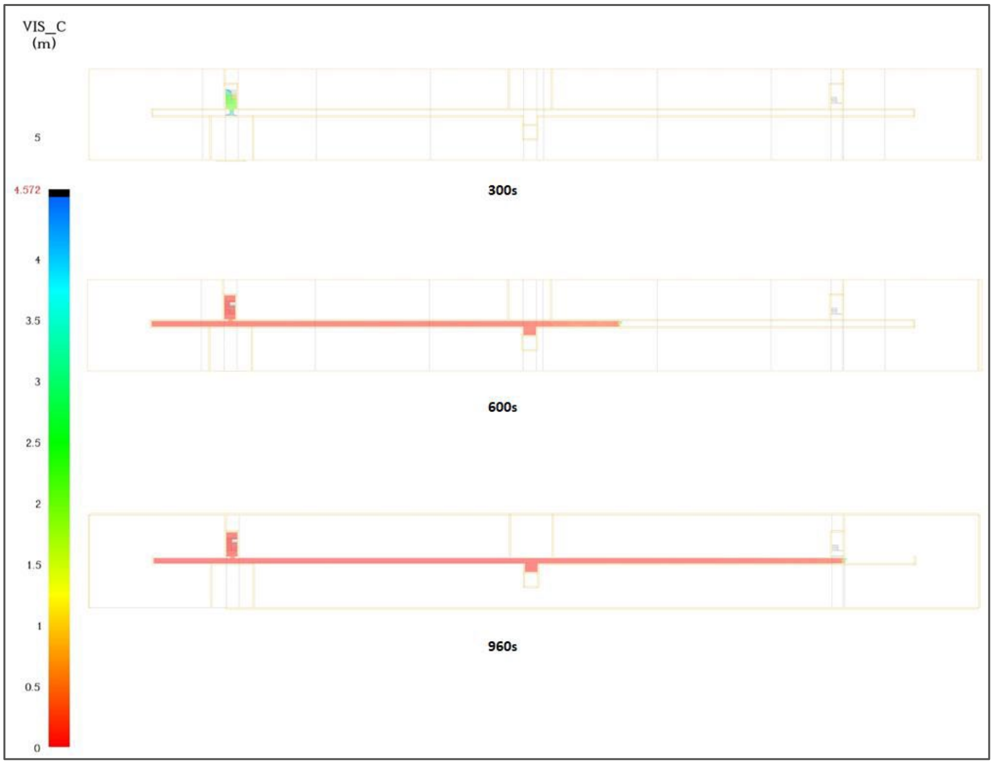


Figure H-8. Building 1, Scenario 1-3. Plan view of floor directly above the fire floor corridor visibility tenability criterion of 15 feet at 300 seconds, 600 seconds and 960 seconds

Scenario 1-4 (Figure H-9)

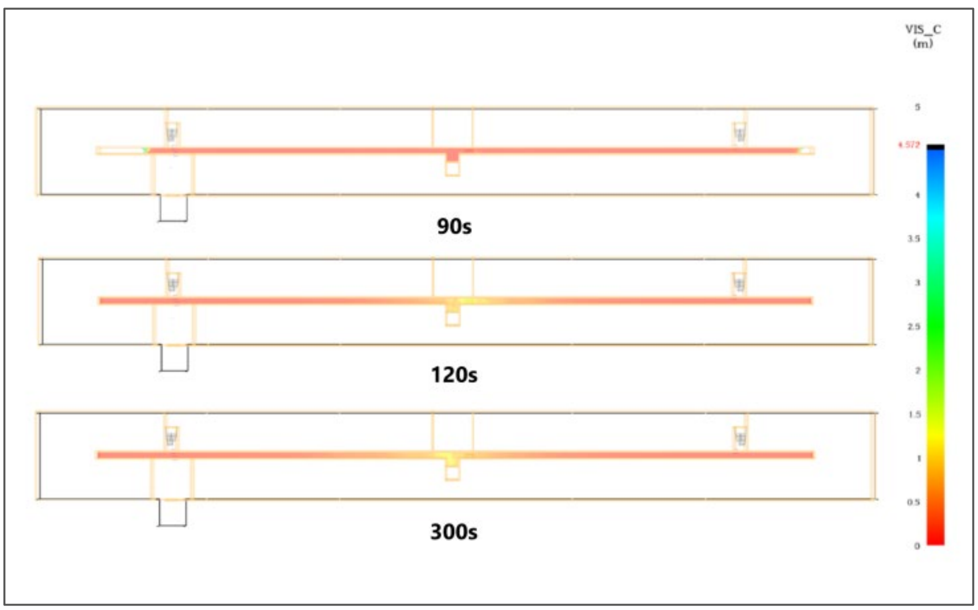
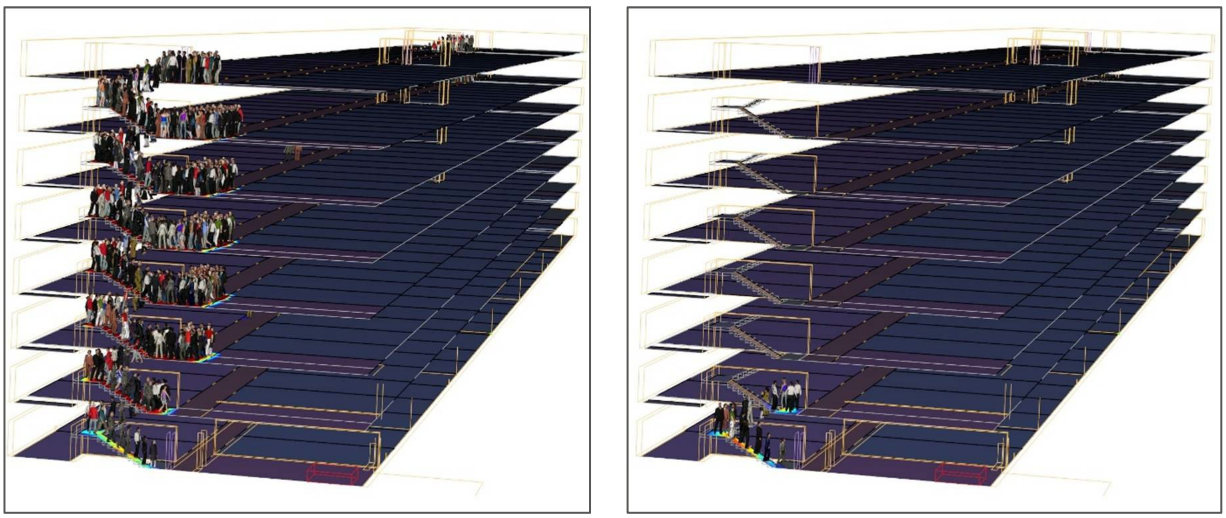


Figure H-9. Building 1, Scenario 1-4. Plan view of fire floor corridor visibility tenability criterion of 15 feet at 90 seconds, 120 seconds and 300 seconds

Egress Modeling Results

The occupant load on each level of Building 1 is 204 people. The Movement Time required to complete egress from the individual floor using two stairways is less than 420 seconds.

The Movement Time required to complete egress from the entire building is less than 960 seconds when two stairways are available (Figure H-10). When one of the stairways is blocked and only one stairway is available for egress, the Movement Time required to complete egress from the entire building exceeds 1800 seconds.



300s **900s**

Figure H-10. Building 1 egress results with two stairways available, at 300 seconds and 900 seconds of Movement Time

Building 2 and Building 4

Fire Modeling Results

Scenario 2-1

Once again, the visibility results were found to be the criteria that is the first to exceed tenability limits (Figure H-11). The areas of the figures in shaded colors show the tenability conditions corresponding to the scale shown in the figures.

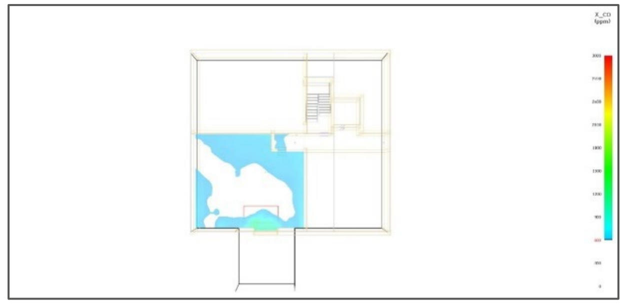
Figure H-11. Building 2 and 4, Scenario 2-1. Plan view of fire floor corridor of visibility tenability criterion of 15 feet at 120 seconds, 150 seconds and 300 seconds

Figure H-12 and Figure H-13 are provided for the reader as representative of temperature and CO concentration results for the remaining Building 2, Building 3, and Building 4 scenarios (Scenarios 2-2, 2-3, 3-1, 3-2, and 3-3).

300s

600s

Figure H-12. Building 2 and 4, Scenario 2-1. Plan view of fire floor corridor exceeding temperature tenability criterion of 140°F at 300 seconds and 600 seconds



300s

600s

Figure H-13. Building 2 and 4, Scenario 2-1. Plan view of fire floor corridor exceeding CO tenability criterion of 600 ppm at 300 seconds and 600 seconds

Scenario 2-2 (Figure H-14 and Figure H-15)

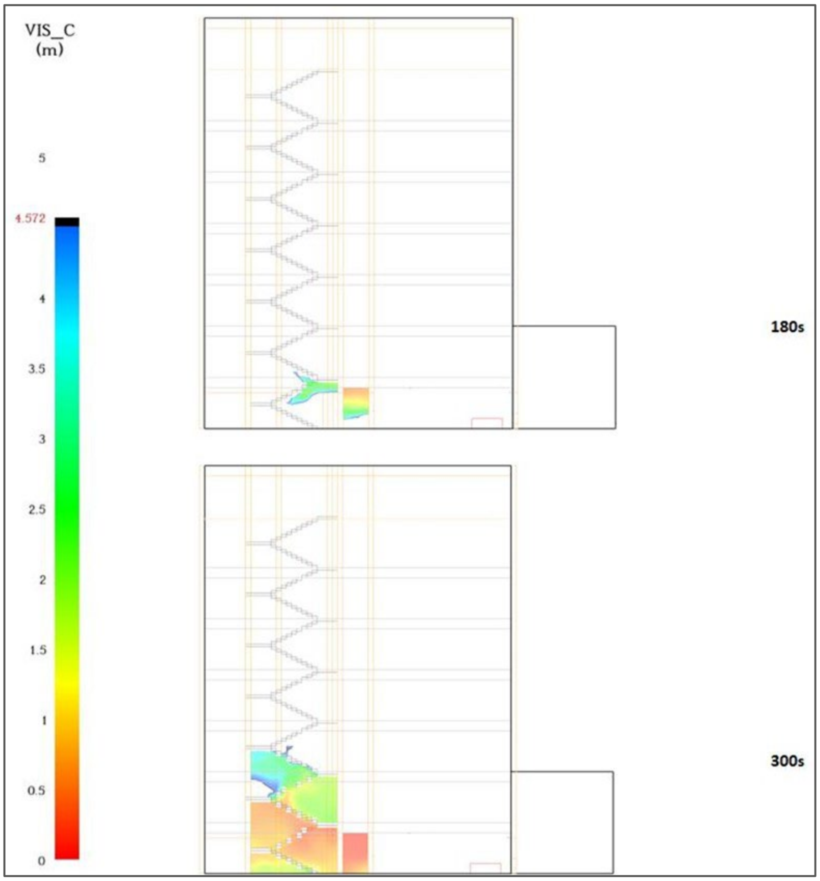


Figure H-14. Building 2 and 4, Scenario 2-2. Elevation view of visibility tenability criterion of 15 feet at 180 seconds and 300 seconds

Figure H-15. Building 2 and 4, Scenario 2-2. Plan view of fire floor corridor visibility tenability criterion of 15 feet at 120 seconds, 150 seconds and 300 seconds

Scenario 2-3 (Figure H-16)

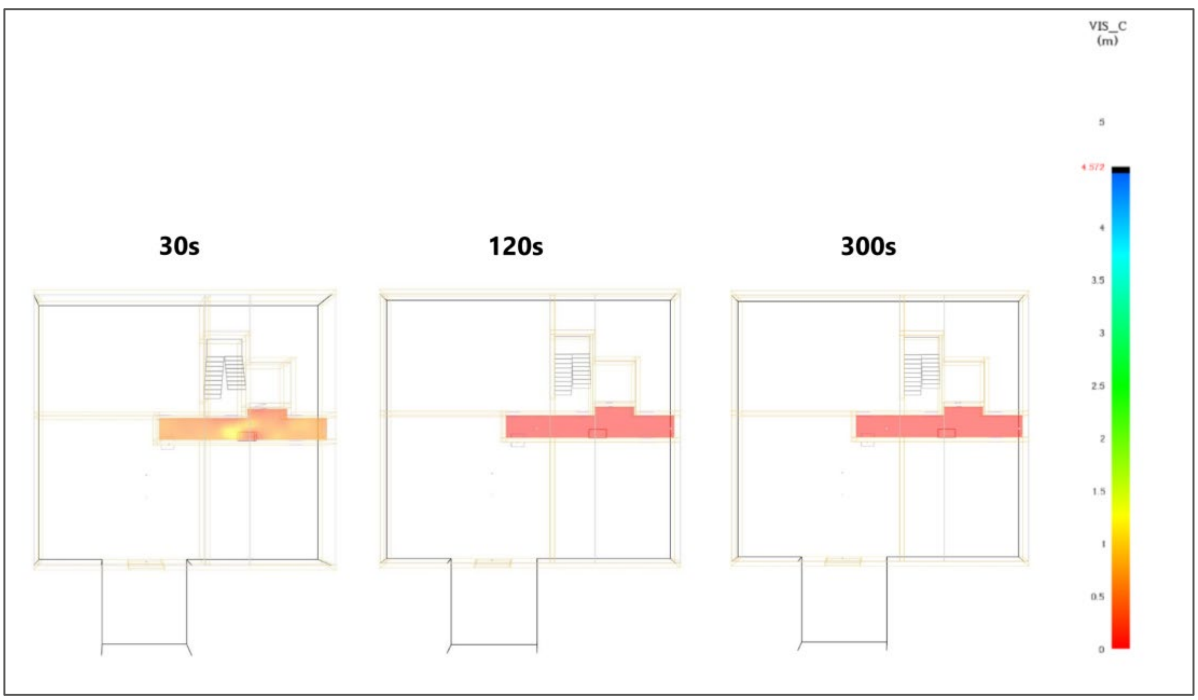


Figure H-16. Building 2 and 4, Scenario 2-3. Plan view of fire floor corridor visibility tenability criterion of 15 feet at 30 seconds, 120 seconds and 300 seconds

Egress Modeling Results

The occupant load on each level of Building 2 and Building 4 is twenty people. The Movement Time required to complete egress from the individual floor is less than 30 seconds (Figure H-17).

Without counter-flow, the Movement Time required to complete egress of the building from Building 2 and Building 4 is approximately 150 seconds and 210 seconds, respectively (Figure H-18). The Movement Time of Building 4 was also considered with counter-flow to determine the impact the fire service would have on escaping occupants using the conservative assumptions identified in the report. For Building 4, when considering counter-flow, the Movement Time required to complete egress from the building with either of the 44-inch wide and 48-inch-wide stairways is approximately 300 seconds.

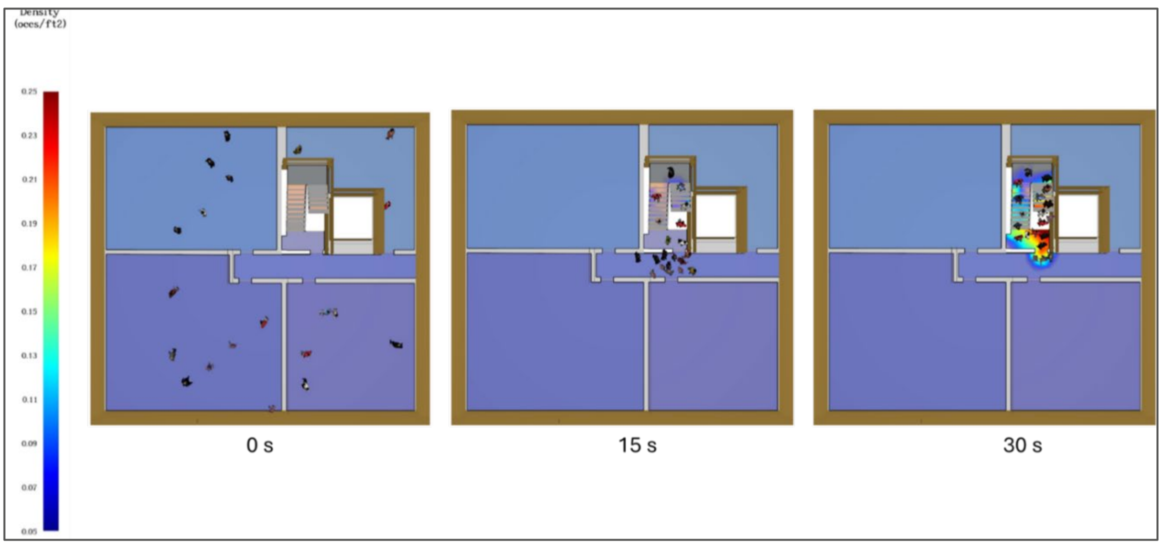


Figure H-17. Building 2 and 4 egress results on the fire floor at 0 seconds, 15 seconds and 30 seconds of Movement Time

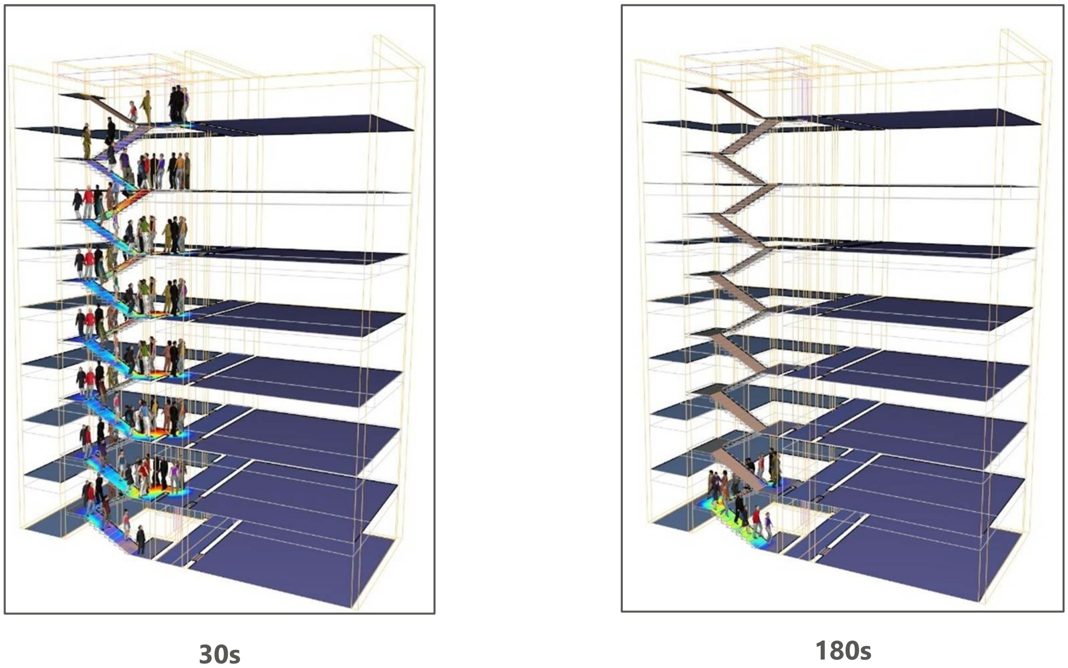


Figure H-18. Building 4 egress results within stairway at 30 seconds and 180 seconds of Movement Time

Building 3

Fire Modeling Results

Scenario 3-1

Once again, the visibility results were found to be the criteria that is the first to exceed tenability limits. The plan view of fire floor corridor visibility tenability criterion of 15 feet at 120 seconds, 150 seconds and 300 seconds is shown in Figure H-19. The areas of the figures in shaded colors show the tenability conditions corresponding to the scale shown in the figures. Temperature was above the tenability criterion of 140°F in the entire fire floor corridor at 300 seconds. CO concentration was above the tenability criterion of 600 ppm in the entire fire floor corridor at 300 seconds.

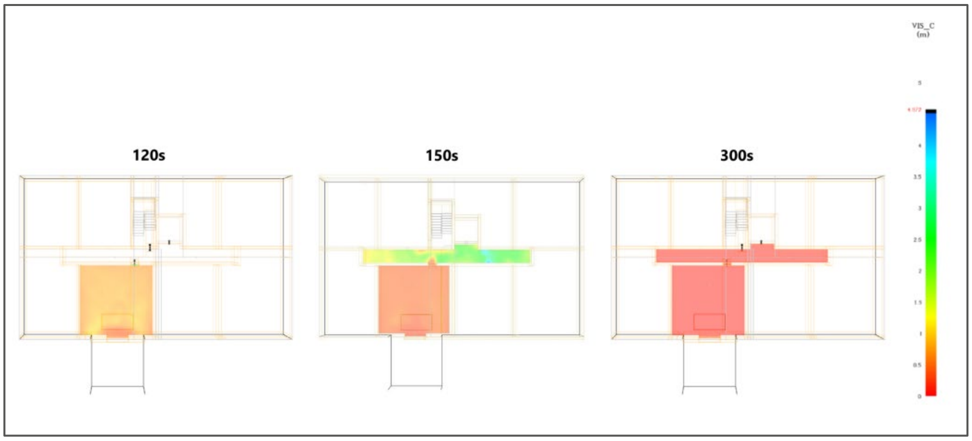


Figure H-19. Building 3, Scenario 3-1. Plan view of fire floor corridor visibility tenability criterion of 15 feet at 120 seconds, 150 seconds and 300 seconds

Scenario 3-2 (Figure H-20 and Figure H-21)

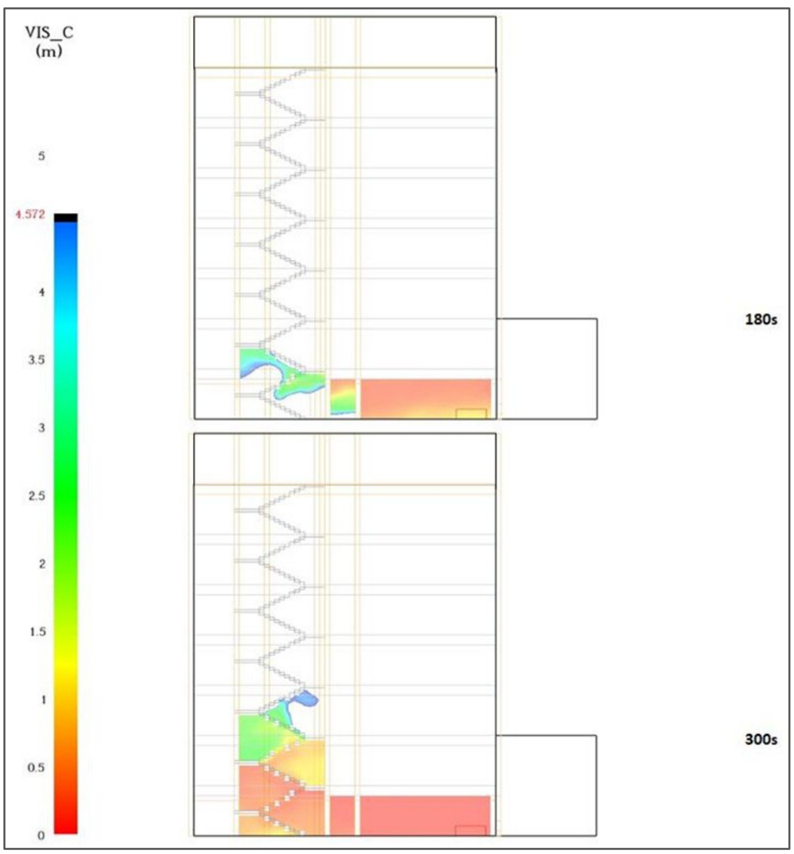


Figure H-20. Building 3, Scenario 3-2. Elevation view of visibility tenability criterion of 15 feet at 180 seconds and 300 seconds

Figure H-21. Building 3, Scenario 3-2. Plan view of fire floor corridor visibility tenability criterion of 15 feet at 120 seconds, 150 seconds and 300 seconds

Scenario 3-3 (Figure H-22)

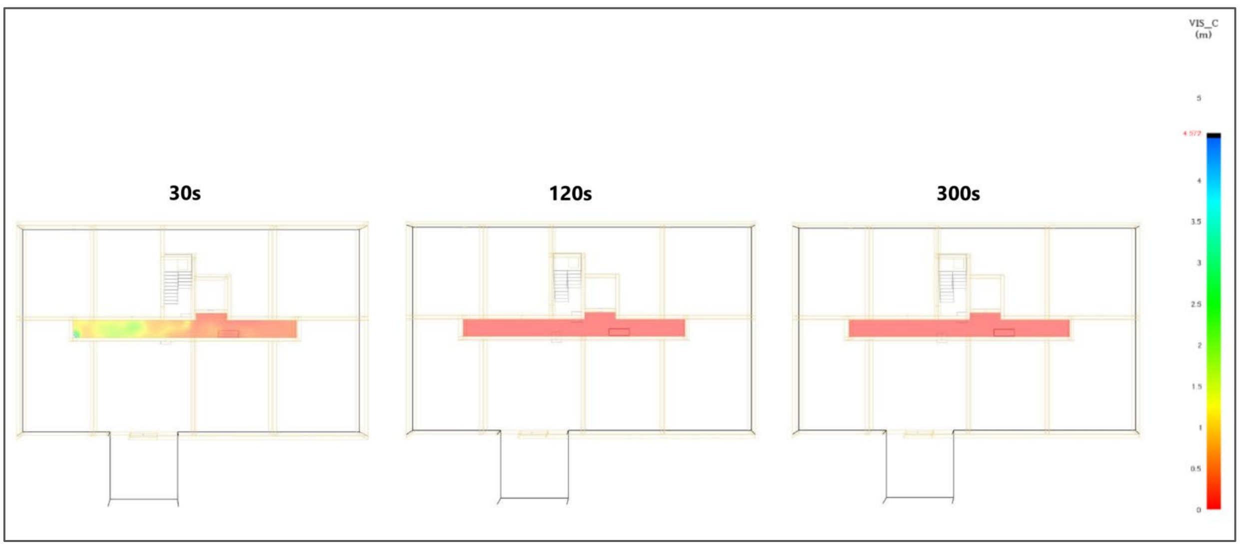


Figure H-22. Building 3, Scenario 3-3. Plan view of fire floor visibility tenability criterion of 15 feet at 30 seconds, 120 seconds and 300 seconds

Egress Modeling Results

The occupant load on each level of Building 3 is thirty people. The Movement Time required to complete egress from the individual floor is less than 60 seconds (Figure H-23).

Without counter-flow, the Movement Time required to complete egress of the building from Building 3 is approximately 300 seconds (Figure H-24). Egress of Building 3 was also considered with counter-flow to determine the impact the fire service would have on escaping occupants using the conservative assumptions identified in the report. When considering counter-flow for both the 44-inch wide and 48-inch-wide stairways, the Movement Time required to complete egress from Building 3 is approximately 450 seconds.

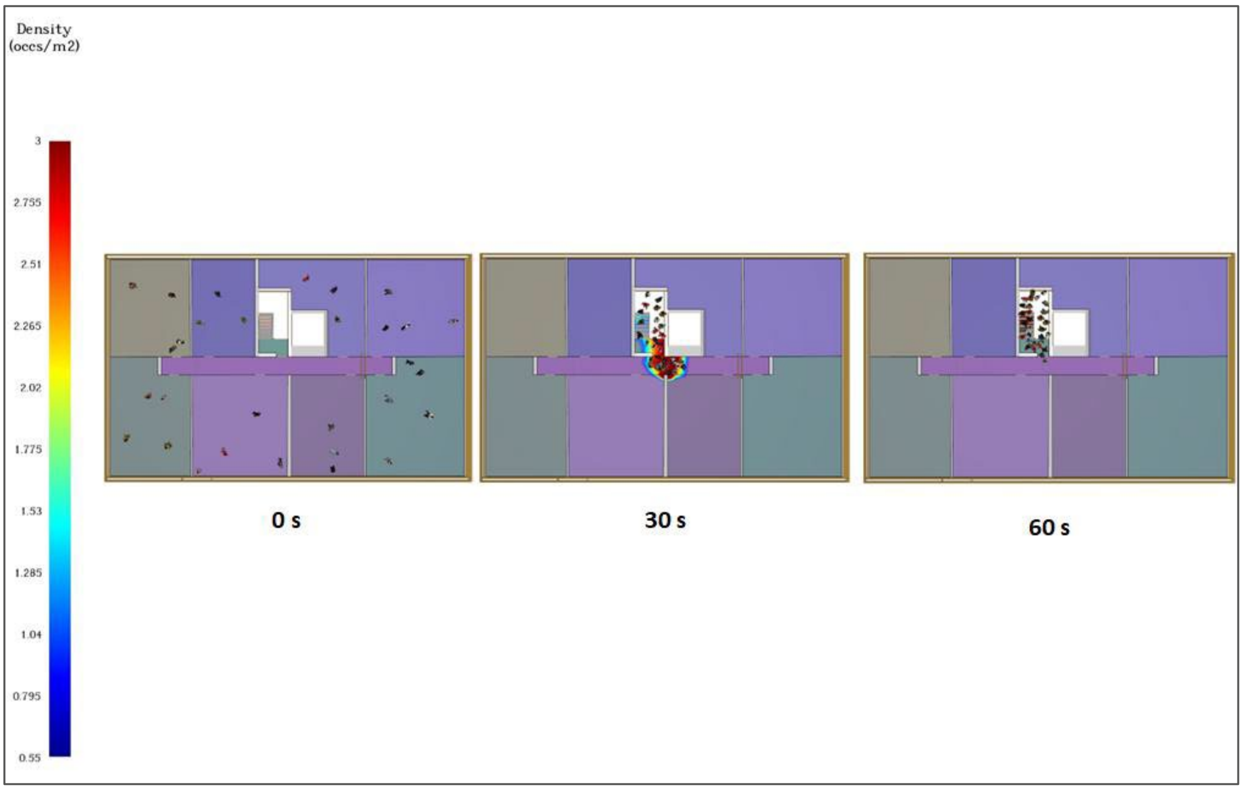
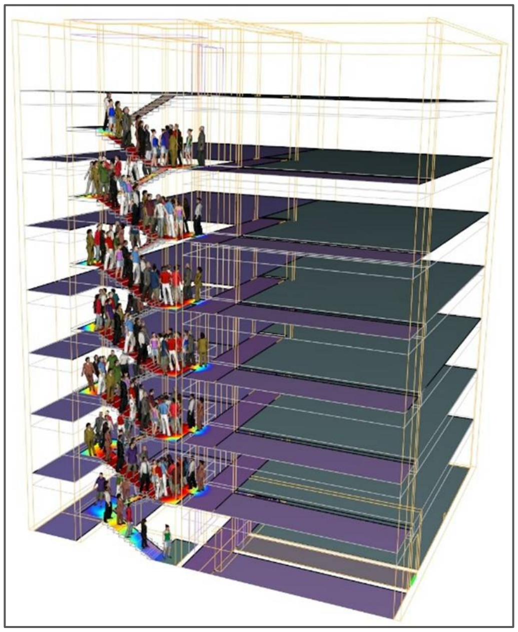
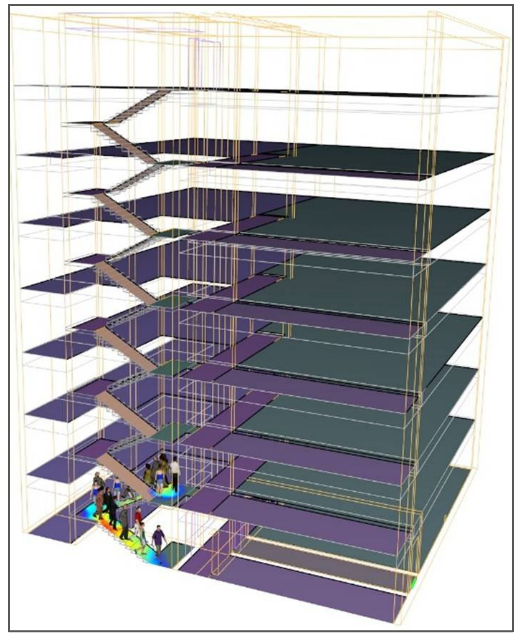


Figure H-23. Building 3 egress results on the fire floor at 0 seconds, 30 seconds and 60 seconds of Movement Time



60s



270s

Figure H-24. Building 3 egress results within the stairway at 60 seconds and 270 seconds of Movement Time

APPENDIX I – UNCERTAINTY DISTRIBUTIONS

Narrower uncertainty distributions indicate higher confidence in the reported results whereas wide uncertainty distributions indicate that there is significant variability in the reported results. This report used a Monte Carlo analysis to sample the event tree 10,000 times over the system reliability distributions for each fire scenario in each building. Each variable was sampled independently, which is consistent with the way it was reported in the data. Additional samplings beyond 10,000 in the Monte Carlo study did not change the uncertainty by more than 1 percent. Table I-1 shows the results of the uncertainty study.

The results are presented as the 5 percent, 50 percent, and 95 percent percentiles of the risk distribution for each building and fire type. The 5 percent percentile indicates the lower tail of the distribution where 95 percent of results are expected above the 5 percent value and 5 percent of results below it. The 95th percentile indicates the upper tail of the distribution where 5 percent of results are expected above the 95 percent value and 95 percent of results are expected below it. The 50th percentile reports the median point where one-half of the results are below and one-half of the results are above. This study uses the values close to the median for reporting purposes; however, it is important in a quantitative risk study to understand the distribution of the results to put the median result in sufficient context.

Table I-1. Monte Carlo Distribution of the Comparative Building Risk Based on System Uncertainty

Building Geometry (No.)	Dwelling Unit Fire Percentile			Corridor Fire Percentile		
%	5th	50th	95th	5th	50th	95th
1	92.3	109.6	128.4	93.2	110.4	129.4
2	4.34	5.14	6.02	4.71	5.57	6.51
3	13.4	15.9	18.7	14.0	16.5	19.3
4	8.88	10.5	12.3	9.33	11.02	12.9

The sprinkler system has the greatest impact on risk and there is adequate data available from the State of Minnesota to create reliable distributions. However, the performance data for mitigating systems in the egress pathway are much more limited. The uncertainty bands show a range of risk for each structure that correlates to the performance of each system. Properly maintained systems generate risk values expected to fall in the lower end of the distribution whereas poorly maintained systems would fall in the higher end. Figure I-1 through Figure I-8 below show the uncertainty distributions for the dwelling unit and corridor fire scenarios for each of the four building geometries.

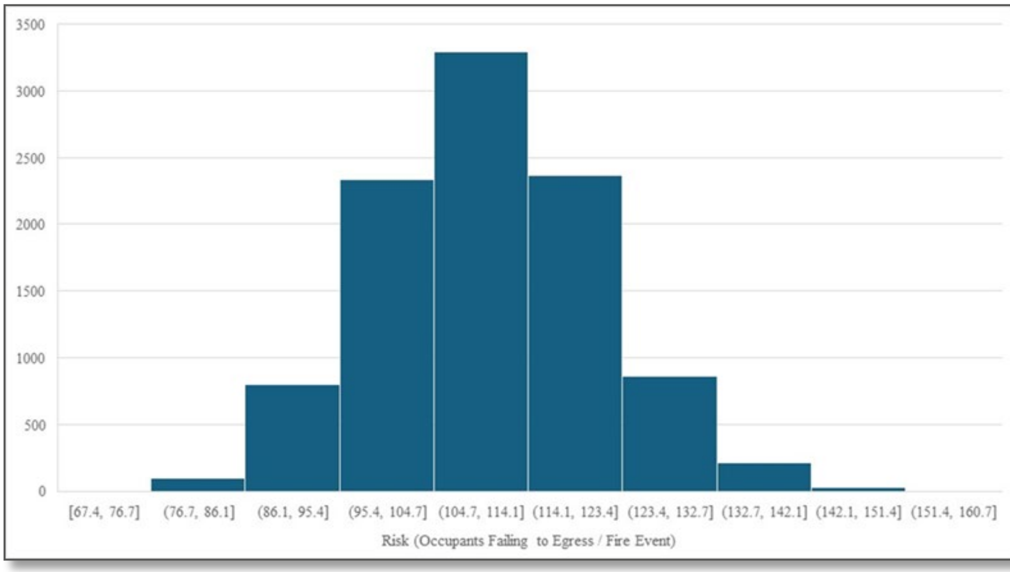


Figure I-1. Uncertainty distribution for Building 1 dwelling unit fire

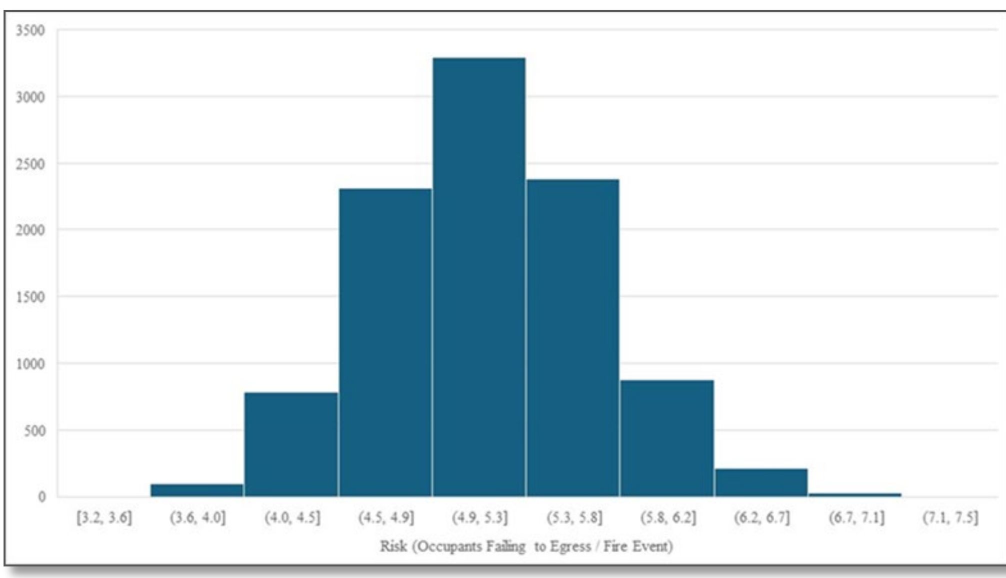


Figure I-2. Uncertainty distribution for Building 2 dwelling unit fire

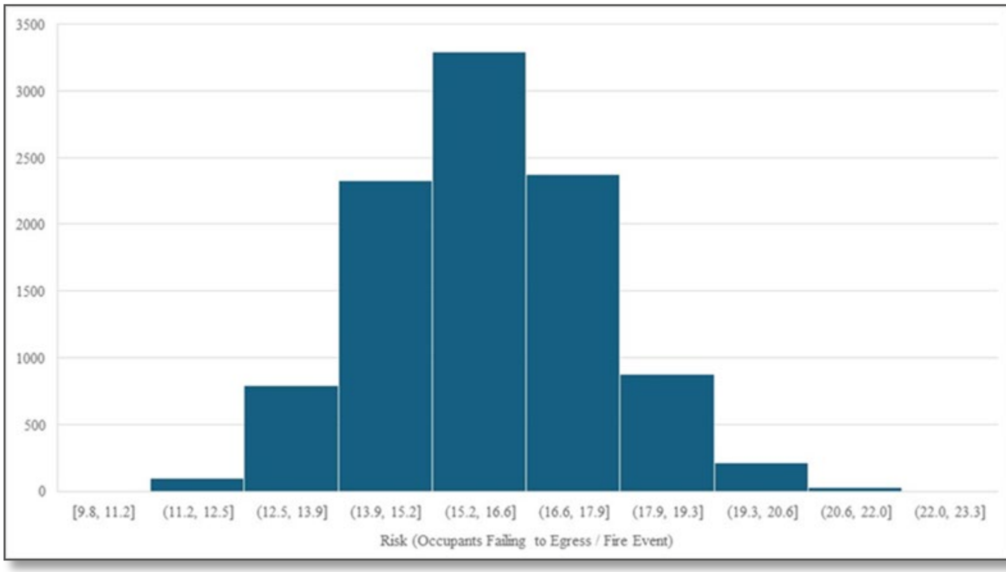


Figure I-3. Uncertainty distribution for Building 3 dwelling unit fire

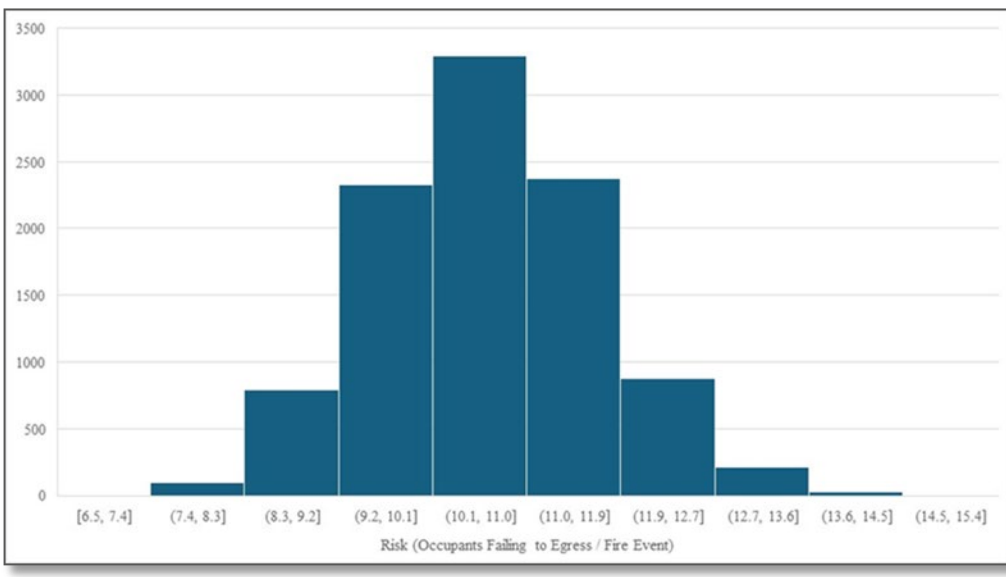


Figure I-4. Uncertainty distribution for Building 4 dwelling unit fire

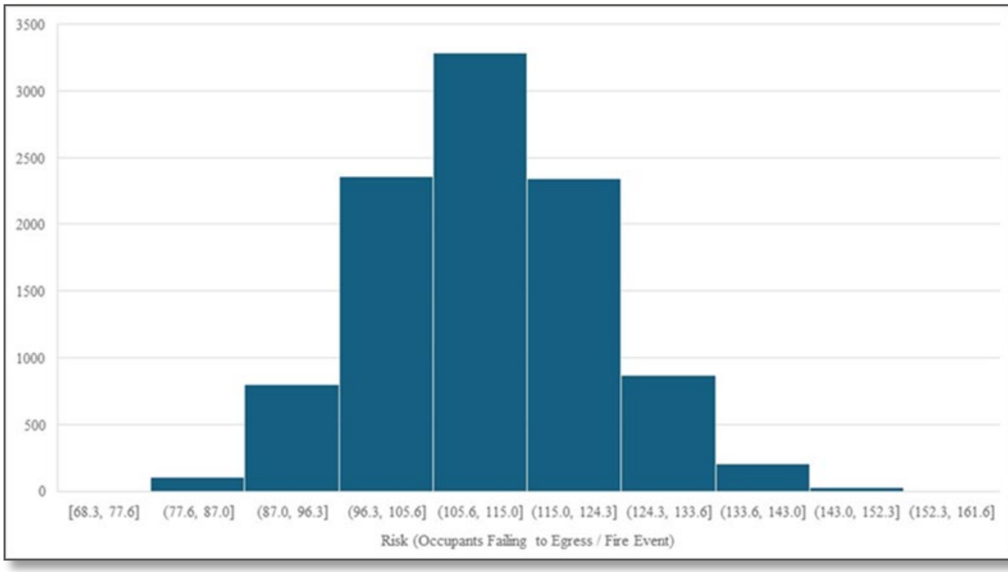


Figure I-5. Uncertainty distribution for Building 1 corridor fire

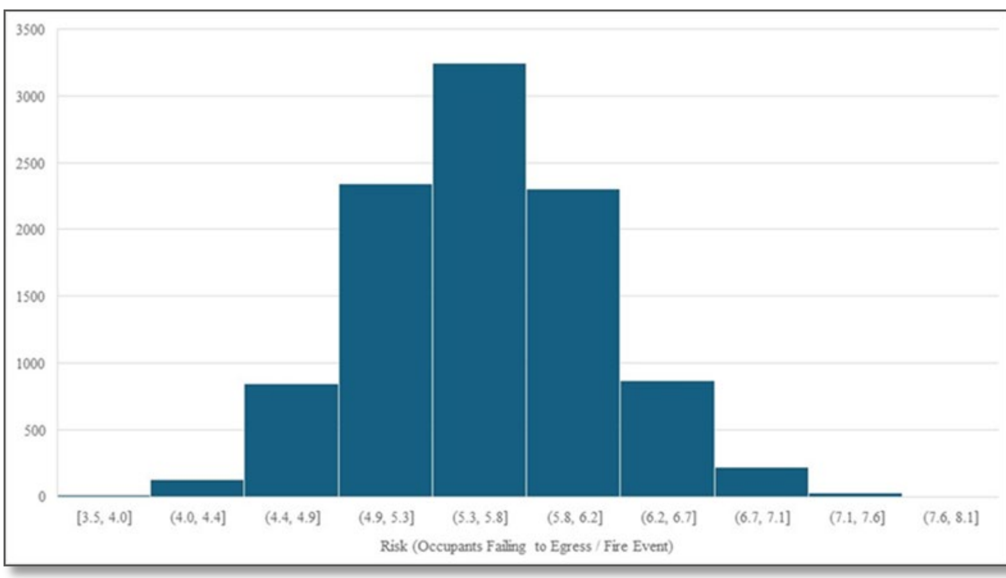


Figure I-6. Uncertainty distribution for Building 2 corridor fire

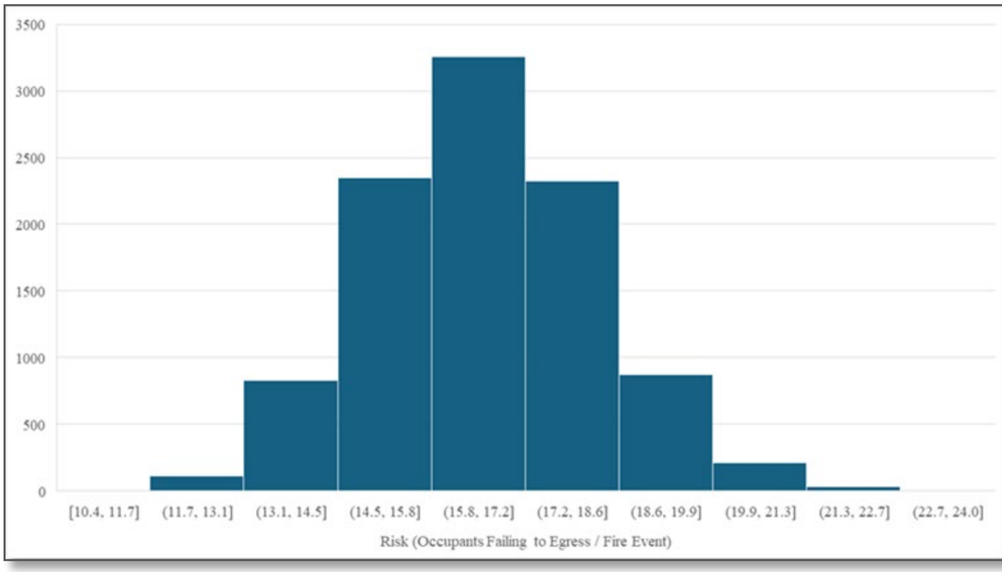


Figure I-7. Uncertainty distribution for Building 3 corridor fire

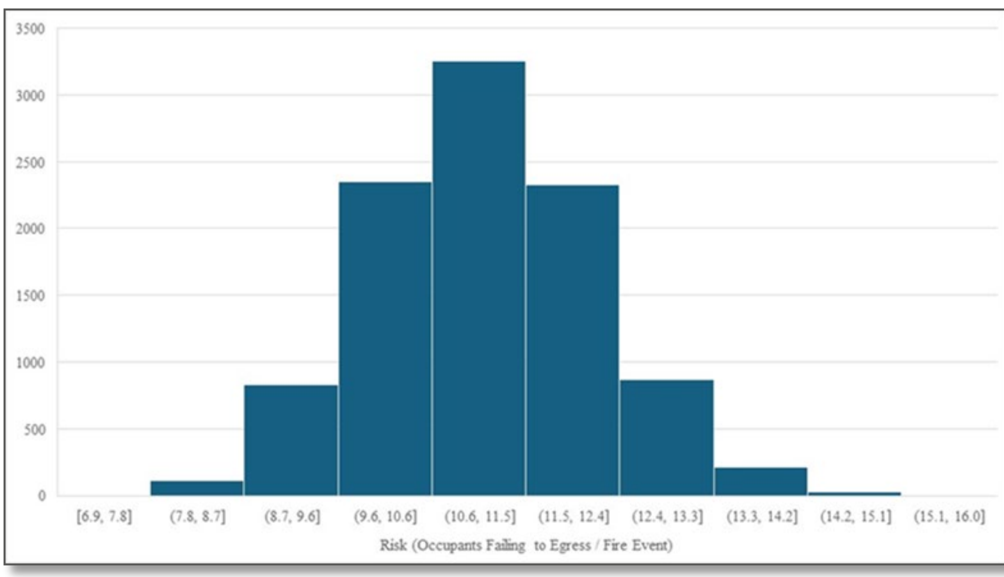


Figure I-8. Uncertainty distribution for Building 4 corridor fire