Minnesota Single-Exit Stairway Apartment Building Study

State of Minnesota RFP 2000016452

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State of Minnesota RFP 2000016452 Response

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PROPRIETARY USE

This report was developed for the State of Minnesota Department of Labor and Industry and was based upon data from the State of Minnesota and direction provided by the Department, and should not be used, or relied upon, by others without permission of the State of Minnesota and the authors.

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 (Client) documenting the risk-informed approach (RIA) used to study multi-family residential dwelling buildings, hereafter referred to as "MFDs," with a single-exit stairway.

The Minnesota Legislature mandated a data-driven study to evaluate conditions under which apartment buildings with a single means of egress above three stories and up to 75 feet in height could achieve life safety outcomes equivalent to or better than those required by the current Minnesota Building Code (MBC). The Client created a Technical Advisory Group (TAG) that consisted of architects, code officials, developers, fire fighters, fire marshals, fire protection engineers, and housing experts and 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. 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 an 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 configurations, and define the fire scenarios and consequence used in the comparative analysis.
- Develop four building geometries used in this study: (1) a code-compliant 8-level building with two exit stairways; (2) a code-compliant 4-level building with a single exit stairway; (3) a prototype 8-level building, 6,000 square feet (sf) per level, with a single exit stairway; and, (4) a prototype 8-level building, 4,000 sf per level, with a single exit stairway.
- Prepare an event tree based on the data reviewed and input from TAG to quantify the likelihood of different end states occurring based on select mitigating systems identified by data succeeding or failing. For the purposes of this analysis, a fire ignition was assumed to have occurred, i.e., a probability of 1.0, an assumption supported by the TAG.

This 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 agreed 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 systems to the overall risk as defined within and quantify the uncertainty of the risk 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 understand how the different building geometries and mitigating systems compare to one another.
- 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 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 diverse 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 risk of the prototype single-exit stairway MFDs (Building 3 and Building 4) 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%. If this reliability can be increased to approximately 96%, 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 MFD compliant with the MBC having the observed sprinkler system reliability.
3. A properly operating automatic sprinkler system provides the most significant comparative risk reduction impact.

4. The number of exit stairways factors into the risk calculation 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 comparative risk profile given the multiple failures (sprinkler system, dwelling unit door, stairway door) that need to occur.
5. Almost 97% of the comparative risk for each scenario reviewed 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 results in no signal 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 likely either defended in place or rescued by fire fighters. 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 building systems for fire risk mitigation measures.
6. In the scenario where the sprinkler system fails to control the fire and the door to the dwelling unit of fire origin is left open, the combustion products can freely flow into the corridor. The corridor volumes in the single-exit stairway MFD buildings are expected to be sufficiently small such that the corridor becomes untenable before an occupant can begin to evacuate, affecting all occupants on the floor where the fire originated. Thus, reliable door closers are important fire risk mitigation measures if the sprinkler system fails.
7. In the scenario where 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 can 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 make the decision to evacuate. In this scenario, all occupants in the single-exit stairway building fail to evacuate. However, occupants on floors other than where the fire originated in multiple-exit stairway MFDs can use the unaffected exit stairway to egress.
8. The Consultants have proposed no modifications to the MBC for residential MFDs, Group R-2 occupancies per the MBC, for construction type requirements based on height and area, fire resistance ratings of structural elements, dwelling unit separations and corridor separation requirements. The Consultants did not find adequate data to calculate the risk impact of the construction type.

9. The Consultants reviewed mitigation measures where the risk of the prototype MFDs exceeded the baseline risk of code-compliant buildings using the event tree. While many concepts were evaluated, it was not an exhaustive evaluation of all possible mitigation measures. Instead, the focus was on measures where the available data could support quantitative evaluations to compare the risk of the various prototype building geometries, as documented in the Recommendations. These and other options are ultimately up to Minnesota policy makers. If other options are selected, a similar evaluation is suggested to be conducted, noting that significant subjective engineering judgement would likely be necessary due to the lack of available data.
10. The lack of available data on fire service operations in single-exit stairway buildings and comments from TAG reinforce that tactical response questions remain for effectively fighting fires in a single-exit stairway buildings more than three stories in height. However, the egress modeling demonstrates that the issue of cross-flow within the prototype single-exit stairway MFD building is not a significant factor due in part to the limited building height and number of occupants in buildings.

Recommendations

To reduce the estimated risk of the prototype MFD single-exit stairway building to less than or equal to that of a code-compliant single-exit stairway MFD, the following recommendations were developed for the Minnesota policy makers to consider on an individual basis.

1. **Provide smoke detectors in the common means of egress of MFDs more than three stories in height**.
   Providing smoke detectors in common egress areas of fully-sprinklered MFDs, such as corridors, would provide a diverse means of activating the building fire alarm system that is independent from the sprinkler system. The addition of the common area smoke detectors reduces the comparative risk of the prototype single-exit stairway MFDs (Building 3 and Building 4) 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 three stories tall**.
   Create a more robust ITM program to increase the reliability of a sprinkler system flowing on demand. Based on the MFIRS data, the current observed reliability of a sprinkler system flowing on demand is approximately 88%. If this reliability can be increased to approximately 96%, the estimated risk of either prototype single-exit stairway MFD (Building 3 and Building 4) would be less than or equal to that of a code-compliant single-exit stairway MFD having the observed sprinkler system reliability. The ITM program for MFD buildings should also include periodically inspecting that dwelling unit and exit stairway door closers function properly, and that doors are not propped open.

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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 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.[1,2,3] 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.[45]

The Consultants were tasked with reviewing data and conducting this analysis to provide information to the Minnesota policy makers so that they can make a more 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 sound fire protection principles. The RIA evaluates two example code-complying MFDs to define a benchmark risk. That same RIA is then applied to calculate the risk of two prototype single exit stairway MFD buildings up to 75 feet in height. Where the risk of the prototype MFD exceeds the benchmark, different mitigating systems are considered to reduce the prototype buildings' risk equal to or less than that of the benchmark allowed by the Minnesota Building Code (MBC).

The risk-informed approach 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.

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.

BACKGROUND

Single-Exit Stairway Buildings

The increased utilization of single-exit stairway MFD buildings has received increasing national attention as a means to help alleviate the housing shortage in the United States.[6] Other states and cities have or are also looking into this topic, including the States of Colorado,[7] New York,[8] and California,[9] and Dallas.[10]

The cities of 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.[11] Additionally, New York City has allowances for single-exit stairway residential 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.[12]

There have also been several studies conducted,[13] a national symposium,[14] articles published,[15,16] and changes proposed to the MBC and the model International Building Code (IBC) related to single-exit stairway building designs[17] to help reduce the cost of construction and increase useable building area.

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.[18,19,20] Some studies[21] 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 to attempt to quantify the impacts of such proposed changes.

However, much of the previously published work by others generally lacked adequate technical support using fire data, system reliability data, consequence analysis and input from stakeholders. The State of Minnesota has commissioned this study to provide additional context via its request for proposal for this Single-Egress Stairway Apartment Building Study. This study differs in that it analyzed state and national data, used risk analysis tools to evaluate the 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 amendments reflecting the jurisdictions’ unique needs and conditions. The IBC reflects the complex, layered approach to fire protection as documented in the several hundred pages that provide detailed design and construction requirements.

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 layer 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 U.S. 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[22] and single-exit stairway MFDs can fail to safeguard occupants.[23] A data-driven RIA can help add context to the features and systems in the building codes 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 protection of people (occupants, emergency responders), property, operations, 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 sociotechnical system, many items must come into balance.[24,25]

To reduce the number of decision variables for a large percentage of building designs, 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 USA. 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.[26]

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.[27,28,29]

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, 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 generally 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 risk reduction 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 a risk-informed approach (RIA).[30,31,32]

An 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 US National Aeronautics and Space Administration (NASA),[33] the U.S. Nuclear Regulatory Commission (NRC),[34] the U.S. Government Accountability Office (GAO),[35] and the U.S. Federal Energy Regulatory Commission (FERC).[36] An 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.[37]
- In its simplest form, risk can be viewed as the combination of the probability (frequency, 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 for these variables. As a result, in most cases, many things have to go wrong for a fire to occur (fire frequency is very low), and many things have to 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 of the level of fire 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 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 taken into account 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 safety risk. The data used in this comparative evaluation 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.
- An 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 evacuation modeling.[38]
- The assumptions and bases of model input parameters are critical to the goodness and validity of modeling. It has been famously said that all models are wrong, but some are useful.[39] 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. An 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 risk 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 MBC. It also allows for additional mitigating features to be evaluated to determine their impact on the 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 looked at holistically to understand whether expected system performance can be achieved.[40] 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).

- The comparative RIA is effective as a tool for the relative comparison of the risk of different structures 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 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 egress stairway residential building four stories in height and up to 75 feet in height equivalent or better in safety to 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 as "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, 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 a RIA that involved the following steps:

- Review literature and data to understand the different types of multi-family dwelling (MFD), residential buildings currently allowed by the MBC.
- Review Minnesota and national fire loss data over a 20-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, an assumption supported by 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 being the point when agreed 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. Determination of consequences ranged from simple correlations based on engineering judgment to smoke / fire / egress modeling.

- Based on the data reviewed, identify potential mitigating 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.
- 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 risk for each end state. The sum of the individual end state's risk yields the total building risk.
- Compare the risk of different MFD geometries. Evaluate different mitigating options for the prototype buildings to understand 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 understand how the limited different building geometries and mitigating building 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 exit access and to exit, are key components. Different building configurations (e.g., different occupant loads, travel distances, etc.) would yield different outcomes. It was agreed by TAG and by budget to limit this analysis to a single two-stairway reference building configuration.
- Quantify the risk achievement worth (RAW) to identify the critical systems and uncertainty to understand the risk distribution of the identified systems.
- 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 fire fighters, fire protection engineers, and housing advocates. Members of the TAG and a 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 shared significant insight during these discussions, summarized as follows:

1. The Consultants presented the RIA as outlined above at the first TAG meeting. The TAG and the Consultants concurred on the RIA that uses event trees to calculate the 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.
    a. 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:
    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 building (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 eight units per level. This is identified as "Building 4" in this report.

    The building geometries used in this study are summarized in Table 1. 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 within this report for the RIA and received commentary from TAG, ultimately resulting in the buildings' "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 No.	Building Type	No. of Levels	Floor Area per Level (sf)	No. of Units per Level	No. of Exit Stairs	Occupants Per Level
1	MBC Code-Compliant	8[A]	40,625	No Limit	2	204
2	MBC Code-Compliant	4[B]	4,000	4	1	20
3	Prototype	8[A]	6,000	8	1	30
4	Prototype	8[A]	4,000	4	1	20

[A] Seven levels above grade and one basement level

[B] Three levels above grade plane and one basement level

DATA SUMMARY

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

- The death rate of fires in single-family homes is approximately 6 times higher than the fatality rate of occupants in multi-family residential buildings built in the year 2000 or later. [41]
- Approximately 50% of MFD fires start in the kitchen; however, fires that start in the living room or bedroom are responsible for most civilian MFD fatalities.[42]
- 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.[43]
- Within the state of Minnesota, approximately 1% 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% of these fire events involved a single fatality. All of the multi-fatality fire events occurred in non-sprinklered buildings. [44]
- 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 stairs.[45]
- Fires in common egress pathways like corridors and stairways have not resulted in civilian fatalities in the State of Minnesota between 2004 - 2024.[46]
- The following sprinkler system reliability data used in this study were determined based on the MFIRS fire event database for MFDs between 2004 and 2024:[47]
  - 42% 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% of the reported fire events in MFD that were protected throughout by an automatic sprinkler system.
  - When the sprinkler system flowed on demand, the system successfully controlled the fire in 98% of the events, resulting in an operational reliability of 86%.
- 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.[48] 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 models in this analysis are provided in the Fire Scenarios section of the 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 7 stories above the grade plane but may include up to 8 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 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)
- 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

While not included in the appended code summary, the following codes and standards were also referenced in the preparation of this document:

- International Fire Code, 2024 Edition (IFC)
- Minnesota State Fire Code, 2020 Edition (MFC), based on the 2018 International Fire Code
- Seattle Fire Code, 2021 Edition (SFC), based on the 2021 International Fire Code
- 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 and are summarized herein. 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 a minimum width not less than 36 inches (IBC, MBC, SBC Sections 1005.3.1 and 1011.2, NFPA 101 7.2.2.2.1.2 and 7.3.3.1). Stairways serving less than 50 occupants are allowed to have a minimum width not less than 36 inches (IBC, SBC 1005.3.2 and 1020.3, MBC 1005.3.2 and 1020.3, NFPA 101 30.2.3.3 and 30.2.3.4).

The following paragraphs are a summary of the major criteria affecting single-exit stairway MFDs. A more detailed summary is provided in Appendix E and includes specific code sections and language relevant to the construction and design of multi-family residential buildings having only one exit.

Single-Exit Stairway Building Criteria

Minesota Building Code and International Building Code

Both the Minnesota Building Code (MBC) and the International Building Code (IBC) currently allow a single exit from a story of a MFD building where the story: is the basement, or the first, second, or third story above grade plane; does not contain more than 4 dwelling units; and, has a maximum exit access travel distance of 125 feet (MBC 1006.3.3 and IBC 1006.3.4). The IBC also allows an occupiable roof above the first or second story above grade plane to have a single exit per the same limitations (IBC 1006.3.4). Single exits are allowed from a story of a MFD building with sleeping units where the story: is the first above or below grade plane; has a maximum occupant load not exceeding 10 people; and, has a maximum exit access travel distance of 75 feet (MBC 1006.3.3 and IBC 1006.3.4). The IBC also allows an occupiable roof over the first story above grade plane (IBC 1006.3.4). The above provisions are given the fact that the MBC and IBC require the MFD buildings to be sprinklered.

Corridor walls are required to be 1-hour fire resistance rated they unless meet requirements of MBC Table 1020.1 where they are allowed to be ½-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 ½-hour fire resistance rating if protected with an automatic sprinkler system (MBC 708.3).

NFPA Life Safety Code

The NFPA Life Safety Code (NFPA 101) has similar requirements to the IBC regarding single exits from buildings. A building is allowed to have a single exit where the total number of stories does not exceed four, there are not more than four dwelling units per story, and the building is equipped throughout with a sprinkler system designed in accordance with NFPA 13. In addition, the exit travel distance from a dwelling unit entrance door to an exit door is required not to exceed 35 feet, the exit stairway (including opening protections) 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 (NFPA 101 30.2.4.6).

Seattle Building Code

The Seattle Building Code (SBC) was recently amended to promote greater use of single-exit MFD buildings. The SBC has similar single-exit stairway allowances as the IBC but includes additional allowances specific to MFD buildings. Not more than 5 stories of a MFD building are allowed to be served by a single exit where the building has not more than six stories above grade plane, not more than four dwelling units per floor, the building structure has not less than 1-hour fire resistive rated construction, is equipped throughout with an NFPA 13 sprinkler system, and the stairway is pressurized (SBC 1006.3.4). If an elevator is provided, the elevator hoistway is also to be pressurized unless it opens into a rated elevator lobby (SBC 1006.3.4).

Proposed Building Code Changes

A number of jurisdictions are considering amendments to their building codes to include additional allowances for single-exit stairway MFD buildings. A change has been proposed to the model IBC that would allow MFD buildings up to six stories in height to have a single-exit stairway. The proposed change would require buildings to be of Types I, IIA, or IV construction, have 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 stairway enclosure. The stairway enclosure would also be required to be a smokeproof enclosure (IBC Proposed Change E24-24).

Proposed changes were also considered by the local authorities in Dallas, TX and in the State of Colorado. Changes were proposed to the Dallas Residential Code (DRC) that would allow MFD buildings to have up to eight total dwelling units and up to four dwelling units per story and up to four dwelling units per floor and be regulated by the DRC which typically allows buildings to have a single means of egress. The Colorado General Assembly recently passed HB24-1239 which requires the 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.

Property Maintenance

Minnesota does not have a state-wide property maintenance code that addresses the periodic inspection, testing and maintenance of buildings' fire protection features and systems. Rather, many cities and counties adopt an edition of the International Property Maintenance Code as part of their local ordinances. Adoption and enforcement of property maintenance provisions are needed to assure a high degree of function and effectiveness of passive features and active fire protection systems. 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 is 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 sprinkler systems through, among other things, the omission of sprinklers in certain low-hazard, non-living spaces which reduced the installation and maintenance costs of such systems.

Unless modified by local amendments, 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). The MBC, SBC, and NFPA 101 allow NFPA 13R systems where the building has not more than four stories and a maximum height of 60 feet (MBC 903.3.1.2, SBC 9.3.3.1.3.2, NFPA 101 30.3.5.1.2).

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 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 fire 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.[49] 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 along with additional information about the fire model. Additionally, in reviewing news articles[50] about other fires in the U.S. 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.[51] 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.[52] 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 relayed on an e-bike fire based on commentary from 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.[53] This research focused specifically on e-bikes and their fire behavior. This test indicates that the peak heat release rate was approximately 900 kW.[54]

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:

1. No building can be designed to be completely risk-free. For example, building codes and standards in the U.S. 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 apartment of fire origin who are intimate with the fire are outside of the scope of this analysis.
2. 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.

3. 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 for evacuation is provided outside the dwelling unit of fire origin.
4. Regulatory decision-making for buildings is focused on societal risk – not individual risk. As such, the risk metric is based on comparing the risks of limited 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 predicted 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 floor of fire origin; and,
   c. If a door to an exit stairway from the corridor on the floor of origin is opened and smoke enters the exit stairway, 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 is further acknowledged in meetings with TAG that although this analysis identifies building occupants who may be at-risk 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 is outside the scope of this study.

Fire And Egress Modeling

Fire Dynamics Simulator (FDS) was selected for the fire modeling analysis. FDS is a computational fluid dynamics (CFD) software developed by NIST that models fire-driven fluid flow. FDS has the ability to simulate actual fire conditions where the smoke layer naturally varies in height as it moves away from the fire plume. See Appendix F for the details of the fire modeling.

Following the description of consequence in the above section and fire scenario selection, the results of the FDS fire modeling for the building geometries are summarized in **Table 2Table 2**. The visibility tenability limit was reached first and that time is shown in the Table 2.

Table 2. Estimated Tenability in Corridor on the Fire Floor

Item	Building No.	Fire Origin	Stairway Door Position	Corridor [Stairway] Floor Above} Tenability Time (Minutes)
1	Building 1	Dwelling unit in front of stairway	Closed	~10
2	Building 1	Dwelling unit in front of stairway	Open	~10 [~3]
3	Building 1	Dwelling unit in center of building	Closed	~5
4	Building 1	Dwelling unit in front of stairway	Open {Open on Floor above Fire Floor}	~10 [~3] {~16}
5	Building 1	Corridor	Closed	~1.5
6	Building 2/4	Dwelling unit	Closed	~2.5
7	Building 2/4	Dwelling unit	Open	~2.5 [~3]
8	Building 2/4	Corridor	Closed	~0.5
9	Building 3	Dwelling unit	Closed	~2.5
10	Building 3	Dwelling unit	Open	~2.5 [~3]
11	Building 3	Corridor	Closed	~0.5

Notes: (1) For dwelling unit fire location, the door between the corridor and the dwelling unit of fire origin was modeled in the open position,120 seconds after fire ignition. (2) For the corridor fire location, the doors between the corridor and the dwelling units were modeled in the closed position.

The time for an occupant to exit a building includes multiple steps that are more than just the movement time, as defined by the SFPE Handbook. In summary, these are: detection time, pre-movement time and movement time as the three major components in egress time. See Appendix G for a more detailed discussion. Detection time is the time to detect a fire and provide a notification signal to the occupants; pre-movement time is the time from notification to the time an occupant begins to egress, and movement time is the time it takes to actually travel to a defined exit or a place of refuge. For our report the movement time is the actual travel time to discharge from the building, as supported by TAG.

Egress modeling was conducted with Pathfinder,[55] a modeling software that simulates egress from buildings. The egress modeling considered egress time from the two-exit stairway building and the single-exit stairway buildings. The egress modeling was conducted using the floor plans of the four building geometries to identify movement time as one of the components of the egress time. Modeling was also used to consider the effect of a wider, 48-inch stairway in the single-exit stairway prototype buildings to determine movement time for occupants as well as the case of cross-flow, i.e., occupants egressing at the same time firefighters are using the stairway to access the fire floor for rescue and firefighting. The results of the egress modeling are shown in Appendix H.

Table 3Table 3 identifies a movement time for these buildings, acknowledging that some occupants may take longer or may not be able to egress at all on their own, depending on multiple variables. However, in reviewing the literature, the variation in pre-movement time for occupants in residential occupancies is due in part to people potentially sleeping when alarm notification occurs, and the potential need to locate others prior to starting evacuation. As such, the pre-movement time of a mid-rise residential building varies widely from as little as one minute to as long as about nineteen minutes, with the mean for the four reported events[56] ranging from two and one-half minutes to just under ten minutes.

With such varying and lengthy pre-movement times compared to the time for the corridor to become untenable, the identification of the consequences for this comparative assessment was simplified to be those occupants who would be impacted by untenable corridor conditions per the FDS analysis (available safe egress time) if the pre-movement time of 9.7 minutes[57] plus movement time from the fire floor, was greater than the estimated time for the corridor to become untenable. See Appendix G for more information. This is the case regardless of whether the building has one or two exits.

As such, the value of the fire modeling was to show the relatively short time for the corridor on the fire floor to become untenable if the sprinkler system fails to operate and the door to the dwelling unit of fire origin is left open.

Furthermore, 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. For context, the total occupant load of the prototype building is less than that of a single floor of the two-exit building. The marginal increase in width has no effect on movement time in the two prototype buildings under normal conditions. However, when evaluating the wider stairway's effect on cross-flow, when occupants are egressing and firefighters are simultaneously using the same stairway, the increased width does not have an impact in the model, 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 cross-flow does not consider obstructions on the stairs such as hoses. This is shown in **Table 3**.

Table 3. Summary of Egress Modeled Estimated Movement Times[1]

Building	Stairway Width (In.)	Movement Time: Fire Floor Only (Min.)	Movement Time: Building Discharge (Min.)	Movement Time: Building Discharge with Cross Flow (Min.)
1	44	5-7	16	NA
2	44	0.5	2.5	NA
3	44	0.5-1	5	7.5
3	48	0.5-1	5	7.5
4	44	0.5	3.5	5
4	48	0.5	3.5	5

1. Modeling results are a summary of approximate movement times for occupants to discharge from the building using average movement speeds.

"NA" indicates that the scenario was not modeled as it was not the subject of this report as confirmed by TAG.

Conditional Fire Event

The Consultants define risk as a combination of the probability of an event occurrence and 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; that is, to evaluate the 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 comparative approach used to benchmark the code-compliant MFD buildings and the prototype MFD buildings.

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 calculates 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 (up branch) or fail (down 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.[58] 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 risk. This allows a user to better understand the risk-significant scenarios and propose measures to mitigate the risk.

The Consultants developed an event tree to predict the likelihood of different end states of a fire event in an MFD using the mean probabilities (Figure 1)**Figure 1**. The event tree is applicable to fire scenarios within the dwelling unit or in the corridor for both single-exit stairway and multi-exit stairway buildings.

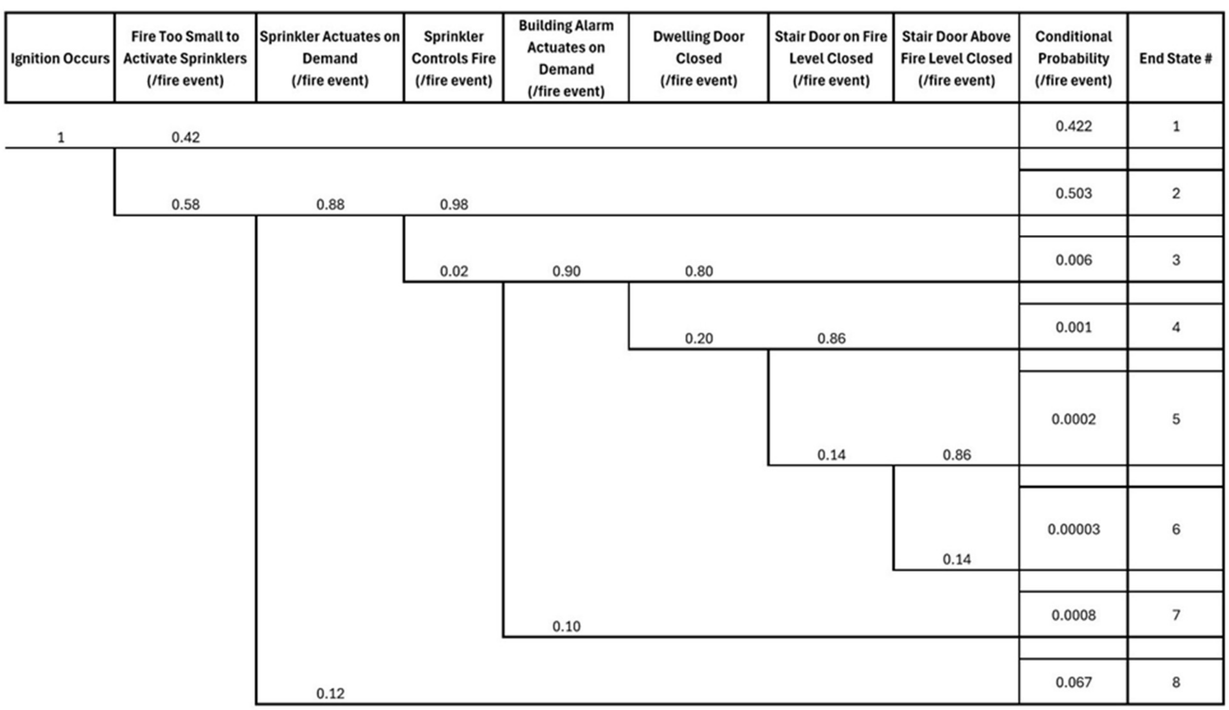


Figure 1. Event Tree

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 modeling to predict 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. 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 successfully controls the fire. 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 actuates and the door to the dwelling unit where the fire originated is closed. 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 fails to control the fire. The building fire alarm actuates and 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 can make the decision to evacuate. The occupants on the floor where the fire originated fail to evacuate.

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

End State 5

The fire is large enough to activate the sprinkler system, which activates on demand. The sprinkler fails to control the fire. The building fire alarm actuates and 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 both egress pathways untenable before occupants can make the decision to evacuate. All 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 predict the number of occupants on the floor where the fire occurred who can evacuate before the corridor becomes untenable. Occupants on other floors evacuate using the unaffected exit stairway.

End State 6

The fire is large enough to activate the sprinkler system, which activates on demand. The sprinkler fails to control the fire. The building fire alarm actuates and 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 both egress pathways untenable before occupants can make the decision to evacuate. All 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 predict the number of occupants on the floor where the fire occurred and the floor above where the fire occurred who evacuate before the corridors become untenable. Occupants on other floors evacuate using the unaffected stairway.

End State 7

The fire is large enough to activate the sprinkler system, which activates on demand. The sprinkler fails to control the fire. The building fire alarm 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 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 Results

This section reports the comparative results for the dwelling unit and corridor fire scenarios in each of the four MFD building geometries. **Table 4** provides the predicted risk for each building configuration as defined within. **Figure 2 Error! Reference source not found.**and **Figure 3** visually depict this information from fires that start in the dwelling and the corridor, respectively. The risk is framed as conditional upon a fire occurring and is, therefore, not based on a unit of time.

Table 4. Impacted Occupants from Comparative Risk-Informed Approach

Building 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
					Corridor	110
2	1	4	4,000	20	Dwelling Unit	5.1
					Corridor	5.6
3	1	8	6,000	30	Dwelling Unit	15.9
					Corridor	16.5
4	1	8	4,000	20	Dwelling Unit	10.5
					Corridor	11.0

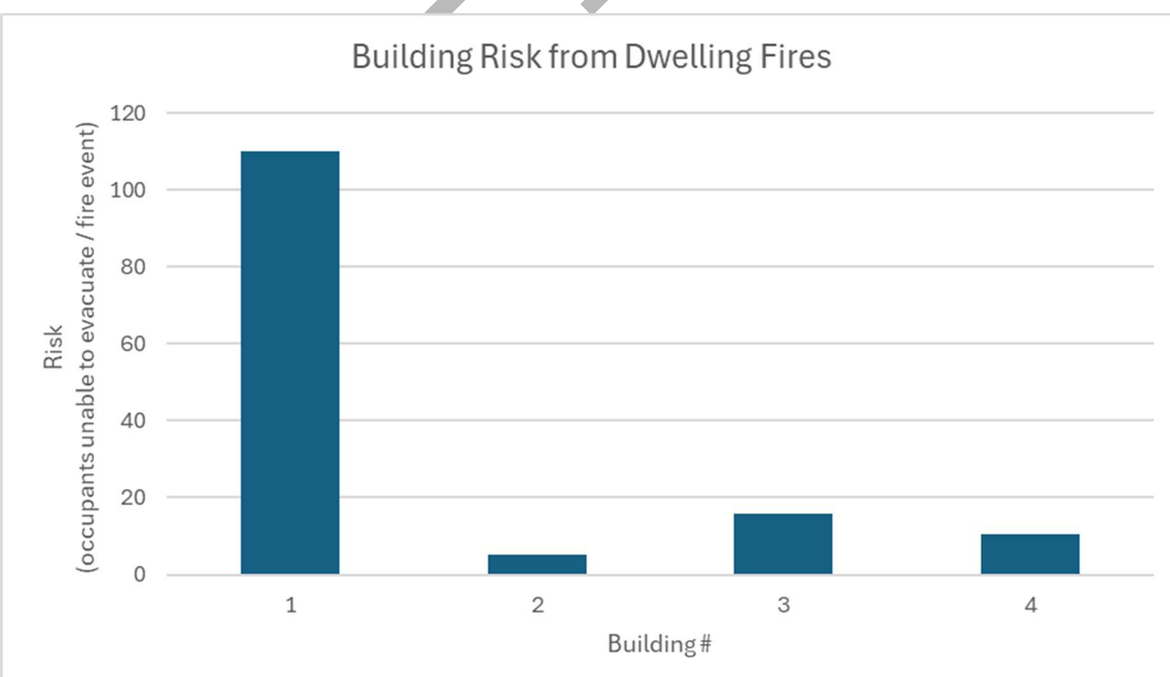


Figure 2. Risk of Code-Compliant and Prototype MFDs for Dwelling Unit Fires

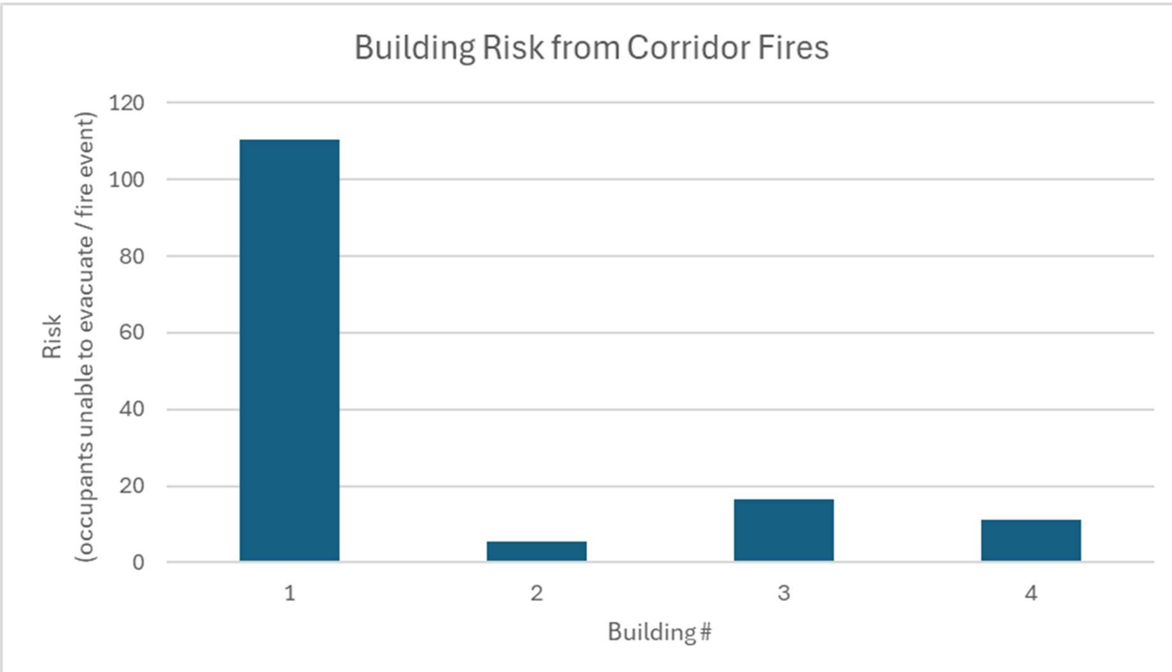


Figure 3. Risk of Code-Compliant and Prototype MFDs for Corridor Fires

Error! Reference source not found. These results indicate that the risk of prototype Buildings 3 and 4 is significantly lower than the risk results of Building 1. This can be attributed to the significantly larger number of occupants in Building 1 who never receive the cue to evacuate upon the sprinkler system failing to flow on demand.

The risk of Building 3 and Building 4 is a factor of 3 and a factor of 2 higher, respectively, compared to the Building 2 risk. This is also due to the larger occupant loads in the prototype Building 3 and Building 4 having a higher number of occupants unaware that never receive the cue to evacuate after upon the failure of the sprinkler system fails to flow on demand.

This data provides critical insight to the value of the sprinkler system to 1) suppress and control the fire and 2) activate the building-wide fire alarm system to cue occupant evacuation.

POTENTIAL ENHANCEMENTS

An analysis of potential mitigating systems was conducted to reduce the risk of the prototype single-exit stairway MFDs so that it is comparable to or lower than the 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 a 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 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 the smoke detector reliability, the Consultants reviewed the National Fire Sprinkler Association fire event data in multi-family residential dwellings from 2014 to 2023 and selected all 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 in Figure 1 to incorporate the logic for the common means of egress smoke detectors. **Figure 4** and **Figure 5** compare the risk of fires that originate in the dwelling and the corridor, respectively, by adding the common area smoke detection system to the prototype MFDs.

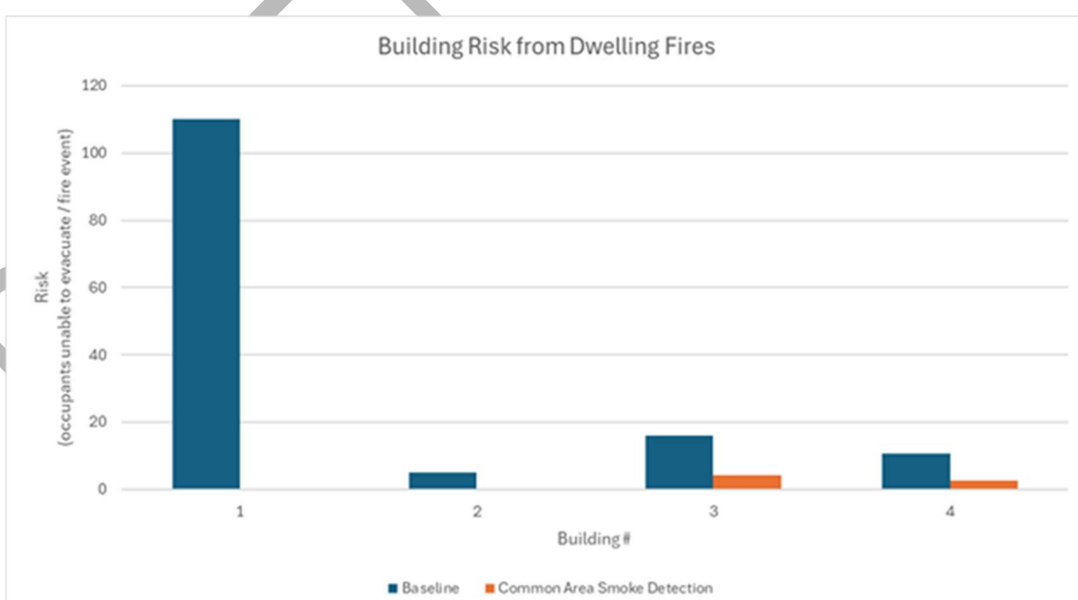


Figure 4. Change in Risk for Dwelling Fires by Adding Common Area Smoke Detection to Prototype MFDs

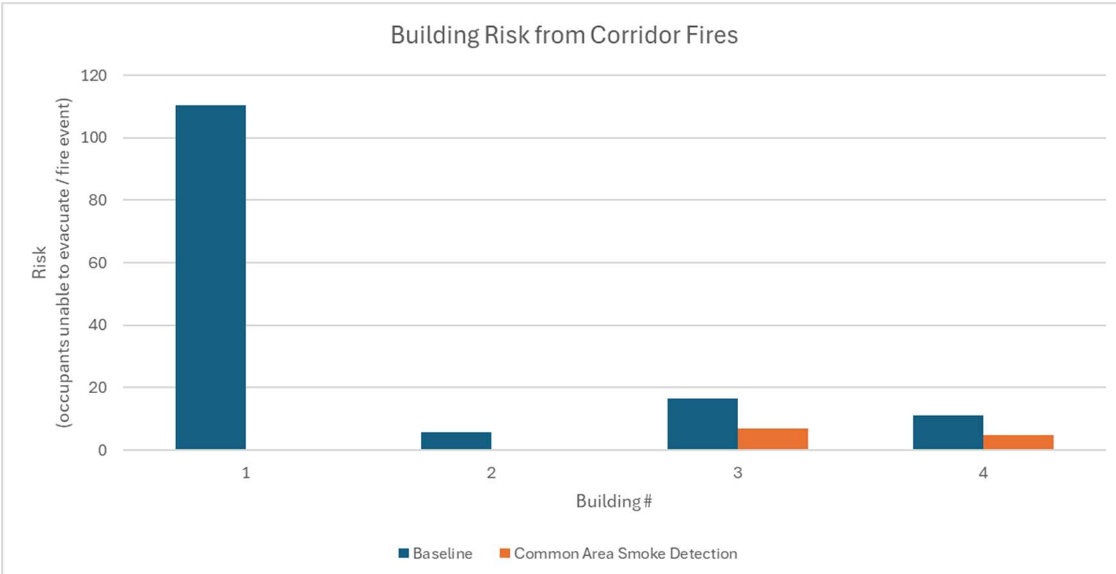


Figure 5. Change in Risk for Corridor Fires by Adding Common Area Smoke Detection to Prototype MFDs.

The addition of smoke detectors in the common means of egress to the prototype building design reduces the risk of the prototype buildings below the code-compliant building risk for each prototype building with the exception of the Building 3 corridor fire scenario. Most important, adding common area smoke detectors reduces the comparative risk of prototype Buildings 3 and 4 below the risk of Building 2 for dwelling unit fires, the most common and lethal type of fire in MFDs. Additionally, the burden 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 small, typically requiring only a smoke detector within each corridor.

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 risk to 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% (the average reliability calculated based on the MFIRS data) to 96% through more rigorous testing and maintenance programs, the risk of the prototype single-exit stairway MFDs can be reduced to a risk similar of the currently code-compliant single-exit stairway MFD.

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.

Additional Considerations

The Consultants considered various other enhanced building features for incorporation into the minimum criteria for single-exit stairway prototype buildings to provide a level of safety equivalent to or better than that provided by currently code-compliant buildings. Some of the enhancements were suggested by TAG, some were included in other codes' requirements for single-exit stairway buildings, and others were identified as a result of the Consultants' experience.

Considerations associated with each of these potential protection enhancements as mitigating 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 delay time and 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 Consultants could not quantitatively evaluate the impact of voice alarm system performance in MFDs.
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 allowed to be constructed per the MBC up to three stories in height using combustible construction with the structural elements having a zero fire resistance rating. The required fire resistance rating for the structural frame increases to one-hour for buildings up to 4 stories in height when of combustible construction, and then 5 stories when the building is of a combination of noncombustible and combustible elements, with the fire resistance ratings of zero or one hour. Buildings greater than 5 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 12 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 criteria require a degree of fire resistance for dwelling unit separations. (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 such that, when fully consumed in an uncontrolled fire, the fuel load would have an effect on the structure equivalent to about a one-hour fire exposure in a standard time-temperature fire test.

The MBC allows a reduction in fire resistance ratings for dwelling unit separations, corridor walls and floor construction in sprinklered buildings, recognizing the record of performance 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 ½-hour (MBC Sections 1020.1 and 708.3).

The building's structural elements and fire barriers are relied upon for a defend-in-place strategy. The fire resistance ratings specified for the fire barriers in the various types 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 short egress time for occupants to evacuate a low-rise building under normal circumstances; and the enhanced features recommended in this report.

In conclusion, the Consultants recommend that the maximum building height of a single-stairway MFD comply with the heights in MBC Table 504.3 for Group R occupancies. Similarly, the Consultants could not quantitatively evaluate the impact of 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[59] stated that the building was not sprinklered 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. 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 remote from one another. However, the Consultants noted that the comparative risk benefit will be relatively small (up to an approximately two percent reduction) because: (1) the single-exit stairway corridor is so small that it will quickly fill up with smoke and obscure the access to either exit; and, (2) the sprinkler system failing 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 high-rise buildings either be designed as smokeproof enclosures or be pressurized as a means to limit smoke spread into the enclosures, and that the building also has a method for the post-fire removal of smoke.

   The efficacy of smoke control provided by stairway pressurization systems is highly dependent on balancing the number of doors assumed to be open and pressure requirements. 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 risk is acceptable. If the sprinkler system is not functional, it is unlikely that the design of a stairway pressurization system would be effective in limiting smoke spread from an uncontrolled fire. The Consultants do not expect that a stairway pressurization system would have a significant risk impact in these low-rise MFD buildings.

5. **48-inch Wide Stairway**. Discussions occurred with TAG to evaluate 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. The wider stairway's effect on cross-flow, when occupants are egressing and firefighters are simultaneously using the same stairway, does not have a material impact in the modeled case, 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 cross-flow does not consider obstructions on the stairs such as hoses or fire service staging. In summary, the Consultants do not find adequate substantiation for increasing the minimum stairway width to 48 inches.

Risk Achievement Worth (RAW)

Risk achievement worth (RAW) calculates the risk impact of different mitigating systems assumed to be unavailable [46]. The ratio of the risk values indicates the relative importance of that system (Equation 1). This helps identify the systems having large impacts on reducing 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 5 provides the RAW factors for each scenario for which reliable data are available on fire safety system performance. The table clearly shows that the sprinkler system is the single-most risk-significant feature according to the RAW factors across all building geometries. 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 5. 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

Uncertainty

Uncertainty is an important metric in risk studies as it reports the confidence of the results. This report used a Monte Carlo analysis to sample the event tree 10,000 times over the top event 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 sampling beyond 10,000 in the Monte Carlo study did not change the uncertainty by more than 1%. Table 6**Table 6Table 6** shows the results of the uncertainty study.

Table 6. Monte Carlo Distribution of the Comparative Risk Uncertainty

Building 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. Appendix I shows the uncertainty distributions for the dwelling unit and corridor fire scenarios in each of the four building geometries.

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 sound fire protection principles. The RIA evaluates code-complying MFDs to define a benchmark risk. That same RIA was then applied to determine the risk of prototype single exit stairway MFD buildings up to 75 feet in height. Where the risk of the prototype MFD exceeds the benchmark, additional mitigating measures are identified to reduce the risk of the prototype to equal to or less than the benchmark buildings currently allowed by the MBC.

The outcomes from this comparative assessment do not reflect absolute metrics for predicting 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 metric in this report is based on comparing the risk of different building geometries to one another and the associated features and systems within, not the individual risk of occupants within a building. 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 risk associated with different MFD geometries and fire protection features. Evaluation of various mitigation options for the prototype buildings to understand the 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.
- Presentation 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 diverse 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 risk of the prototype single-exit stairway MFDs (Building 3 and Building 4) 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%. If this reliability can be increased to approximately 96%, 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 MFD compliant with the MBC having the observed sprinkler system reliability.
3. A properly operating automatic sprinkler system provides the most significant comparative risk reduction impact.
4. The number of exit stairways factors into the risk calculation 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 risk profile (estimated to be 0.02% for fires that start in dwelling units, and 0.09% 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% of the risk for each 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 fire fighters. 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 can make the decision to evacuate, affecting all occupants on the floor where the fire occurred. Thus, reliable door closers are important fire risk mitigation measures.

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 make the decision to evacuate. In this scenario, all occupants in the single-exit stairway building fail to evacuate. However, occupants in multiple-exit stairway MFD 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 mitigating measures where the risk of the prototype MFD exceeded the baseline risk using the event tree. While many 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 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

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 does 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 does 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[60,61] and is one reason that the UL FSRI has developed the new National Emergency Response Information System (NERIS) system for fire data reporting. 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 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 RIA of this type.

RECOMMENDATIONS

Consistent with the stated purpose of this study, recommendations have been developed to reduce the 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. The recommendations are based upon the RIA to identify features that significantly impact the risk.

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

Providing smoke detectors in common egress areas, such as corridors, in MFDs that are sprinklered throughout provides a diverse 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 risk of the prototype single-exit stairway MFDs (Building 3 and Building 4) 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 three stories tall.

Create 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%. If this reliability can be increased to approximately 96%, 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 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, and that doors are not propped open. The risk-significance of the dwelling unit and exit stairway doors will rise as the sprinkler system reliability increases.

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, Sec. 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 75 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 Fire Chiefs Association, Minnesota Professional Firefighters 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

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 safety requirements. This method has since evolved and has become known as the "Systems Approach" to fire safety analysis.

The National Fire Protection Association "Committee on Systems Concepts" has developed a similar version of the GSA systems approach 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 safety 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 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 safety goals for the building.

There are two primary ways to use the Fire Safety Concepts Tree. One approach includes developing the mathematical probability of success in reaching agreed upon numerical probability goals. For example, it could be decided that the goal was 99.7% probability of success in having not more than one fire death per 100,000,000 hours of personnel exposure, or a 99.6% 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% probability of success in confining a fire to a work station, 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 safety system. 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.

The Fire Safety Concepts Tree can also be used in a subjective approach. In that case, the Fire Safety Concepts Tree is used as a method of organizing thoughts regarding the design or evaluation of fire safety. 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 all interested parties.

In the case of the single-exit stairway design, the Fire Safety Concepts Tree clearly demonstrates that the fire risk of a building does not depend upon a single feature, such as its means of egress. Fire risk depends upon a number of 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 the single-exit building analysis that identifies the various fire protection features of a building and their relationship to one another, showing how various fire protection features and combinations of features can work to achieve an objective (B1). Overall, the Systems Concept provides a powerful method and an organized approach to evaluating a building's level of fire risk against established performance objectives. This approach helped establish the comparative risk assessment used in this study.

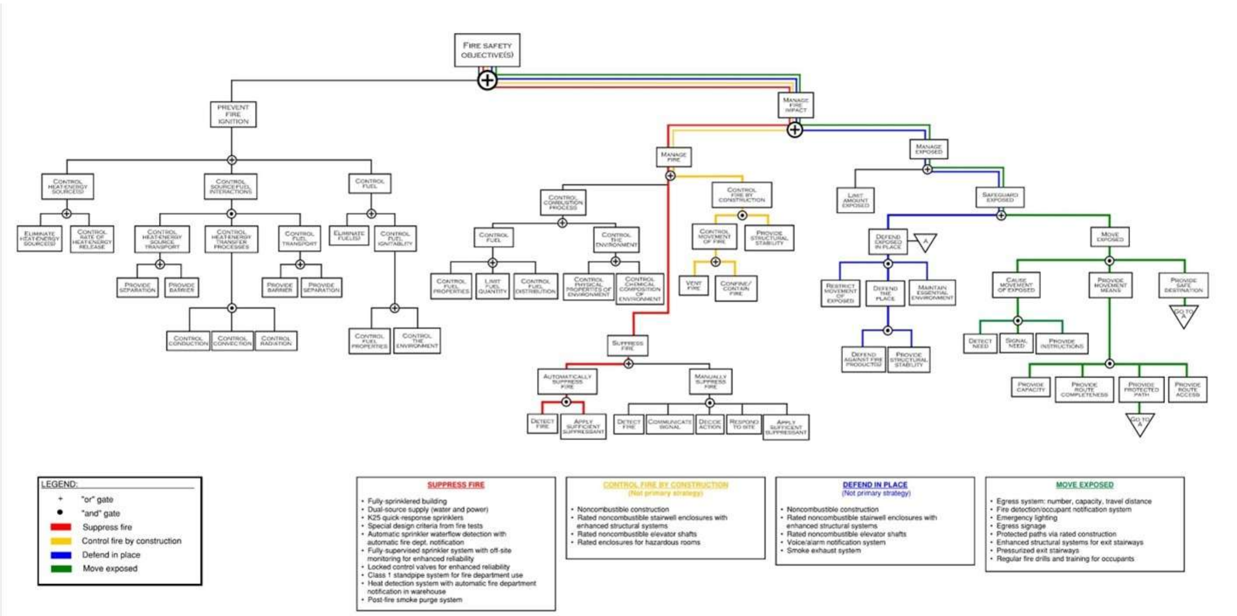


Figure B1. Guide to the Fire Safety Concept Tree with Notes Applicable to the Typical Single-Exit Stairway Building Configuration

Having a minimum of two means of egress from a building has been 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 safe egress. Yet, building codes have allowed limited circumstances where a single exit can provide a reasonable level of safety based upon factors such as building height and the number of building occupants at risk. Such determinations have been made on a consensus basis over many years by the fire safety community based upon subjective determinations of tolerable risk.

It should be noted that 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, as demonstrated by the fire record in the United States. This report, in fact, identifies several such scenarios where occupants may be exposed to a common atmosphere affecting an exit access corridor that provides access to multiple exits. The viability of building exits is affected by building geometry, fuel load, occupant density, the presence of automatic sprinklers, and other factors.

As stated in NFPA 550, one of the most important uses of NFPA 550 is for communication with professionals 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 B1 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 safety features in a building. It also shows how all building features work together as a system that provides for the fire safety 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 safety 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, we have presumed that an ignition has occurred and will, therefore, focus on the building's fire protection features related to "managing fire impact" which involves managing the fire and managing the exposed. The relationship of the means of egress to other major fire safety features can be clearly seen in Figure B1 from 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 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 safety 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 B1), 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 size. 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.

A "Manage-by-Construction" issue relates to the walls between the dwelling units and walls and doors between the dwelling units and the corridors. The MBC presently requires a minimum one-half hour construction between dwelling units and common corridors serving more than 10 occupants in new, sprinklered multi-family residential construction. Such separations can be compromised if doors are left open. If we consider fire history, the introduction of self-closing doors on sleeping rooms over the last 40 years has reduced fatalities in this occupancy by a considerable degree, yet we must consider such a scenario in our analyses. 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 all of these elements. Of greatest concern with respect to life safety are smoke and gases.

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 safety 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 facility 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 safety ramifications, particularly if the areas contain a large amount 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 safety 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 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 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 fire is controlled by automatic suppression, the red line on Figure B1 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. That is also how one can view the reduction in the number of means of egress under limited circumstances.

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 has been no multiple loss of life reported in fully-sprinklered buildings where occupants were not intimate with the fire.

The high degree of reliable performance is partially due to the electrical supervision 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 sprinkler system impairment, such as a closed valve. Improperly closed valves account for the largest portion of the unsatisfactory sprinkler performance.

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, etc., can also be electrically monitored to further assure the operability of the sprinkler system. An analysis of the reliance placed upon the sprinkler system to accomplish fire safety goals will dictate the relative degree of reliability necessary for the sprinkler system.

The Consultants 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 assure 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, fire safety can be accomplished by taking measures to "Manage the Exposed" rather than to "Manage the Fire." This refers to protection of people and/or valuable contents. Again, a number of choices are involved including the limiting of the amount exposed (control of the number of occupants), as previously discussed, 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 rated construction. (See the blue line on Figure B1). 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 B1). 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 movement. An automatic fire alarm system is the normal 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, exit travel distance to an exit and redundancy. Exit capacity relates to having adequate width of doors and stairways for the population 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 on each floor (with some exceptions) and the physical separation of the exits to reduce the probability that a single incident will not 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 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

This study is based upon a sprinkler system of 86% as described in the Event Tree. 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.[62] 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[63] where all systems were required to be electronically supervised and monitored off-site by third parties.

According to Johansson [include reference (2003)], a study of sprinkler system reliability in the U.S. indicated a reliability of 98.5 percent. Arvidsson and Hult [include this reference] (2006) found that the probability of a sprinkler system extinguishing a fire was 96 percent, and that the probability of an unextinguished fire being controlled was 50 percent. Taken in combination, that means the probability of a fire being either extinguished or controlled is 98 percent.

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% of the time and were 96% effective, resulting in a combined operational performance of 91%.[64]

NFPA (Ahrens 2017) provides statistical data that, at first glance, look less promising. According to this study of sprinkler system effectiveness over several years, systems were effective 88 percent of the time (Figure B2). As reported in that document, sprinkler systems either failed to operate or they operated ineffectively 12 percent of the time.

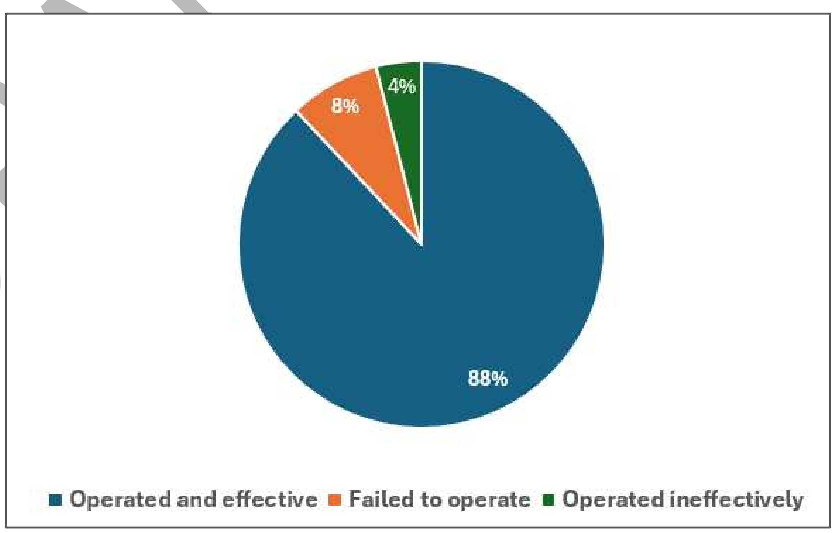


Figure B2. Sprinkler system operation and effectiveness (Ahrens)

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%). 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%). Obstructions to sprinkler water reaching the fire can be minimized by proper system design and regular system inspections.

Reason 3: Manual intervention (13%). 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%). The sprinkler system density and site water supply are to be designed for the hazard; it is unlikely that the nature of the combustibles in a residential environment will materially change over time.

Reason 5: Lack of maintenance (8%). The 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%). 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% [0.07 x 0.12 = 0.0084]. The resulting reliability is 99.1 percent. An appropriate evaluation of the NFPA (Ahrens 2017) 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.

Nevertheless, the reliability used for this analysis is 86 percent [0.88 x 0.98].

APPENDIX C – TECHNICAL ADVISORY GROUP AND SUMMARY OF COMMENTS

As part of the project, the State of Minnesota 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 Consultants appreciate the time, effort and dedication of the TAG Members in the interest of public safety.

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 Firefighter's Association
Nick Erickson	Housing Development Advocate	Housing First Minnesota
Patrick Farrens	Fire Chief/Tactical Analysis	Minnesota Fire Chiefs Association
Jim Fisher	Fire Prevention Advocate	Governor's Council on Fire Prevention
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 Marshal's Association of Minnesota
Melisa Rodgiguez	Fire Protection Engineer	Governor's Council on Fire Prevention
David Selinsky	Licensed Professional Architect	Minnesota Chapter, American Institute of Architects

Name	Role	Organization
Stephen Smith	Advocate for Single-Exit Stairways	Center for Building in North America
Amanda Swanson	Chief Deputy State Fire Marshal	Minnesota DPS/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
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

TAG Comment Summary

A summary of the comments discussed at the TAG meetings is provided below, in no particular order.

- 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.
- 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.
- Data inconsistency and associated reliability were discussed and acknowledged, but the Consultants reviewed all data provided by TAG along with insights or caveats associated with such data.
- 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.
- For single-exit stairway buildings, the concepts of education and realistic expectations for defend-in-place strategies should be discussed and formally documented. Some of this is currently part of a larger human behavior discussion beyond the scope of the building code.
- Minnesota building departments are engaged and active, but some variability exists across the state in working with building owners in reporting, inspection and enforcement.
- 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. However, 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.
- In a single stairway design, the compartmentation integrity should have increasing importance.
- Egress width for stretcher maneuverability and potential elevator access should be considered in potential rule-making efforts.
- Flexibility in unit designs and sizes should not be limited in rule-making; 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, i.e., three plus bedrooms.
- Other jurisdictions have allowed various versions of single exit buildings, including Seattle and New York City.
- 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.
- 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 where injuries occur and impacts on the fire service. Ignition sources and fire spread data could be reviewed as well, where available.

- Inspection, testing, and maintenance records were discussed with common modes of failure addressed.
- 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.
- Human behavior related to egress during a fire event should be discussed, although it is acknowledged that the building code does not explicitly address human behavior.
- Appropriate context to the data from NFPA, Appendix D and other sources is important to note to frame conclusions within the context of the data.
- The use of emergency escape and rescue openings and other means 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 and large areas of coverage.
- Inspection, testing and maintenance for both active and passive protection systems currently has a large variation in enforcement, but this should be standardized to increase compliance for important systems.
- Construction type and fire resistance ratings of compartmentation walls were acknowledged as being reviewed but were viewed as being adequately addressed by the current building code and are acceptable at this time.
- Accessibility requirements are not part of this study, but with the importance of the issues the potential for various egress requirements are reviewed.

APPENDIX D – DATA AND FIGURES

National Fire Protection Association

The National Fire Protection Association (NFPA) is an organization that performs fire event research, publishes standards, and provides information to the public regarding fire safety. NFPA Research published findings from data collected on residential home fires, including 1- or 2-family dwellings as well as apartments (see Figure D1). Fire events are much more common in 1- or 2-family homes compared to multi-family dwellings, 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.

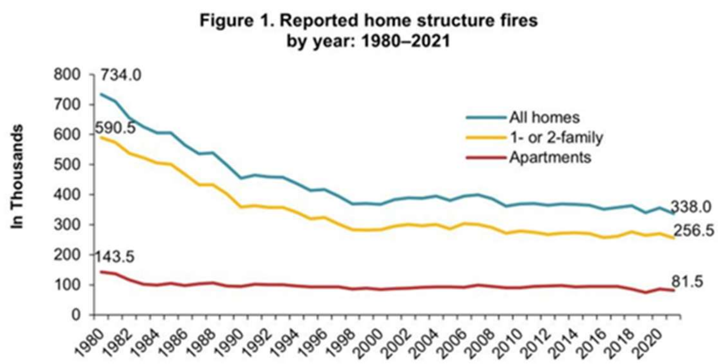


Figure D1. Reported home structure fires by year: 1980-2021[65]

To supplement this data, a study by Pew Charitable Trusts titled "Modern Multifamily Buildings Provide the Most Fire Protection" evaluated the death rates of single-family homes, MFD built 1999 or earlier, and MFD built 200 or later. Figure D2 illustrates the significant reduction in annual death rates for MFD constructed in the year 2000 or later, signifying safety advancements in the U.S. building codes for multi-family housing.

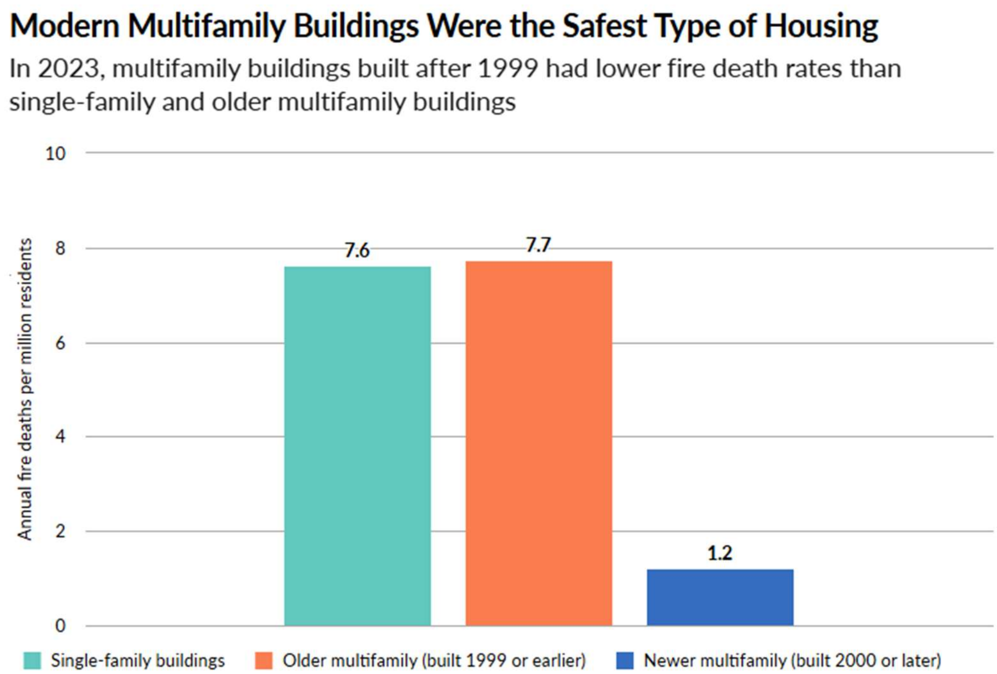


Figure D2. Annual Death Rates of Single-Family versus Multi-Family Dwellings[66]

NFPA also published home fire deaths by area of fire origin by year. (Figure D3) These data are not separated by residential building type, e.g., single-family, multi-family, etc. Fires that start in the living room and bedroom are responsible for approximately three times as many annual deaths compared to kitchen fires from 2000 - 2020.

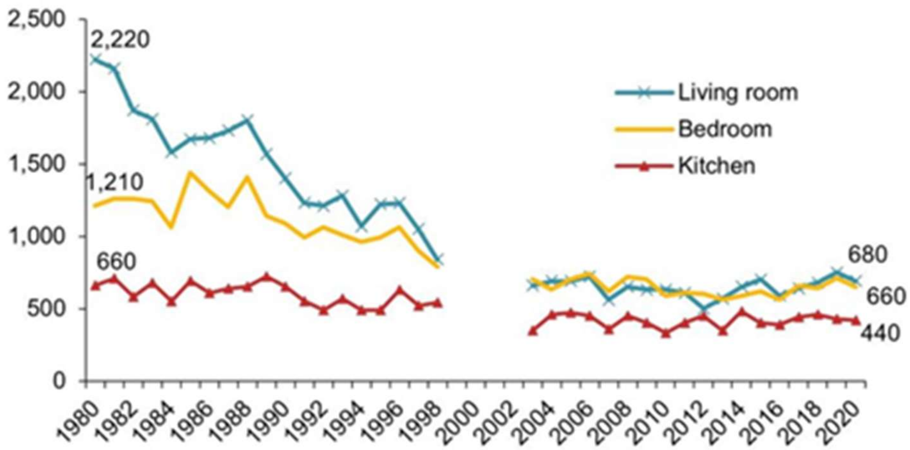


Figure D3. Home fire deaths by area of fire origin and year: 1980-2020[67]

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 death rates, fires by area of origin, item first ignited, extend of flame spread, civilian deaths in by sprinkler presence, and civilian deaths by detection presence. Much of this data were categorized by MFD 1-3 stories, 4 – 6 stories, and 7+ stories. The objective of reviewing this data set is to better understand trends causing civilian deaths 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 and onwards.

The data produced some valuable insights. Figure D4 shows that most civilian deaths occur in non-sprinklered buildings up to 3 stories: on average, 88% of civilian deaths occurred in non-sprinklered MFDs up to 3 stories from 2004 - 2023. Only 2% of the deaths occurred for the same period in sprinklered MFDs up to 3 stories. The Minnesota Building Code (MBC) allows MFD buildings up to 3 stories to have a single stairway. Although the stairway count was not part of the data set, the impact of sprinklers to reduce civilian fatalities in MFDs where a single stairway is permitted is significant.

Additionally, Figure D5 shows that deaths in sprinklered buildings are uncommon events: the average number of annual civilian deaths in the USA in sprinklered 1 – 3 story, 4 – 6 story, and 7+ story MFD are 9.3, 4.5, and 7.0 deaths, respectively. Comparatively, the number of annual civilian deaths in the USA in non-sprinklered 1 – 3 story, 4 – 6 story, and 7+ story MFD are 483, 23.9, and 18.6 deaths, respectively.

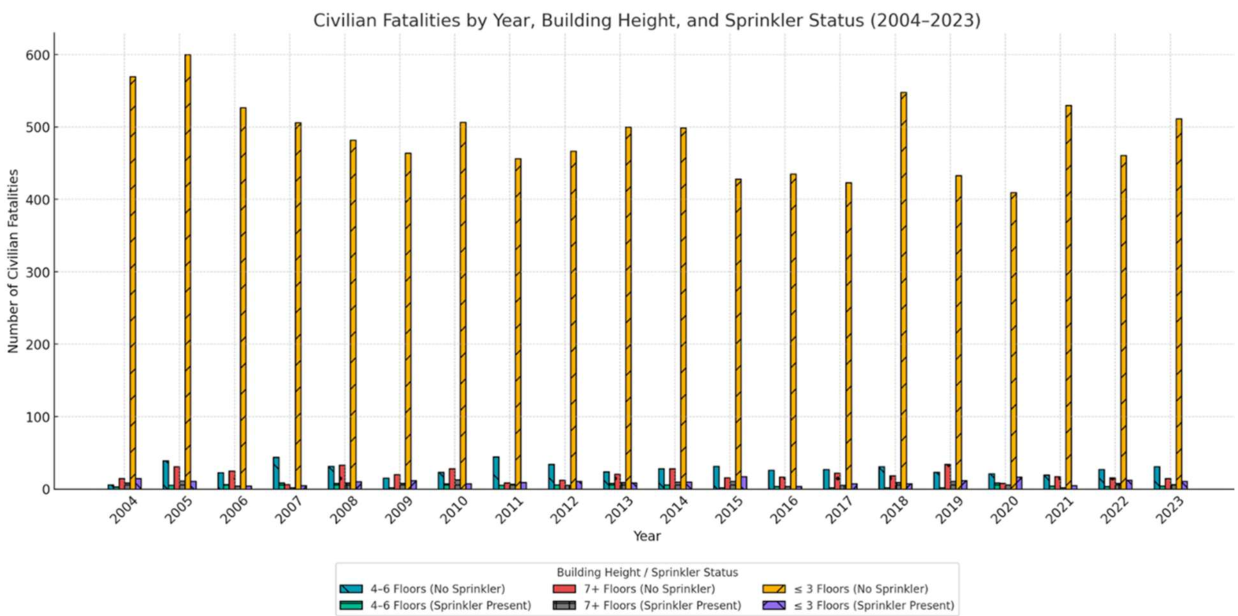


Figure D4. NFPA Custom Multi-Family Housing Fire Event Data (2004-2023)

Given that most of the fires occur in 3 story MFDs (which are believed to be the largest of the three housing height categories), the Consultants normalized the data to calculate the civilian deaths per 1,000 fire events based on MFDs at 1 – 3, 4 – 6, and 7+ stories. The non-sprinklered 1-3 story MFDs has the highest death rate at approximately 5.5 fatalities per 1,000 fire events. The second and third highest death rates were non-sprinklered 4-6 story and 7+ story buildings at approximately 5 fatalities per 1,000 fire events. The presence of an automatic sprinkler system installed throughout the MFD reduced the civilian death 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 sprinklers to reduce the civilian death rate in different MFD geometries.

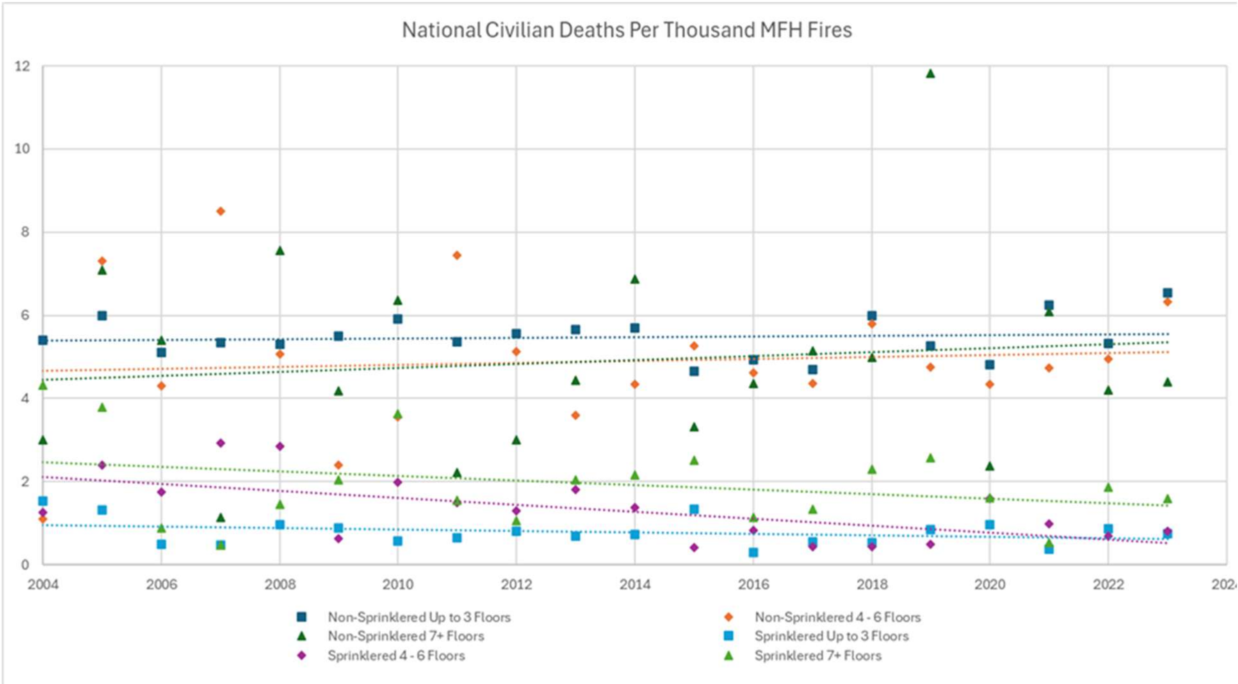


Figure D5. NFPA Custom MFD Fire Event Data (2004-2024)

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% of fire departments across the State annually report their fire event data. The Consultants reviewed these annual reports to determine:

1. How does the Minnesota data compare to the NFPA national data?
2. The number of multi-family residential building fires
3. The number and nature of civilian and firefighter deaths

The MSFMO also created an export of the MFIRS database 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 death counts, and fire service injury counts. The Consultants pared this data from 2004 (to align with the adoption of NFIRS version 5.0) – 2024 (the last full year of data). The Consultants also pared the data to only reflect MFD buildings since these most closely match the types of structures for the study.

There are similar trends between the national data provided by NFPA and the state data provided by the MSFMO. The Minnesota data reporting the area where a fire is most likely to start (the kitchen) and the areas where the fire originates that causes the largest number of civilian fatalities (the living room / bedroom) compares well with the national NFPA data: approximately 50% of the Minnesota MFD fire events started in the kitchen and almost 55% of the civilian deaths occurred in fires starting in the common living room or bedroom. Similarly, the comparison of the Minnesota civilian fatalities per 1,000 reported fire events in 1, 2 family homes versus MFD matches the national trend of 1,2 family homes having a significantly higher civilian fatality rate compared to MFD. The Minnesota data also included firefighter injuries per fire event. Figure D6 identifies firefighter injuries in MFDs of 1 – 3 floors in height, 4 – 6 floors in height, and 7 or more floors in height in both sprinklered and non-sprinklered buildings.

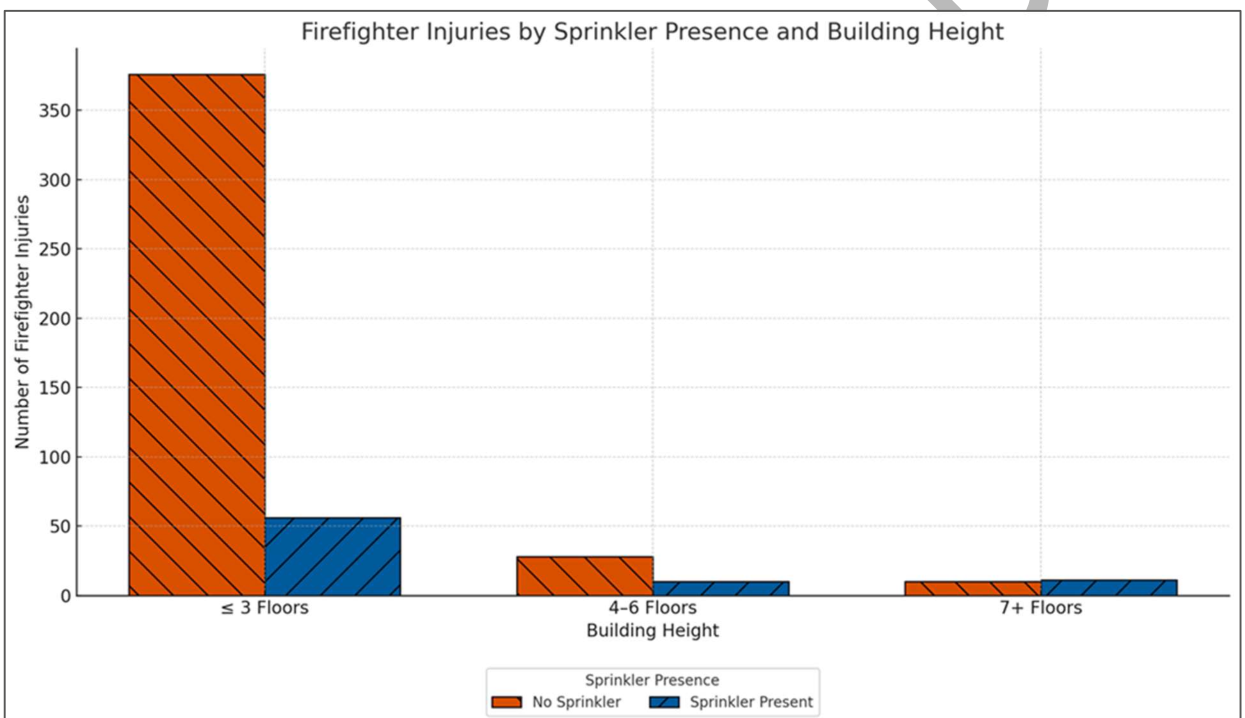


Figure D6. Minnesota Fire Event Data (2004-2024, Multifamily Dwelling)
Source: Minnesota State Fire Marshal's Office

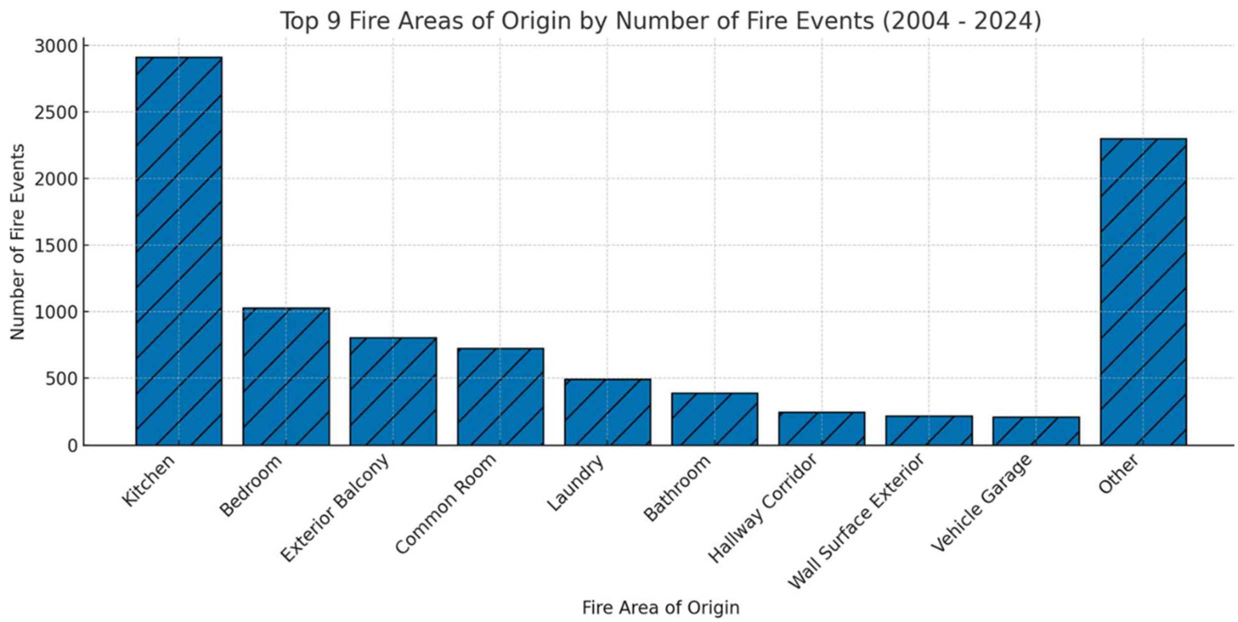


Figure D7. Minnesota Fire Event Data (2004-2024, Multifamily Dwelling) *Source: Minnesota State Fire Marshal's Office*

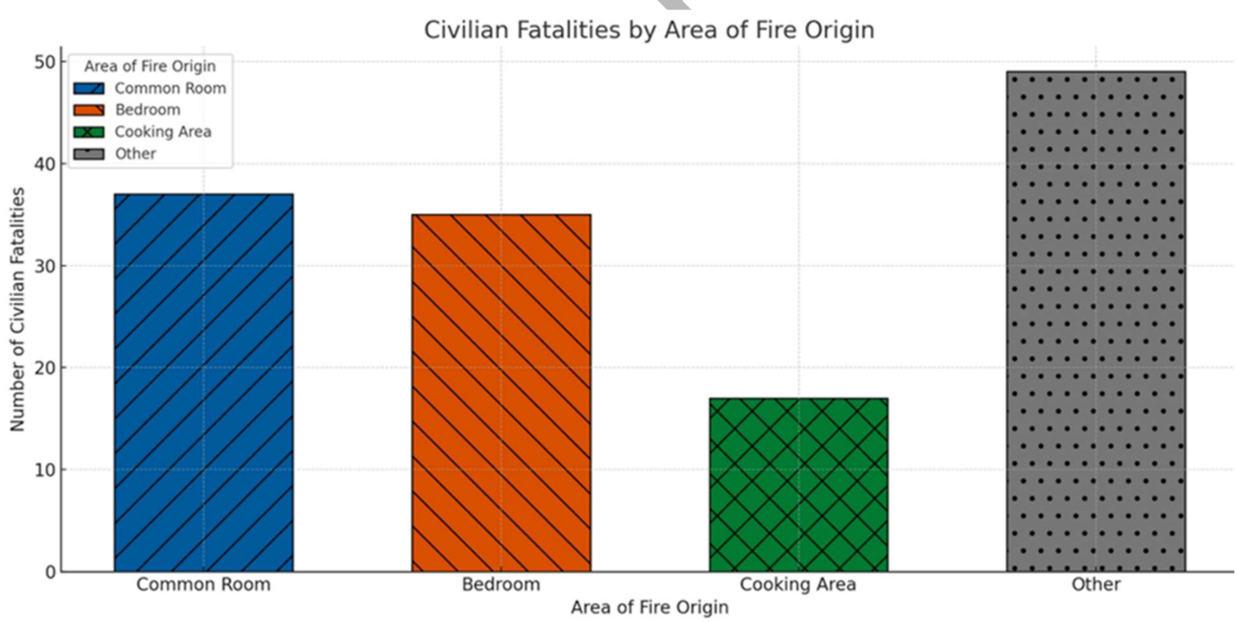


Figure D8. Minnesota Fire Event Data (2004-2024, Multifamily Dwelling) *Source: Minnesota State Fire Marshal's Office*

The Consultants also reviewed the location of fires in MFDs and focused on fires that occurred in the means of egress (corridors, stairwells, or ramps). 179 fire events started in the interior stairway or ramp which resulted in 0 civilian fatalities and 6 firefighter injuries. 164 of these fires occurred in 1 – 3 story buildings where a single stairway is permitted per today's MBC. 244 fire events started in hallway corridors which resulted in 0 civilian deaths and 11 firefighter injuries. 188 of these fires occurred in 1 – 3 story buildings.

The Consultants reviewed the number of civilian fatalities per fire event. Of the 9,812 MFD fires that occurred between 2004 and 2024, 98.8% of fire events resulted in 0 civilian fatalities. Of the 138 civilian deaths that occurred during this period, 100 of the fire events involved a single civilian fatality (note that the sprinkler coverage was undetermined for 8 of the fire events where a single fatality occurred). The fire events that resulted in multiple civilian fatalities occurred in non-sprinklered buildings. Evaluating the civilian fatalities by the location where the fatality occurred shows that 75% of fatalities occurred in the area where the fire originated. Civilian fatalities outside the area of origin are not as common, especially for sprinklered buildings.

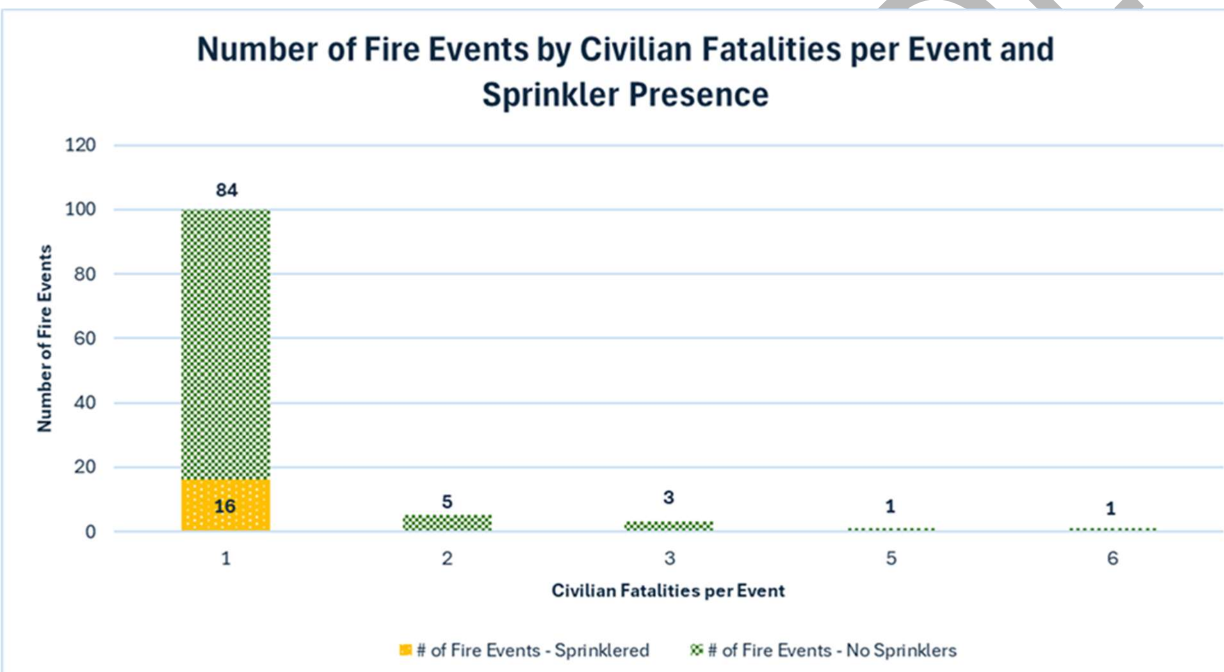


Figure D9. Minnesota Fire Event Data (2004-2024, Multifamily Dwelling) *Source: Minnesota State Fire Marshal's Office*

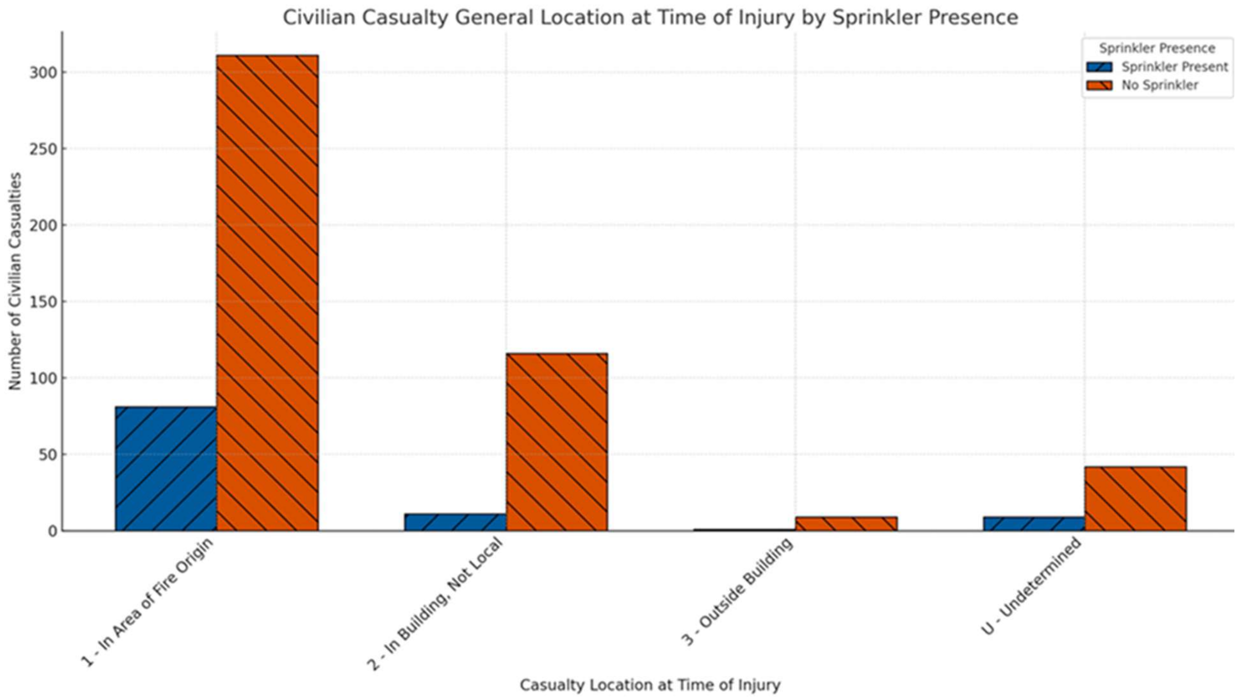


Figure D10. Minnesota Fire Event Data (2004-2024, Multifamily Dwelling), State Fire Marshal's Office

Data Reliability

Beta Distribution

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 if 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 MFD equipped throughout with an automatic sprinkler system, two fire events reported a single civilian death. 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 where the fire is large enough to require sprinkler activation.

Sprinkler Systems

The MFIRS and NFIRS fire event databases include 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% of sprinklers operated effectively, 42% of fires were too small to activate the sprinkler system, 6% of sprinklers did not operate, 1% of sprinklers operated but not effectively, and 1% 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 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[68] performed a study evaluating the position of exit stairway doors with self-closers in hotels (6), apartments / condominiums (2), boarding houses (2), and rest homes (3) in New Zealand. 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 apartments were closed approximately 86% 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 7 summarizes the beta distributions for each system or event, including the 5%, 50%, and 95% of the distribution. The purpose of reporting these values is to provide the 90% confidence range of the system failure and to conduct a holistic uncertainty analysis of the systems for their impact on risk.

Table 7. Beta Distribution Parameters for System Reliability

Description	Parameter – Alpha	Parameter - Beta	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[1]	16	144	5% ~ 0.06 50% ~ 0.10 95% ~ 0.14
Dwelling unit door fails to close[1]	16	64	5% ~ 0.13 50% ~ 0.20 95% ~ 0.28
Exit stairway door fails to close[2]	14	86	5% ~ 0.09 50% ~ 0.14 95% ~ 0.20
[1]Beta distribution parameters assumed based on engineering judgment [2]Beta distribution parameters based on Kevin Frank University of Canterbury thesis			

APPENDIX E – BUILDING CODE CRITERIA

The following sections outline major sections The discussion provided in the following sections is not intended to comprehensively describe all requirements of each reviewed code and standard as they relate to the subject topics. This is a summary, for all requirements the adopted building code should be referenced.

Podium Construction

Podium construction is a building design method where one structure is separated into two buildings under the code using a fire-resistance-rated horizontal element. Such buildings include a lower floor typically having Type I construction (i.e., the podium) that supports multiple floors of light-frame construction above.

The ICC-based codes allow separate MFD buildings to be built above a "podium" where the podium is of Type IA (fire resistive) construction, is equipped throughout with a sprinkler system in accordance with NFPA 13, and where the podium is separated from the MFD building above by a minimum 3-hour fire-resistance-rated horizontal assembly. Additionally, vertical enclosures passing through the rated horizontal assembly are required to be minimum 2-hour fire resistance rated. (One-hour rated construction is allowed under certain conditions.) Also, the maximum building height cannot exceed the most restrictive height limits based on the occupancies of the two buildings (IBC 510.2, MBC 510.2, and SBC 510.2).

MFD Buildings with Type IIA or IIIA Construction

Modified methods for podium construction are permitted for MFD buildings with Types IIA and IIIA construction. Buildings with Type IIA construction are allowed to be up to nine stories and 100 feet in height (as opposed to five stories and 85 feet) where the building is separated by not less than 50 feet from any other building on the lot and adjacent lot lines, exits are enclosed by 2-hour fire-resistance-rated construction, and the first floor construction has a fire resistance rating of not less than 1-1/2 hours (IBC 510.6, MBC 510.6, and SBC 510.5).

The IBC allows the height of MFD buildings with Type IIIA construction to be increased by one story and 10 feet where the first floor construction above a basement has a fire-resistance rating of not less than 3 hours and the floor area is subdivided by 2-hour fire-resistance-rated fire walls into areas of not more than 3,000 square feet. Where the same conditions are met, the MBC currently allows increases in the height limitations to six stories and 75 feet (MBC 510.5).

Similarly, the SBC allows MFD buildings with Type IIIA construction that meet certain conditions to have an increased height up to six stories. Increasing the allowable number of stories to six provides a particular benefit to buildings protected with NFPA 13R systems which are typically limited to a maximum of four stories above the grade plane. For the increased height limitation to apply all stories are required to be less than 12,000 square feet, stories greater than 6,000 gross square feet are required to be subdivided into compartments by 2-hour fire-resistance-rated fire walls, and each compartment is required to be provided with an enclosed exit stairway with a standpipe (SBC 510.10).

Fire-Resistance Ratings of Building Elements

Corridors

The ICC-based codes and NFPA 101 require corridors in MFD buildings equipped throughout with automatic sprinkler systems (excluding corridors within dwelling units or sleeping units) to have fire-resistance ratings of at least 30 minutes (IBC 1020.2, MBC 1020.1, SBC 1020.2, NFPA 30.3.6.1.2). Per the MBC a dwelling unit is a “single unit providing complete, independent living facilities for one or more persons, including permanent provisions for living, sleeping, eating, cooking and sanitation” (MBC 202) and a sleeping unit is a “single unit that provides rooms or spaces for one or more persons, includes permanent provisions for sleeping and can include provisions for living, eating and either sanitation or kitchen facilities but not both. Such rooms and spaces that are also part of a dwelling unit are not sleeping units.” (MBC 202)

Interior Exit Stairway

In the ICC-based codes and NFPA 101, stairway enclosures are typically required to have a fire resistance rating of 2-hours when connecting four or more stories and 1 hour when connecting less than four stories(IBC 1023.2, MBC 1023.2, SBC 1023.2, NFPA 7.1.3.2.1).

Shafts

Similar to the requirements for stairway enclosures, the ICC-based codes and NFPA 101 typically require shaft enclosures such as stairways to have a fire resistance rating of 1-hour when connecting less than four stories and 2-hours when connecting four or more stories IBC 713.4, MBC 713.4, SBC 713.4, NFPA 8.6.5).

Means of Egress Width and Capacity

Interior Exit Stairways

The ICC-based codes and NFPA 101 require minimum widths of egress components to be determined based on the occupant load served by the component. The ICC-based codes and NFPA 101 require minimum stairway widths to be determined based on an egress capacity factor of 0.3 inches per occupant. The egress capacity factor is allowed to be reduced to 0.2 inches per occupant when the building is equipped throughout with an automatic sprinkler system and an emergency voice/alarm communication system. Stairways serving at least 50 occupants are not allowed to have widths less than 44 inches. Stairways serving less than 50 occupants are allowed to have a minimum width not less than 36 inches (IBC, MBC, SBC Sections 1005.3.1 and 1011.2, NFPA 101 7.2.2.2.1.2 and 7.3.3.1).

Corridors

According to the ICC-based codes and NFPA 101, minimum widths of egress components other than stairways are required to be determined based on an egress capacity factor of 0.2 inches per occupant. The egress capacity factor is allowed to be reduced to 0.15 inches per occupant when the building is equipped throughout with an automatic sprinkler system and an emergency voice/alarm communication system. Stairways serving at least 50 occupants are not allowed to have widths less than 44 inches.

Stairways serving less than 50 occupants are allowed to have a minimum width not less than 36 inches. (IBC 1020.2; MBC 1020.1; SBC 1020.2; NFPA 101 30.3.6.1.2)

Fire Alarm Systems

Requirements for the provision of fire alarm systems in each reviewed code and standard is based on the building's number of stories or total number of dwelling or sleeping units. The IBC and the SCB require fire alarm systems where dwelling or sleeping units are located three or more stories above the lowest level of exit discharge (IBC 907.2.9.1 and SBC 907.2.9.1). The MBC is more restrictive and requires fire alarm systems in buildings with dwelling or sleeping units located two or more stories above the level of exit discharge (MBC 907.2.9.1). Each ICC-based code also requires fire alarm systems in buildings having more than 16 dwelling or sleeping units.

NFPA 101 requires apartment buildings having four or more stories in height, or having more than 11 dwelling units to be provided with a fire alarm system unless 1-hour separation is provided between each dwelling unit and each dwelling unit has its own independent exit (NFPA 101 30.3.4.1.1 and 30.3.4.1.2).

Smoke Alarms

Requirements for the provision of smoke alarms in residential buildings are generally similar between each of the codes and standards included in the Code Summary. Each code and standard requires smoke alarms to be provided in each room used for sleeping purposes, outside of each sleeping area in the immediate vicinity of bedrooms, and in each story within a dwelling unit. The SBC also requires smoke alarms in loft spaces (IBC and SBC 907.2.11.2, MBC 907.2.9.1.3, NFPA 101 30.3.4.5).

NFPA 101 has similar requirements to the IBC regarding single exits from buildings. A building is allowed to have a single exit where the total number of stories does not exceed four, there are not more than four dwelling units per story, and the building is equipped throughout with a sprinkler system designed in accordance with NFPA 13. In addition, the exit travel distance from a dwelling unit entrance door to an exit door is required not to exceed 35 feet, the exit stairway (including opening protections) 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 (NFPA 101 30.2.4.6).

Smokeproof Enclosures

In general, smokeproof enclosures are only required by the codes and standards included in the Code Summary in high-rise buildings, (i.e., buildings having floors more than 75 feet above the lowest level of fire department vehicle access). Where only one interior exit stairway is provided, the SBC required that stairway to be a smokeproof enclosure (SBC 1006.3.4). Additionally, proposals for changes to the IBC would require interior exit stairways in single exit MFD buildings to be smokeproof enclosures (Proposal E24-24).

Fire Department Access

At a minimum, 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. Extensions are allowed where the building is equipped throughout with an NFPA 13 or NFPA 13R sprinkler system. The IFC does not prescribe a specific extension distance and leaves that authority to the fire code official. The MFC, SFC, and NFPA 1 allow the extension of fire apparatus access roads 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, 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 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 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 key factors that affect the overall level of fire and life safety 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. Some factors, such as contents within dwelling units and human behavior, will vary depending on the physical location of the building within a country or state, but can also vary greatly between dwelling units within the same building. Fire department response requirements, including response time, will largely 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 stations.

APPENDIX F – MODEL DESCRIPTION

Model Building Geometries

Multiple model building geometries were developed for inclusion in the fire modeling analysis to compare the relative differences in fire safety between buildings with varying layouts. The model buildings used in the fire modeling analysis are described below:

1. **40,625 square foot building:** This building was intended to serve as a baseline in the analysis and represents a typical residential building with two exit stairs. Each floor of the building measures 625 feet long by 65 feet wide (approximately 40,625 square feet in area per floor) and has eight levels. Each story is 10 feet in height. 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 F1 below.
2. **6,000 square foot building:** This building was intended to represent one potential layout for a single-exit stairway MFD residential building. Each floor of the building measures 100 feet long by 60 feet wide (approximately 6,000 square feet in area per floor) and has eight levels. Each level is 10 feet in height. The building's single interior exit stairway shaft is 18 feet by 8 feet with stairways that are 44 inches wide. The building contains 8 dwelling units per level, of roughly equal dimensions. Each residential unit is served by a single corridor that is 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 F2 below.
3. **4,000 SF building:** This building was intended to represent a second, slightly smaller potential layout for a single-exit stairway MFD residential building. Each floor of the building measures 67 feet long by 60 feet wide (approximately 4,000 square feet in area per floor) and has eight levels. Each level is 10 feet in height. The building's single interior exit stairway shaft is 18 feet by 8 feet with stairways that are 44 inches wide. The building contains 4 residential units per level, of roughly equal dimensions. Each residential unit is served by a single corridor that is 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 F3 below.

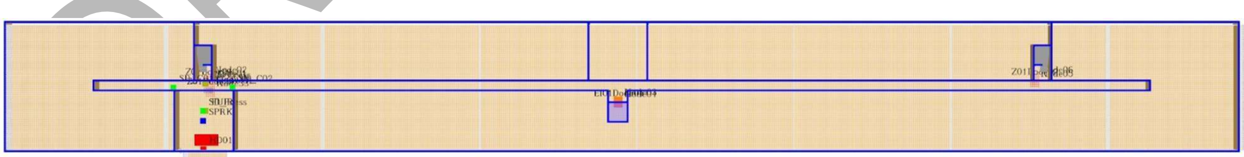


Figure F1. FDS model of the 40,625 sq. ft. building

Figure F2. FDS model of the 6,000 sq ft. building

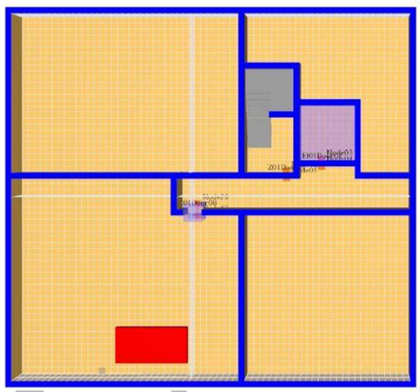


Figure F3. FDS model of the 4,000 sq ft. building

Fire Modeling 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. 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 Fuel Loads

Two design fires with distinct fuel loads were considered in the fire modeling analysis. The first design fire was based on the fuel load for a fully involved room fire that achieved a flashover condition. The fuel load for the second design fire consisted of a micromobility device, specifically an electronic bicycle (i.e., an e-bike), powered by a lithium-ion battery.

Heat Release Rates

Room Fire (Dwelling Unit)

The heat release rate (HRR) for the flashover fuel load was developed based on full-scale residential dwelling room fire tests conducted by NIST.[69] The subject room's nominal dimensions were approximately 12.1 ft. by 12.1 ft. with a 7.9 ft. ceiling that included a 7.9 ft. wide by 6.9 ft. tall opening created in one wall and centered at the front of the room. The rooms 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 F4 and Figure F5. Recorded test data for three room fire tests are provided in Table F1 below and in Figure F6. The HRR curve for the modeling analysis was developed to represent the results of the three room fire tests. The HRR curve for the flashover room fire is provided in Table F2.

Figure F4. Photo of NIST room fire test

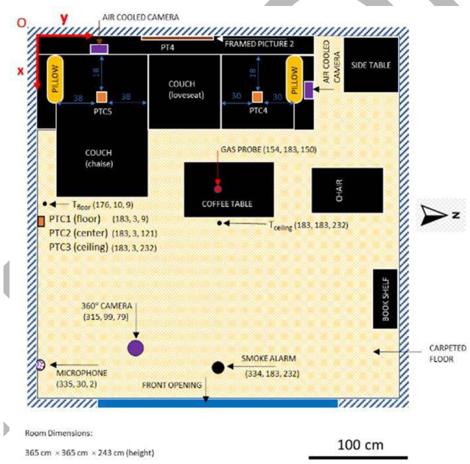


Figure F5. Plan view of NIST room fire test

Table F1. Results of room fire tests conducted by NIST

Test No.	Time to peak HRR (min)	Peak HRR (kW)	Total HRR (MJ)
1	8.1 ± 0.2	9180 ± 550	2550 ± 160
2	21.7 ± 0.2	8420 ± 500	2250 ± 140
3	6.7 ± 0.2	9640 ± 580	2640 ± 160

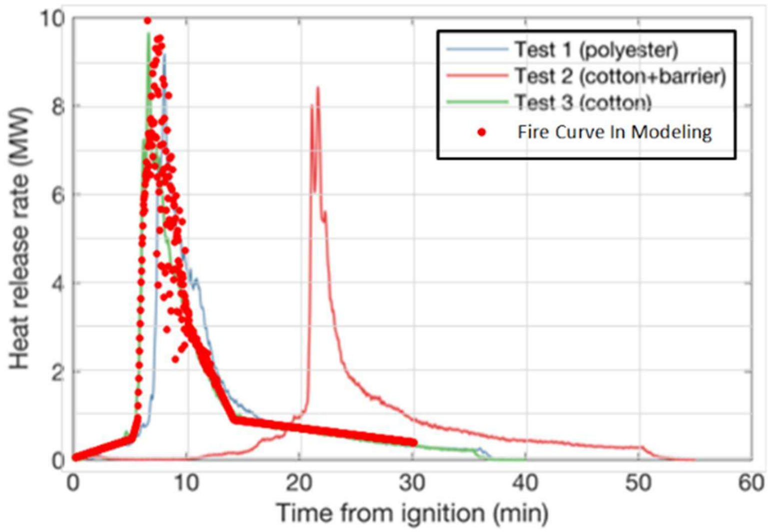


Figure F6. HRR curves of room fire tests conducted by NIST

Table F2. Flashover room fire HRR curve tabulated values

Time (min)	Heat Release Rate (MW)	Fraction of Peak Heat Release Rate
0	0.00	0.0%
5	0.46	5.1%
5.5	0.93	10.3%
6	6.47	71.9%
7	9.00	100.0%
8	6.47	71.9%
10	3.24	36.0%
14	0.93	10.3%
30	0.37	4.1%

E-Bike Fire (Corridor)

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.[70] 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 660Wh 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 Table F3 and Figure F7.

Table F3. E-bike fire HRR curve tabulated values

Time (min)	Heat Release Rate (kW)	Fraction of Peak Heat Release Rate
0	0	0.0%
0.2	54.99	6.1%
0.75	900	100.0%
1.4	80	8.9%
1.67	0	0.0%
30	0	0.0%

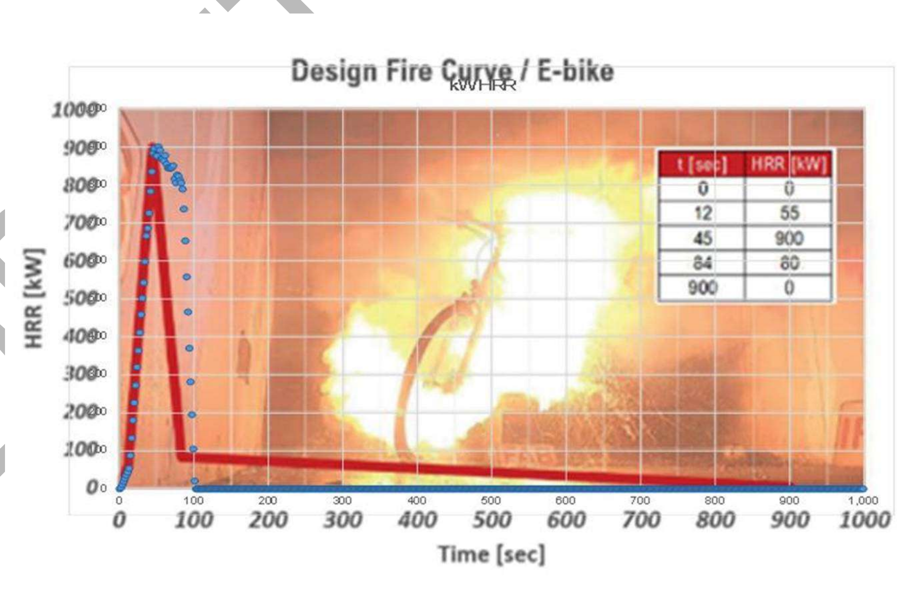


Figure F7. E-bike fire HRR curve

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. Therefore, assuming the main combustible involved in the fire is polyurethane will 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. Flammability properties for the foam are provided in Table F4 below.

Table F4. Properties of Polyurethane Foam GM 27[71]

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.[72] 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 mech for with regard to 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

For all scenarios, the ambient conditions both inside and outside the buildings were set as 70°F. 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 by 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 1 foot tall by one foot wide.

Leakage within the building's interior was modeled based on the gaps between stair doors and elevator doors, their frames, and the floor in accordance with information provided in the Smoke Control Handbook. Stairway doors were assumed to provide a 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,[73] 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 navigate to the nearest exit. This area was monitored in the CFD model for the following impairments for the full duration of the CFD simulation.[74,75]

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 isolate the primary 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.[76] The primary species responsible for asphyxiation in fire include carbon monoxide (CO).

A summary of the thresholds selected for each tenability criteria is provided in Table F5 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 F5. Summary of Tenability Criteria and Thresholds

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, 15 feet for small spaces.[77] 15 feet of visibility is considered as the tenability limit.

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. The following asphyxiates represent the documented[78] greatest hazard to occupants exposed to the fire effluent:

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 always produced in building fires. CO is responsible for most of the fire casualties and can cause confusion and loss of consciousness.

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[79] evaluates FED,

where:

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

Δt =chosen time increment, expressed in minutes,

(C t) = exposure dose causing occupants' compromised tenability, expressed in ppm. min.

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."

Purser[80] 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. 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 be exposed for 20 minutes, the minimum concentration of carbon monoxide could potentially be compromised is 600 ppm. In other terms, the tenability limit for an exposure of 20 min. 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.[81] 140°F along any walking surface within the building was used as a conservative tenability limit.

EGRESS ANALYSIS

Egress Simulator

The Pathfinder® model was utilized to conduct computer-based 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 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. The agent responds dynamically to changing queues, door openings/closures, and changes in room speed constraints (simulating smoke and debris).

Egress Models

The egress model for the 40,625 square foot building included approximately 200 occupants per floor and approximately 16,000 occupants in the entire building (Figure F8). The 6,000 square foot building model included approximately 30 occupants per floor and 240 occupants total in the building (Figure F9). The 4,000 square foot building model included approximately 20 occupants per floor and 160 total occupants total in the building (Figure 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.

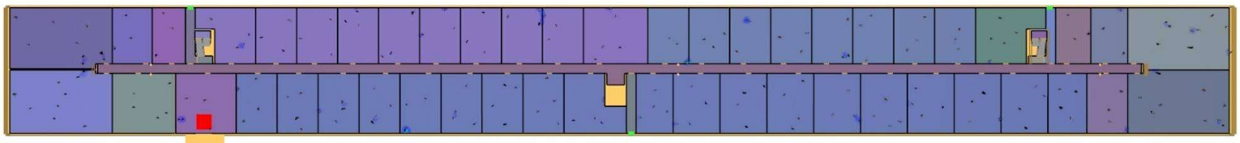


Figure F8. Egress model of the 40,625 sf building

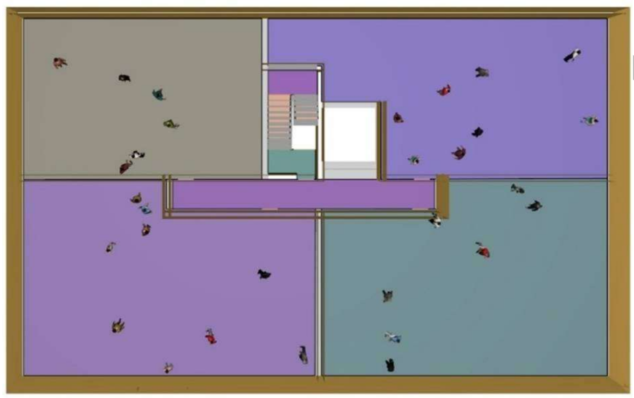


Figure F9. Egress model of the 6,000 sf building

Figure F10. Egress model of the 4,000 sf building

Table F6. Summary of fire modeling scenarios

Scenario No.	Building	Fire Location	Fuel Load	Peak HRR	Dwelling Unit Door Position	Stairway Door Positions
1-1	40,625 square foot building	First floor dwelling unit	Room fire	10 MW	Open	Closed
1-2	40,625 square foot building	First floor dwelling unit	Room fire	10 MW	Open	Open on fire floor
1-3	40,625 square foot building	First floor dwelling unit	Room fire	10 MW	Open	Open on fire floor and floor above fire floor
1-4	40,625 square foot building	First floor corridor	E-bike	0.9 MW	N/A	Closed
2-1	6,000 square foot building	First floor dwelling unit	Room fire	10 MW	Open	Closed
2-2	6,000 square foot building	First floor dwelling unit	Room fire	10 MW	Open	Open on fire floor
2-3	6,000 square foot building	First floor corridor	E-bike	0.9 MW	N/A	Closed
3-1	4,000 square foot building	First floor dwelling unit	Room fire	10 MW	Open	Closed
3-2	4,000 square foot building	First floor dwelling unit	Room fire	10 MW	Open	Open on fire floor
3-3	4,000 square foot building	First floor corridor	E-bike	0.9 MW	N/A	Closed

APPENDIX G – EGRESS

This Appendix provides a brief explanation and additional information affecting the egress analysis within this report. The analysis and findings related to human behavior within the buildings that constitute this study are found within the main body of 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. There are five primary factors affecting human behavior that occur during building fires:

1. The behavior of the fire, hot gases, and smoke;
2. The behavior of the building subjected to the fire (aka "passive fire protection");
3. The behavior of the devices that detect fire, notify people, and suppress a fire, e.g., smoke detectors, fire alarms, and sprinkler systems;
4. The behavior and actions of the occupants within the building; and,
5. 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.

All of these factors overlap in varying manners with the others and can impact one another. The behavior of fire and smoke within the various buildings 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 are not a primary focus of this project but were given consideration appropriate to the scope of this project.

It is also noted that building codes do not typically address the human factors that can affect the fire risk of buildings. In a given scenario, building 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 safer alternative. The *SFPE Guide to Human Behavior in Fire* provides additional information on this emerging field.[82] . This report does not prescribe or assume specific action on the part of building occupants but identifies occupants "at risk" for the various building designs 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. The most notable of these exceptions are hospitals and similar institutional facilities that are designed to have two or more fire-rated compartments within the building. During a fire, this design allows for 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.

Egress Models

The engineering and computational models used in this analysis 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 model utilized for the analysis of this report is "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 the movement of building occupants during a fire event in order to establish the estimated amount of time required for the occupants to safely and completely move to an area of refuge or egress from the building geometries evaluated via exit stairway(s). The model utilized for the egress analysis of this report is "Pathfinder" as described in Appendix F.

The data derived from the egress model resulted in the identification of the Required Safe Escape Time (RSET). The two sub-types of values established for the RSET are a base RSET which utilizes egress by all occupants beginning simultaneously with the ignition of the fire. The other value acknowledges the great variability in egress time required by the various occupants throughout a building and utilizes ranges of time for varying quantities of occupants.

Overlaying the results of the egress models onto the fire model results in the identification of the Available Safe Egress Time (ASET). It is typically the goal to have an ASET that is appropriately greater than the RSET to provide an adequate 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.

The RSET begins at the time from the ignition of the fire and concludes at the time that occupant evacuation is complete.

If the ASET is less than the RSET, then the design would indicate that a hypothetical occupant must find an area of refuge within the building to defend in place or an alternative escape route. Typically, for an MFD this 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, either through windows, from balconies, or from within their dwelling units or other areas.

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 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 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 ten time individual segments that begin with the time of the ignition of a fire, as noted in the "SFPE Handbook of Fire Protection Engineering"[83] as follows:

1. Detection Time: The interval between the fire ignition and the first detection of the fire by a device or an individual.
2. Warning Time: The interval between detection of the fire and the time at which an alarm signal is activated or notification of occupants takes place.
3. Recognition Time: The interval 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.
4. Response Time: The interval 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.
5. Travel Time: The time needed, once movement toward an exit has begun, for all occupants to reach of place of safety.
6. Margin of Safety: The time between when the evacuation is complete and the tenability limit of an area. If the tenability limit is reached in an area prior to the evacuation of all occupants needing to use that area to escape, then those occupants do not have a margin of safety.
7. Pre-Evacuation Time: The interval of time between the time at which a general alarm signal or warning is given and the time at which the first deliberation evacuation movement is made. This consists of two components: recognition time (Item 3) and response time (Item 4).
8. 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-movement Time (Item 7) and the Travel Time (Item 5).
9. Required Safe Escape Time (RSET): The calculated time necessary between ignition of a fire and time at which all occupants can reach an area of safety. This is the sum of the Detection Time (Item 1), the Warning Time (Item-2), and the Evacuation Time (Item-8). RSET is equivalent to the Escape Time.
10. Available Safe Egress Time (ASET): The calculated time available between the ignition of the fire and the time at which tenability criteria are exceeded in the means of egress. The ASET should be longer than the RSET (Item-9) by an acceptable Margin of Safety (Item-6).

Analysis

Considering the various segments of the RSET evaluation for this comparative study, the detection time segment is included in the pre-movement, delay time segment and is not impacted by the number of stairways in a building.

Within the unit of origin of the fire, the Warning Time is not impacted by whether or not a building has one exit stairway or two, and therefore is included in the pre-movement, delay time segment and is not individually evaluated. In units other than the unit of origin, the Warning Time is also not impacted by the number of stairways, but it is highly variable depending on the types and locations of detection devices and alarm devices, and by the manner in which the alarm devices are activated in various areas of the building. Delays in the activation of alarm devices result in delays in the start of Recognition Time. For the purposes of this study the alarm time within the unit of origin has been used as the alarm time within all other units, except where otherwise noted.

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 impact their ability to be awakened by audible or visual alarms. The nature of the audible and visible performance characteristics of the 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 simple terms, research has indicated that variations from half a minute to five minutes are not uncommon, however the extremes can range from as little as a few seconds to hours.[84]

This can be a significant issue, with the understanding that most human beings are asleep approximately one-third of their time during a typical week, and that being asleep can frequently constitute as much as 50% or more of the time that occupants are in their dwelling units, particularly for those who work outside of their homes. Within Recognition Time (which occurs following an alarm), occupants will have variable amounts of time spent prior to leaving their units and initiating Travel Time. The behavior during this 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 Warning Time and the potential start of Travel Time will 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 escape.

Because of this in some fire events, building occupants might not exit their units and reach the exterior of the building prior to the means of egress becoming untenable due to fire, smoke or hot gases, the life safety strategy of defend-in-place is useful, particularly for those who are on the same floor as the unit of origin.

The major variables impacting the Travel Time include the quantity of occupants, their physical characteristics and abilities to self-evacuate or to evacuate with assistance, the physical characteristics of the escape path (corridor and stairway widths, and exit travel distance from the most remote dwelling units to an exit stairway and to an exit discharge door), and the environmental conditions within the egress components (including the presence and intensity of fire, hot gases, and smoke).

For any given building, the individual Travel Time for occupants of each unit varies, with the primary time identified within the analysis of this report as being the maximum for the building. 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 type 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 provide a reasonable level of safety for the public. The codes have been developed for national applications 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, minimum size of windows allowing fire department rescue, building standpipe systems for manual firefighting, 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-escape, or to do so with the assistance of the fire department, are important factors regarding actions of the fire department outside of a 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 escape. For the analysis of multi-story buildings 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. For these reasons, 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 running of a hose line from the standpipe within the stairway to locations of the fire.

For a building with two or more exit stairways, there can theoretically be at least two means of self-escape through stairways. One is an exit stairway that is available until it is taken out of service by the fire department for firefighting operations. The second is the second stairway, which presumably remains available during firefighting operations.

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 used for high-rise buildings where occupants cannot evacuate the building in a reasonable time and firefighting must be conducted from within the building. 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 building, even when they had received audible and visual alarms, or other clues or information, well in advance of that time.[85] 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 defend-in-place strategy requires the presence of certain physical elements that are not always included within tall residential buildings. These include communications systems between the fire department command panel and the individual dwelling units; enhanced passive fire protection between 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 may also consider training of building occupants so that they understand the strategy. Research has indicated that the use of defend-in-place 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, 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 reliability 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 as expected, 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 is achieved through systems that provide building occupants timely and credible information concerning the situation they are in 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 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 being adversely affected. In such cases, affected building occupants may either attempt to escape through the smoke-filled corridor or remain in their residential units. Studies have shown that approximately 60% of people will elect to move through smoke to escape the fire.

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. They usually do not have as 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.*

This information has been identified in this report as it constitutes a viable alternative to the traditional 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.

APPENDIX H – MODELING RESULTS

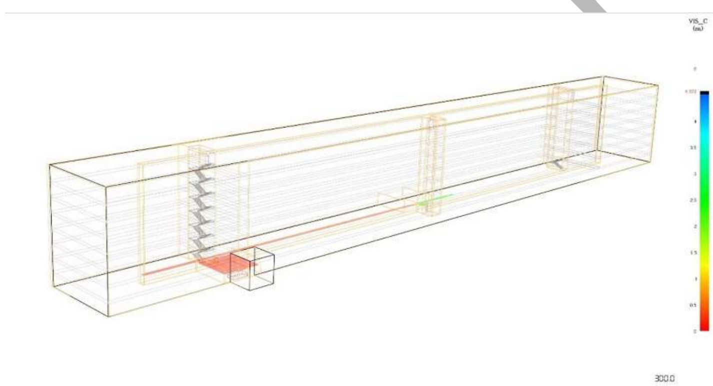
40,625 Square Foot Building Results

Fire Modeling Results

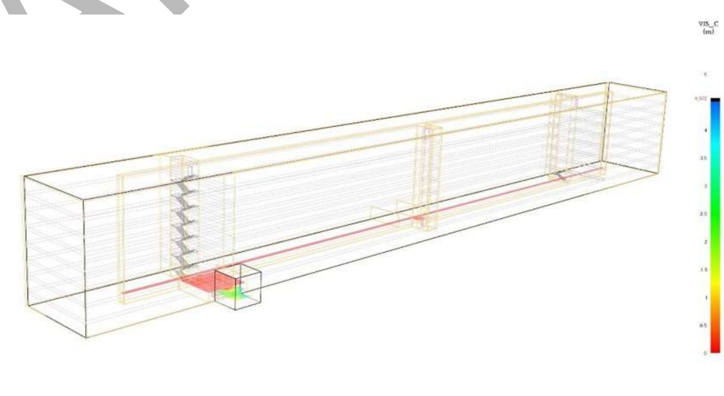
The fire modeling results for all scenarios in the 40,625 square foot building indicated that visibility within occupiable spaces was reduced below 15 feet (the selected tenability criteria) prior to increased temperatures or carbon monoxide concentrations exceeded their respective tentability thresholds. Therefore, visibility was determined to be the limiting factor when determining the ASET for each scenario. Visibility, temperature, and carbon monoxide concentration were each measured at an elevation six feet above the walking surface of the fire floor.

Scenario 1-1

Visibility was reduced below the tenability criterion of 15 feet in approximately 50% of the fire floor's corridor within 300 seconds. Visibility was reduced below 15 feet in all portions of the fire floor corridor within 60 seconds (Figure H1).



300s



600s

Figure H1. FDS visibility results of the 40,625 sf building with stairway door closed. (Visibility tenability criterion: 15 feet).

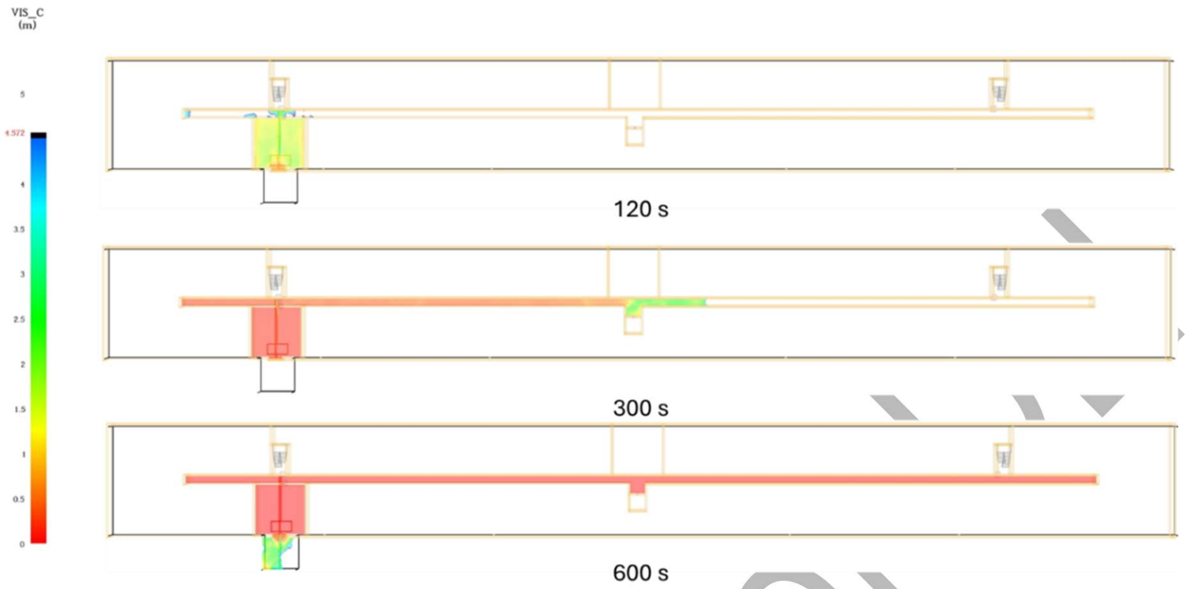
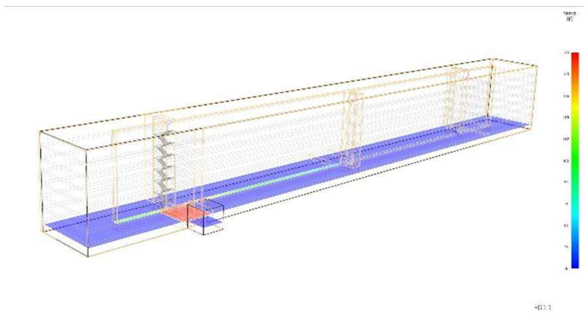
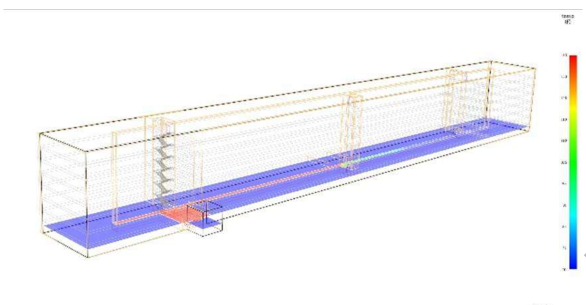


Figure H2. FDS visibility results of the fire floor in the 40,625 sf building with stairway door closed. (Visibility tenability criterion: 15 feet).

Temperature was increased above the tenability criterion of 140°F in approximately 10% of the fire floor corridor at 300 seconds and in 50% of the corridor at 600 seconds. CO concentration was increased above the tenability criterion of 600 ppm in approximately 5% of the fire floor corridor at 300 seconds and in 100% of the corridor at 600 seconds.

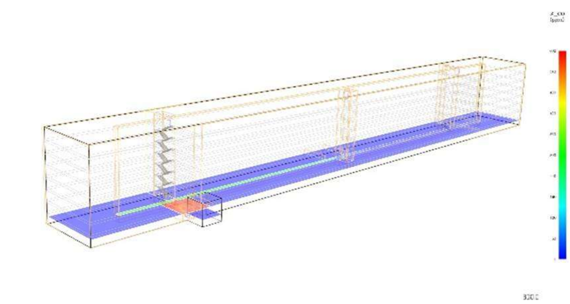


300s

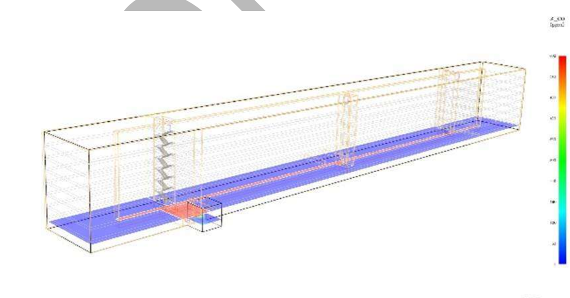


600s

Figure H3. FDS temperature results of the 40,625 sf building with stairway door closed. (Temperature tenability criterion: 140°F)



300s

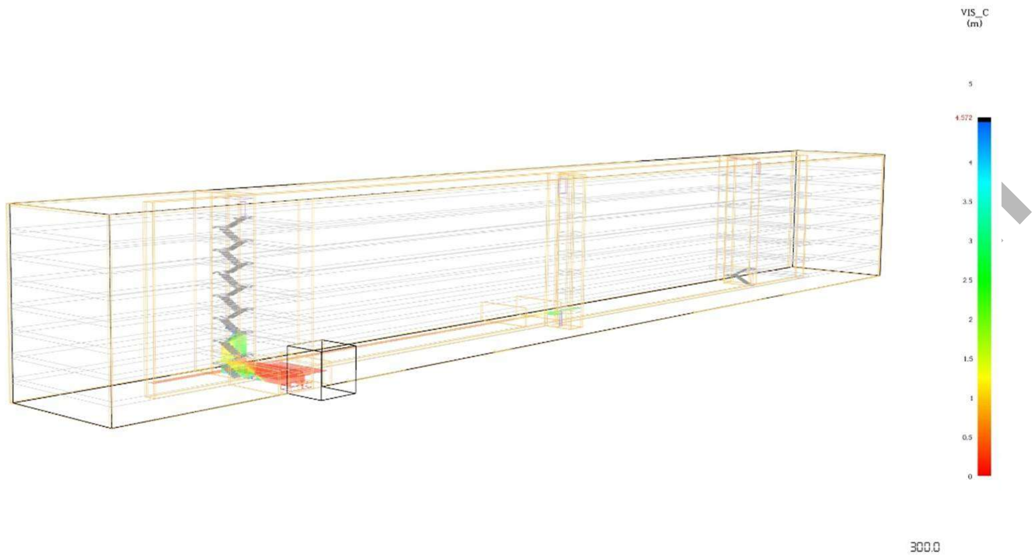


600s

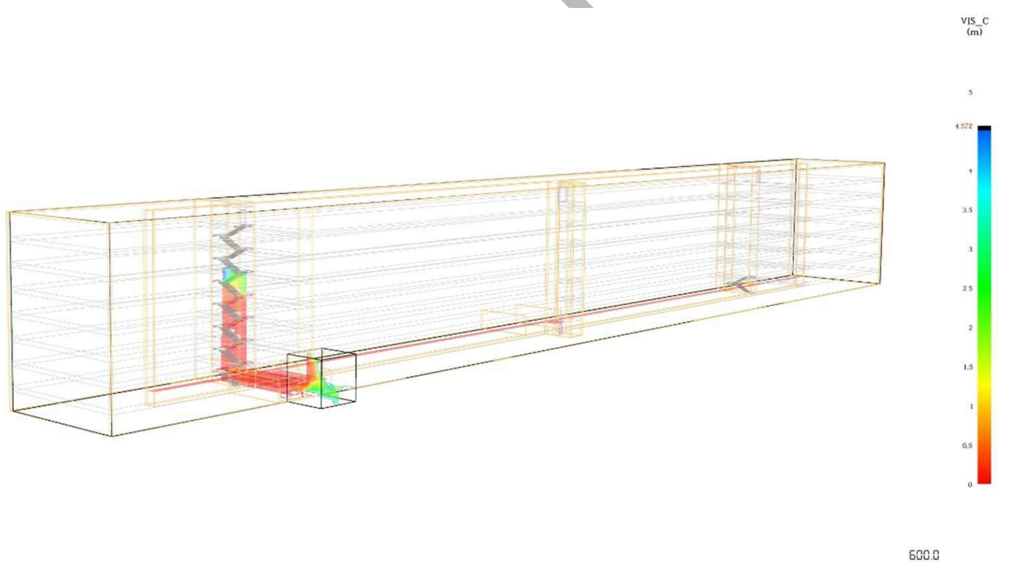
Figure H4. FDS carbon monoxide concentration. results of the 40,625 sf building with stairway door closed. (CO concentration tenability criterion: 600 ppm)

Scenario 1-2

Visibility was reduced below the tenability criterion of 15 feet in approximately 50% of the fire floor corridor within 300 seconds. Visibility was reduced below 15 feet in all portions of the fire floor corridor within 60 seconds (Figure H5).



300s



600s

Figure H5. FDS visibility results of the 40,625 sf building with stairway door open on fire floor. (Visibility tenability criterion: 15 feet)

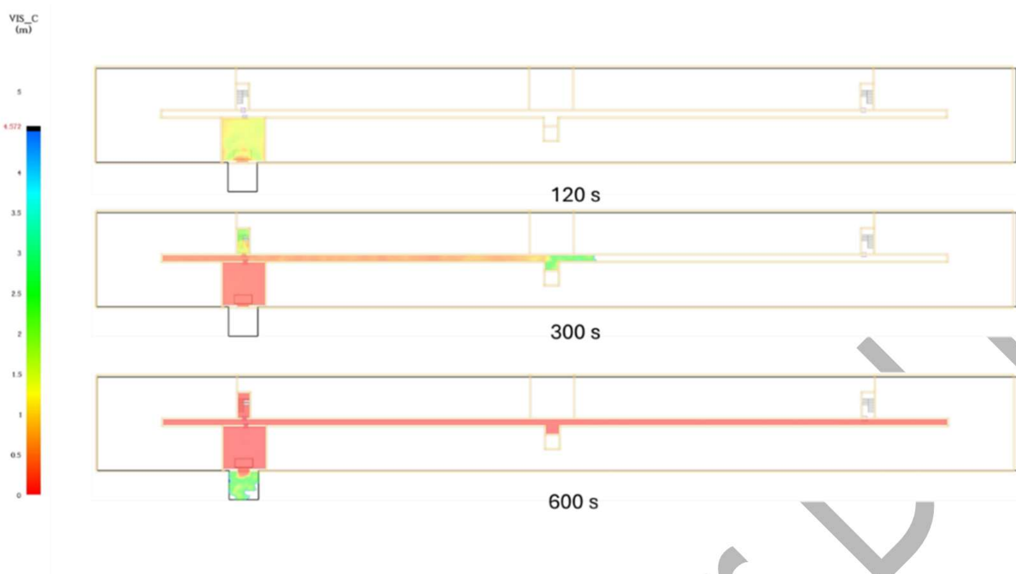
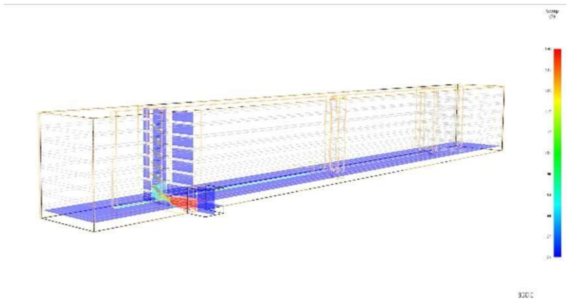


Figure H6. FDS visibility results of the fire floor in the 40,625 sf building with stairway door open on fire floor. (Visibility tenability criterion: 15 feet)

Temperature was increased above the tenability criterion of 140°F in approximately 10% of the fire floor corridor at 300 seconds and in 50% of the corridor at 600 seconds. CO concentration was increased above the tenability criterion of 600 ppm in approximately 5% of the fire floor corridor at 300 seconds and in 100% of the corridor at 600 seconds.



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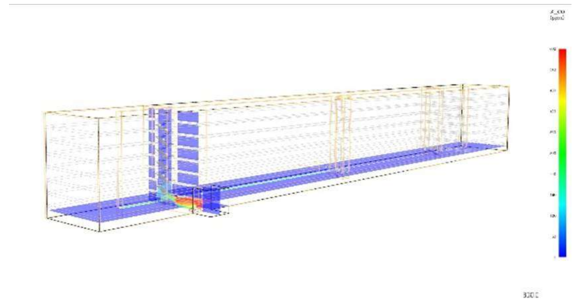

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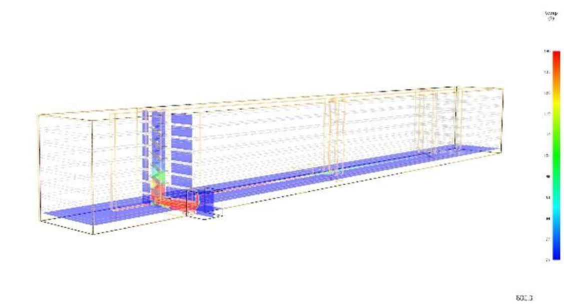
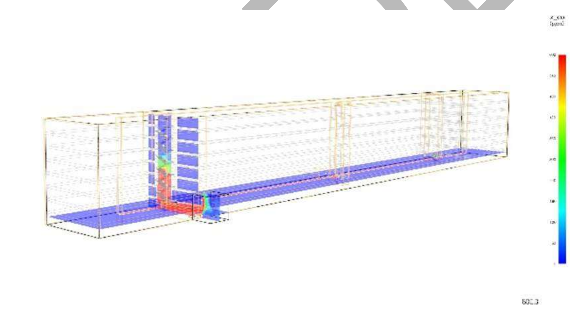


600s



600s

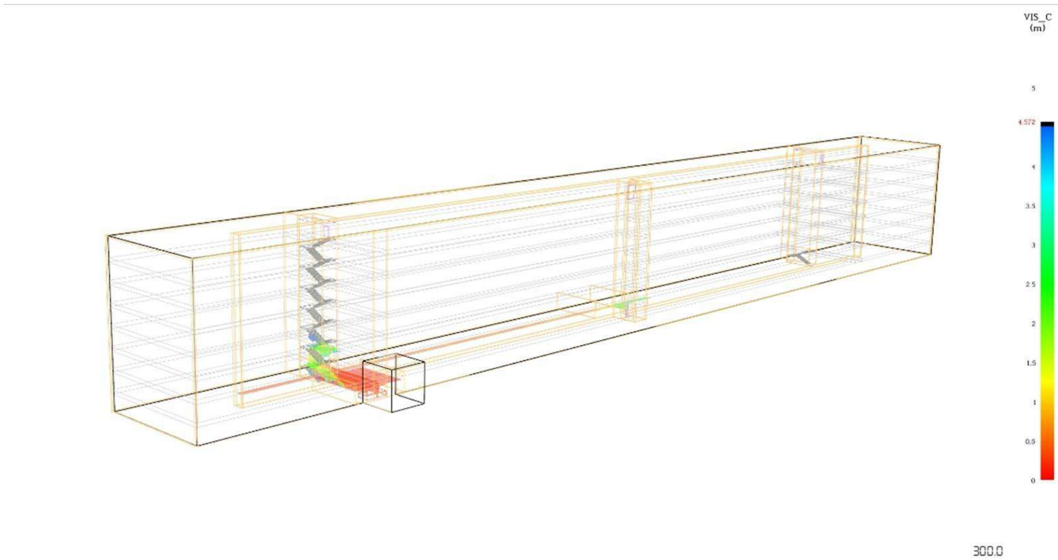
Figure H7. FDS temperature results of the 40,625 sf building with stairway door open on the fire floor. (Temperature tenability criterion: 140°F)

Figure H8. FDS carbon monoxide concentration. results of the 40,625 sf building with stairway door open on the fire floor. (CO concentration tenability criterion: 600 ppm)

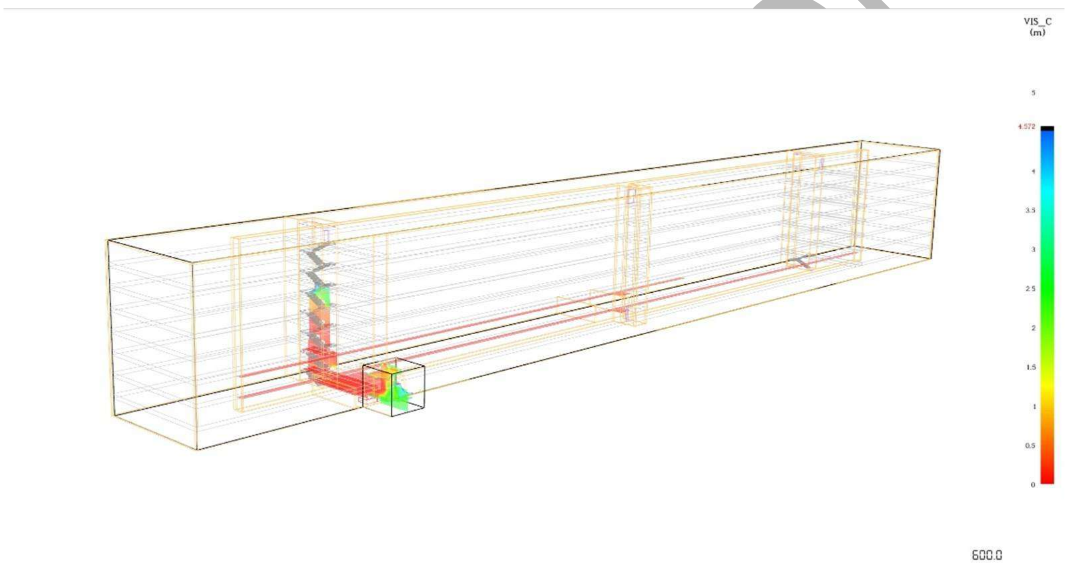
Scenario 1-3

Visibility was reduced below the tenability criterion of 15 feet in approximately 50% of the fire floor corridor within 300 seconds. Visibility was reduced below 15 feet in all portions of the fire floor corridor within 60 seconds (Figure H9).

Visibility was also reduced below 15 feet in approximately 10%-20% in the corridor on the floor directly above the fire floor and in 60% of the corridor at 600 seconds.



300s



600s

Figure H9. FDS visibility results of the 40,625 sf building with stairway door open on fire floor and floor above. (Visibility tenability criteria: 15 feet).

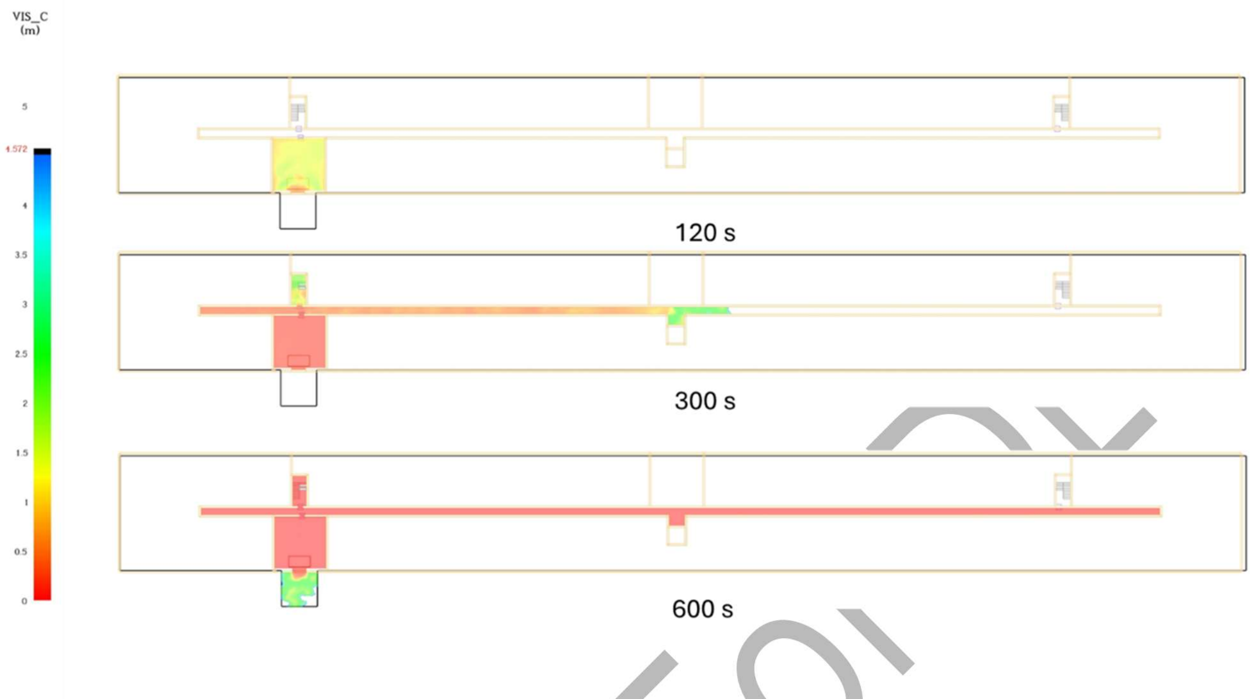
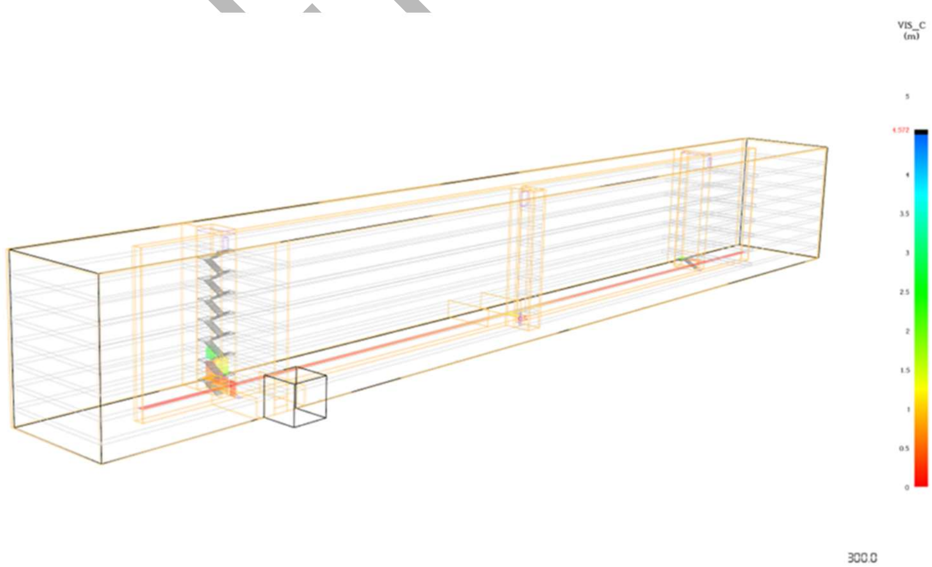


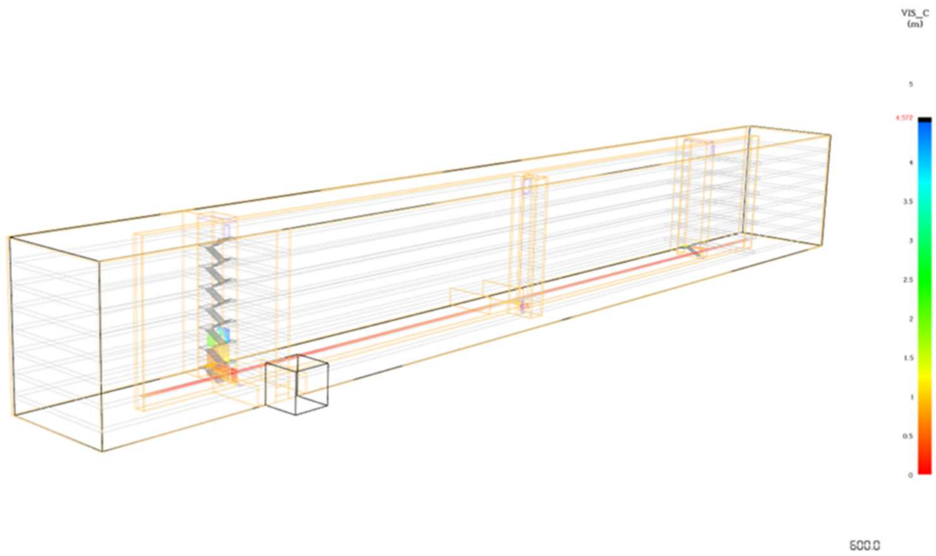
Figure H10. FDS visibility results of the fire floor in the 40,625 sf building with stairway door open on fire floor and floor above. (Visibility tenability criteria: 15 feet).

Scenario 1-4

Visibility was reduced below the tenability criterion of 15 feet in approximately 100% of the fire floor corridor within 90 seconds (Figure H11).



300s



600s

Figure H11. FDS visibility results of the 40,625 sf building with e-bike fire in corridor. (Visibility tenability criterion: 15 feet).

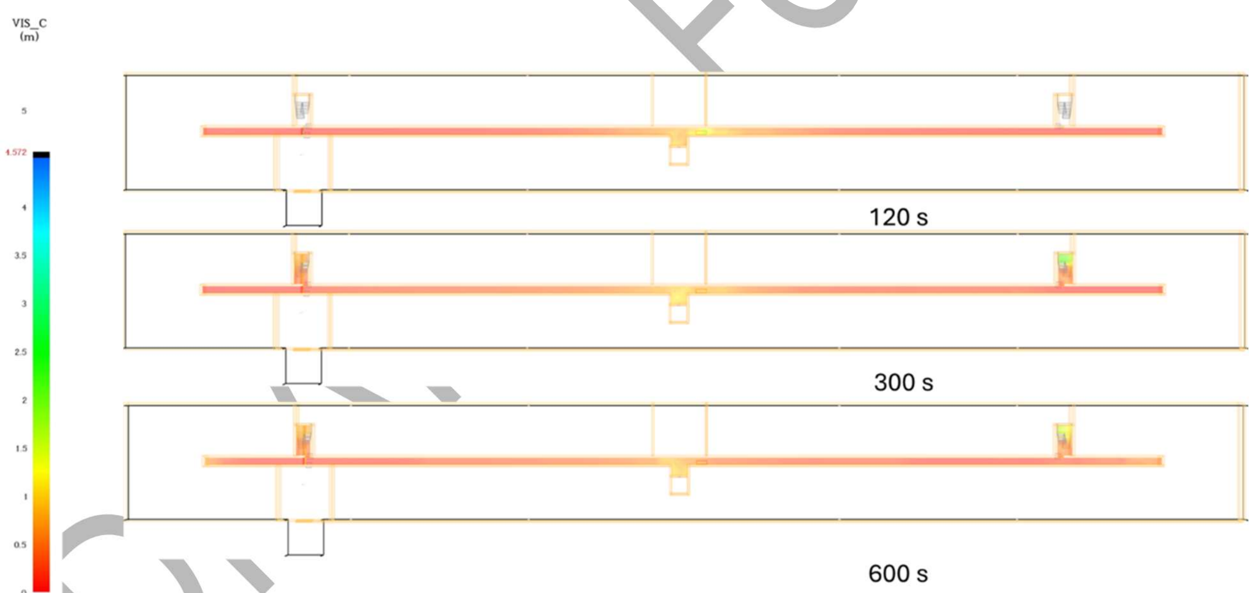


Figure H12. FDS results of the fire floor in the 40,625 sf building with e-bike fire in corridor

Egress Modeling Results

The occupant load on each floor is approximately 200 people. The movement time required to complete egress of the fire floor is approximately 60-120 seconds. See the discussion on consequences.

The movement time required to complete egress of the entire building is about 900-960 seconds when two stairways are available. When one of the stairways is blocked and only one stairway is available for egress, the movement time required to complete egress of the entire building exceeds 1800 seconds.

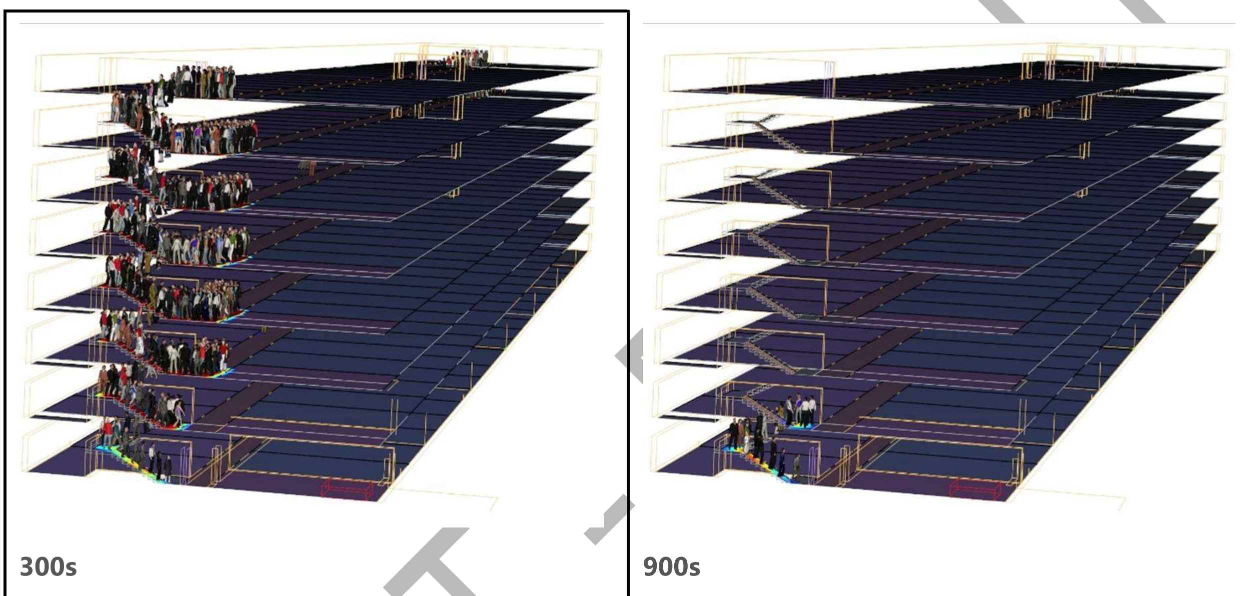


Figure H13. 40,625 square foot building egress model at 300 and 900 seconds where two stairways are available.

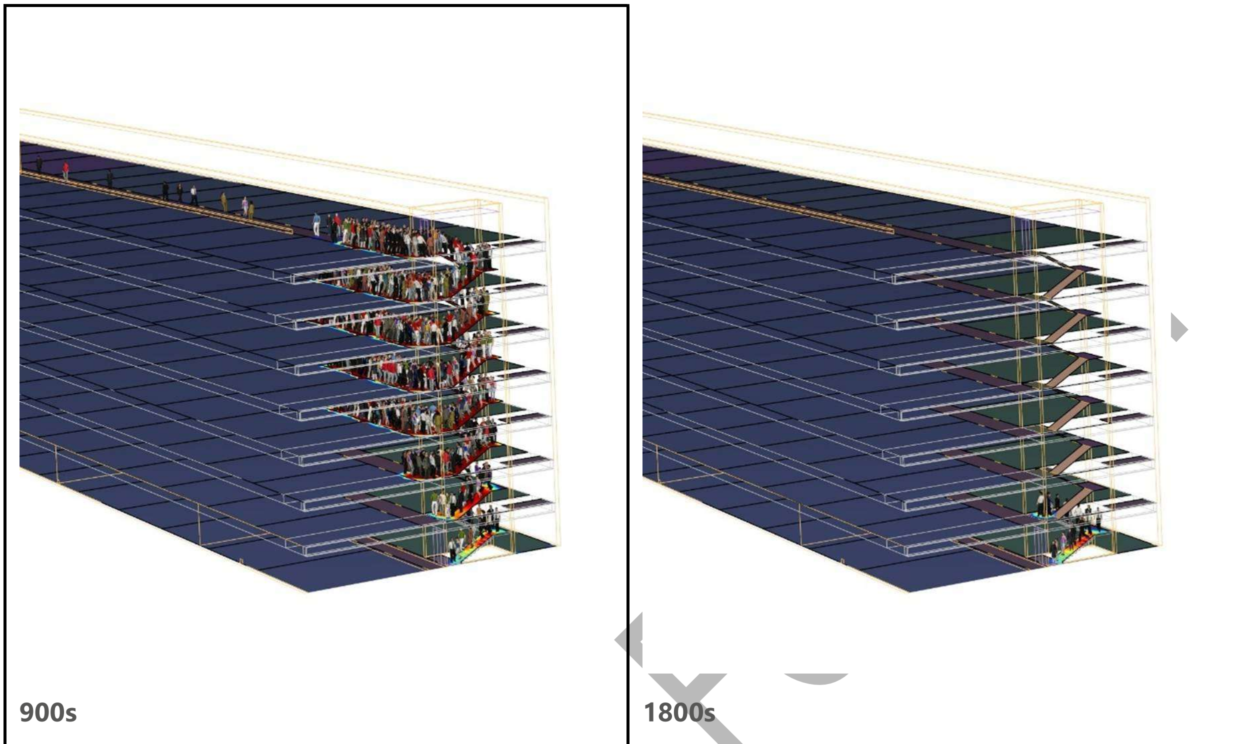


Figure H14. 40,625 square foot building egress model at 900 and 1800 seconds where one stairway is available and one stairway is blocked.

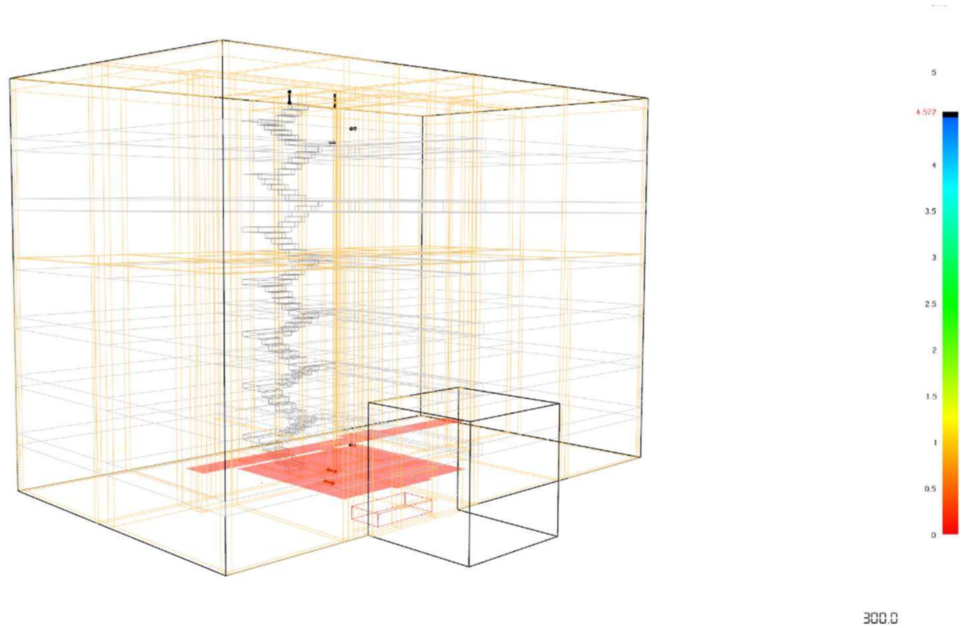
6,000 Square Foot Building Results

Fire Modeling Results

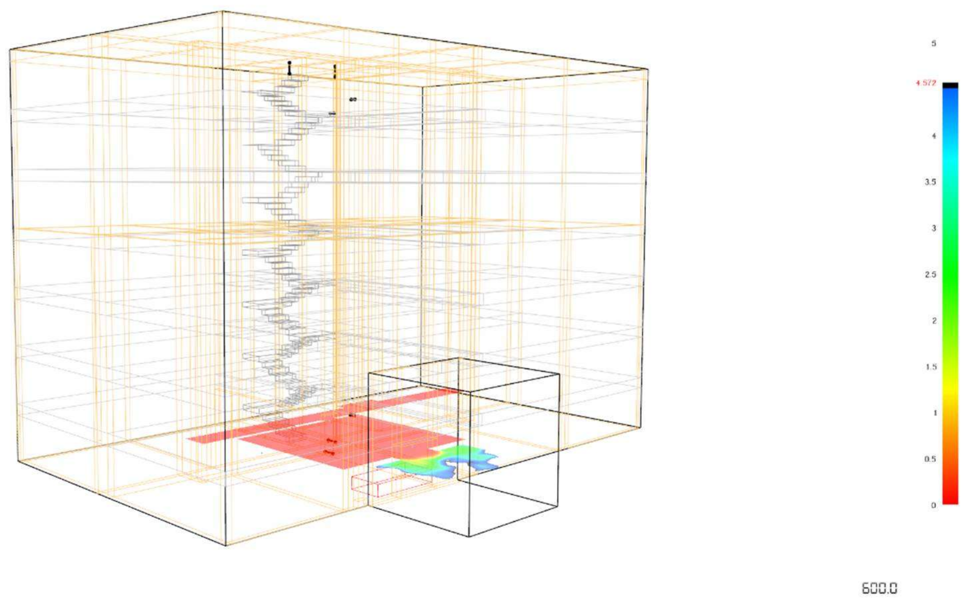
The fire modeling results for all scenarios in the 6,000 square foot building indicated that visibility within occupiable spaces was reduced below 15 feet (the selected tenability criteria) prior to increased temperatures or carbon monoxide concentrations exceeded their respective tentability thresholds. Therefore, visibility was determined to be the limiting factor when determining the ASET for each scenario. Visibility, temperature, and carbon monoxide concentration were each measured at an elevation of six feet above the walking surface of the fire floor.

Scenario 2-1

Visibility was reduced below the tenability criterion of 15 feet in approximately 100% of the fire floor corridor within 150 seconds (Figure H15).



300s



600s

Figure H15. FDS results of the 6,000-sf building with stairway door closed. (Visibility tenability criterion: 15 feet).

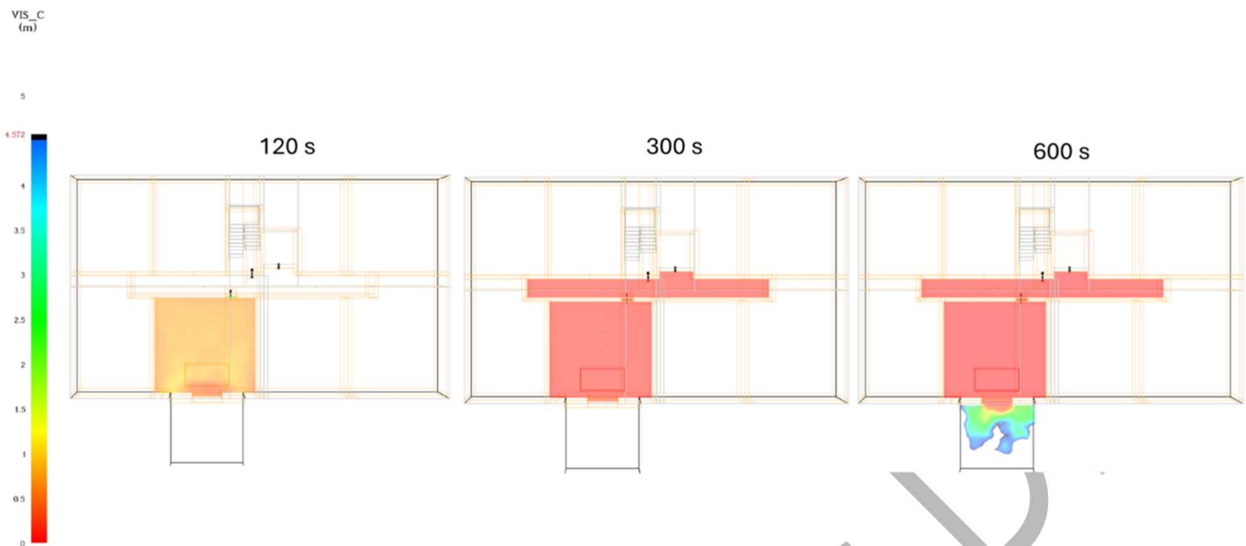
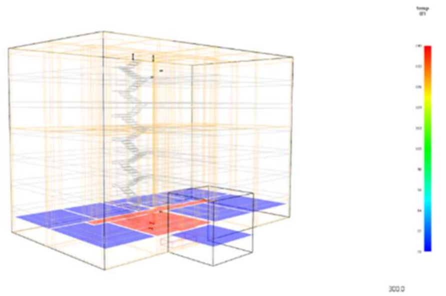
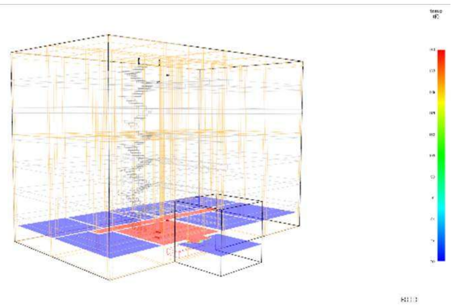


Figure H16. FDS results of the fire floor in the 6,000 sf building with stairway door closed. (Visibility tenability criterion: 15 feet).

Temperature was above the tenability criterion of 140°F in 100% of the fire floor corridor at 300 seconds. CO concentration was increased above the tenability criterion of 600 ppm in 100% of the fire floor corridor at 300 seconds.

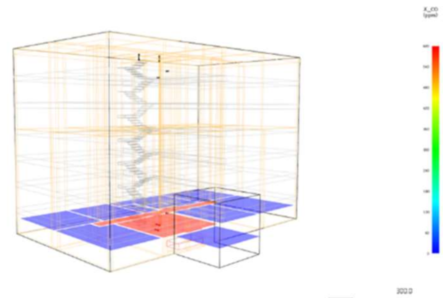


300s

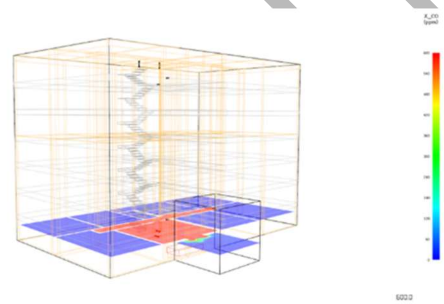


600s

Figure H17. FDS temperature results of the 6,000 sf building with stairway door closed. (Temperature tenability criterion: 140°F)



300s

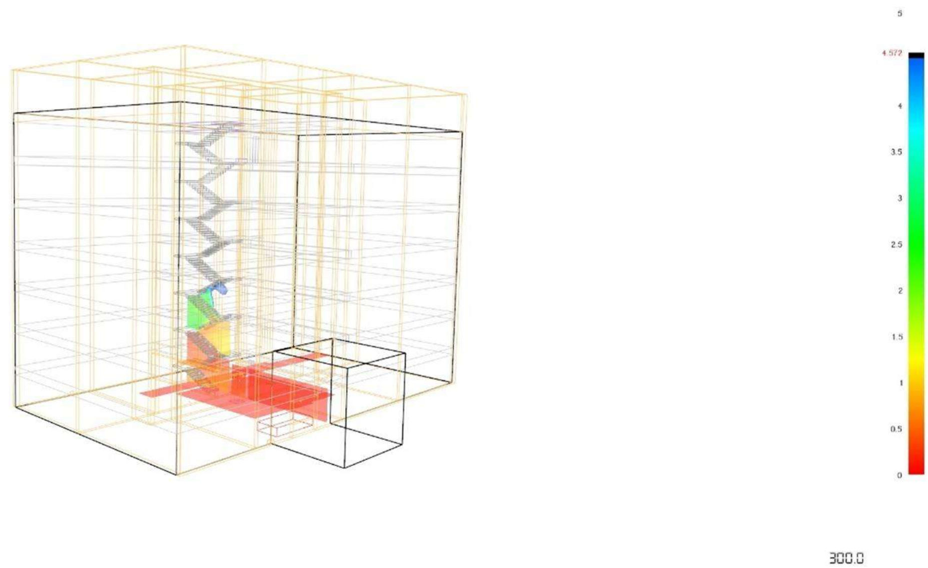


600s

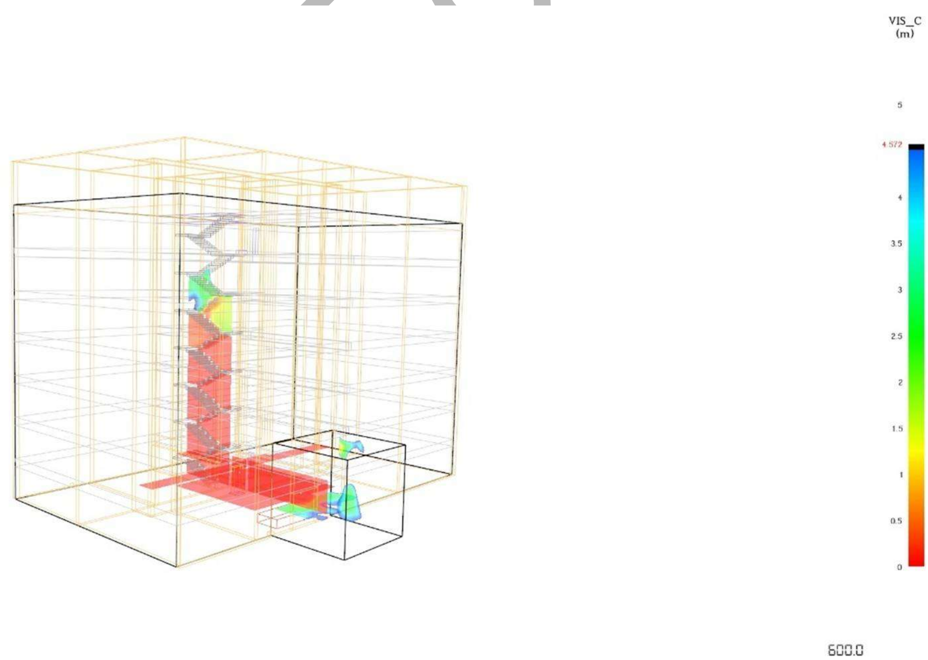
Figure H18. FDS carbon monoxide concentration. results of the 6,000 sf building with stairway door closed. (CO concentration tenability criterion: 600 ppm)

Scenario 2-2

Visibility was reduced below the tenability criterion of 15 feet in approximately 100% of the fire floor corridor within 150 seconds (Figure H19).



300s



600s

Figure H19. FDS results of the 6,000 sf building with stairway door open on the fire floor. (Visibility tenability criterion: 15 feet).

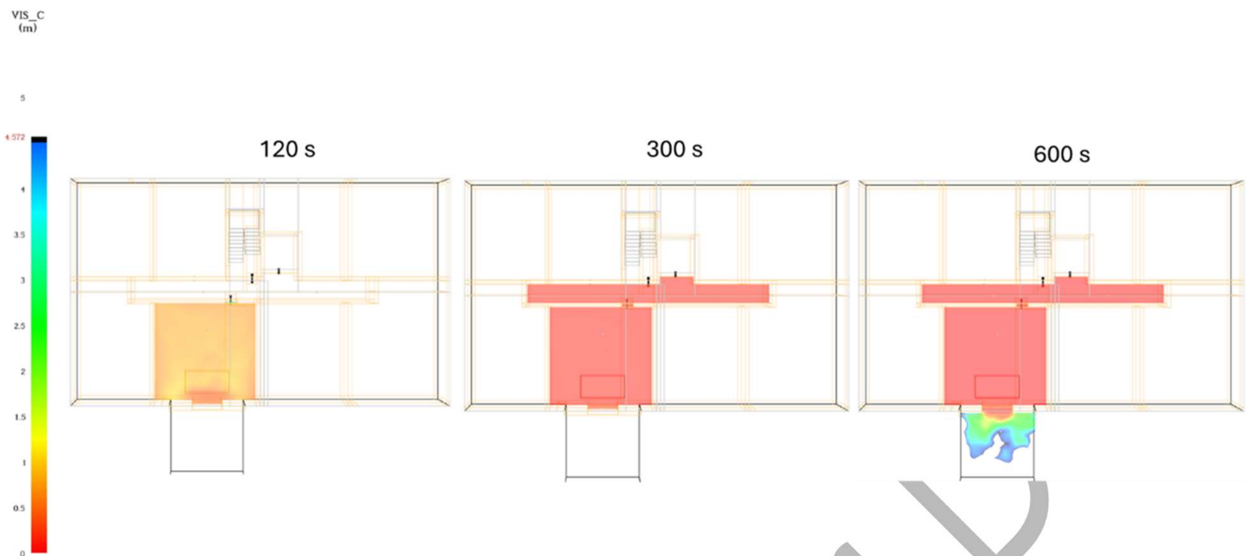
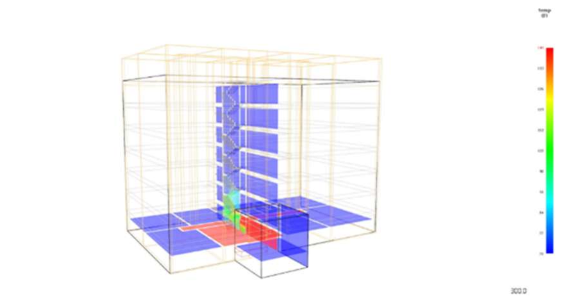


Figure H20. FDS results of the fire floor in the 6,000 sf building with stairway door open on the fire floor. (Visibility tenability criterion: 15 feet).

Temperature was above the tenability criterion of 140°F in 100% of the fire floor corridor at 300 seconds. CO concentration was above the tenability criterion of 600 ppm in 100% of the fire floor corridor at 300 seconds.



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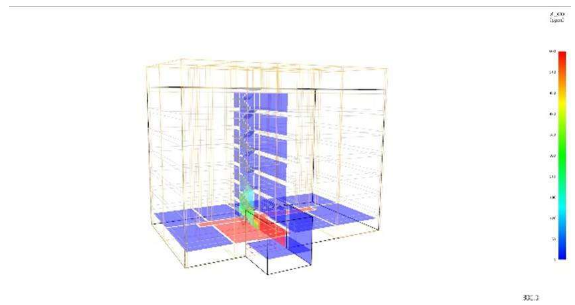

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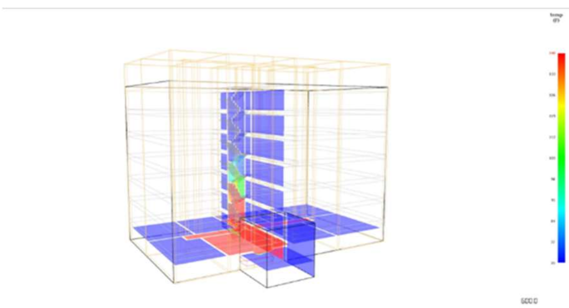

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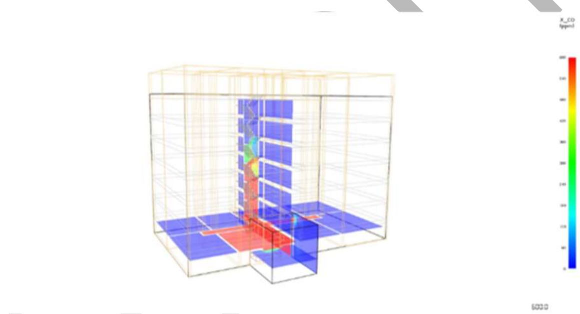


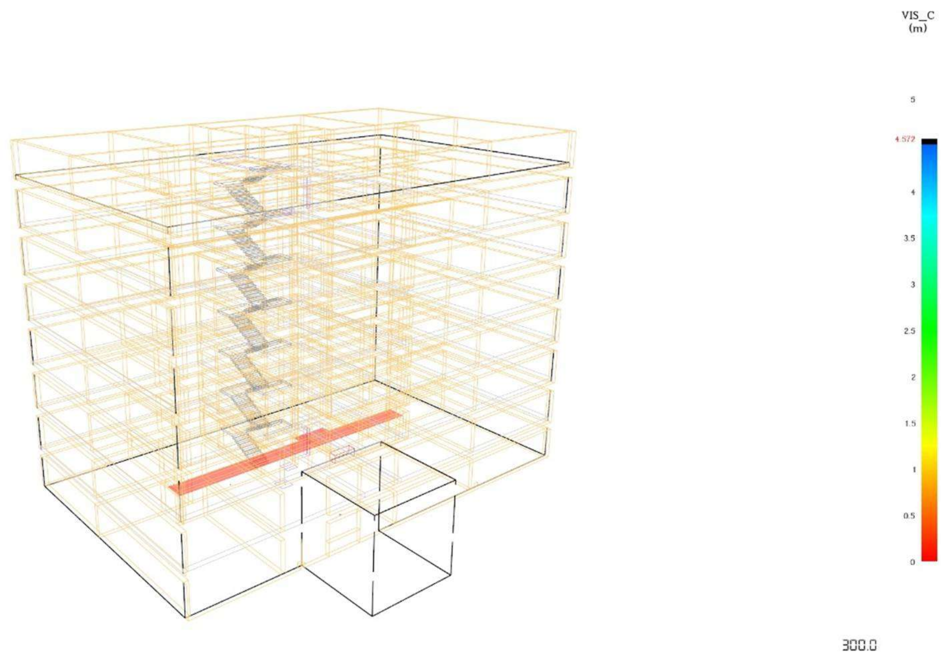
600s

Figure H21. FDS temperature results of the 6,000 sf building with stairway door open on the fire floor. (Temperature tenability criterion: 140°F)

Figure H22. FDS carbon monoxide concentration. results of the 6,000 sf building with stairway door open on the fire floor. (CO concentration tenability criterion: 600 ppm)

Scenario 2-3

Visibility was reduced below the tenability criterion of 15 feet in approximately 100% of the fire floor corridor within 300 seconds (Figure H23).



300s

600s

Figure H23. FDS results of the 6,000 sf building with e-bike fire in corridor. (Visibility tenability criterion: 15 feet).

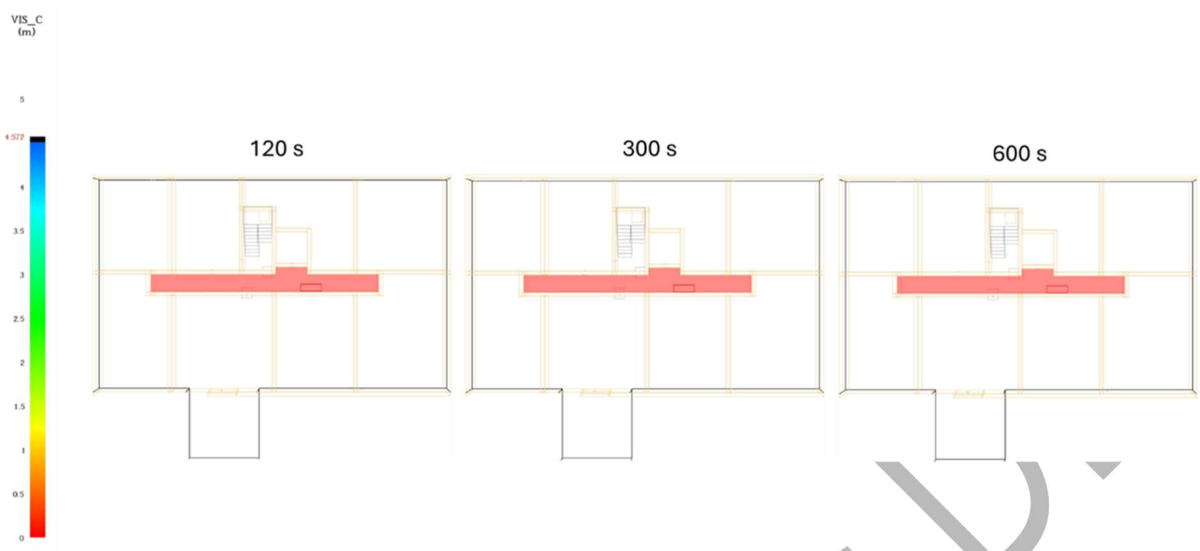


Figure H24. FDS results of the fire floor in the 6,000 sf building with e-bike fire in corridor. (Visibility tenability criterion: 15 feet).

Egress Modeling Results

The occupant load on each floor is approximately 30 people. The movement time required to complete egress of the fire floor is approximately 30-60 seconds. See the discussion on consequences.

The movement time required to complete egress of the entire building is approximately 270-300 seconds.

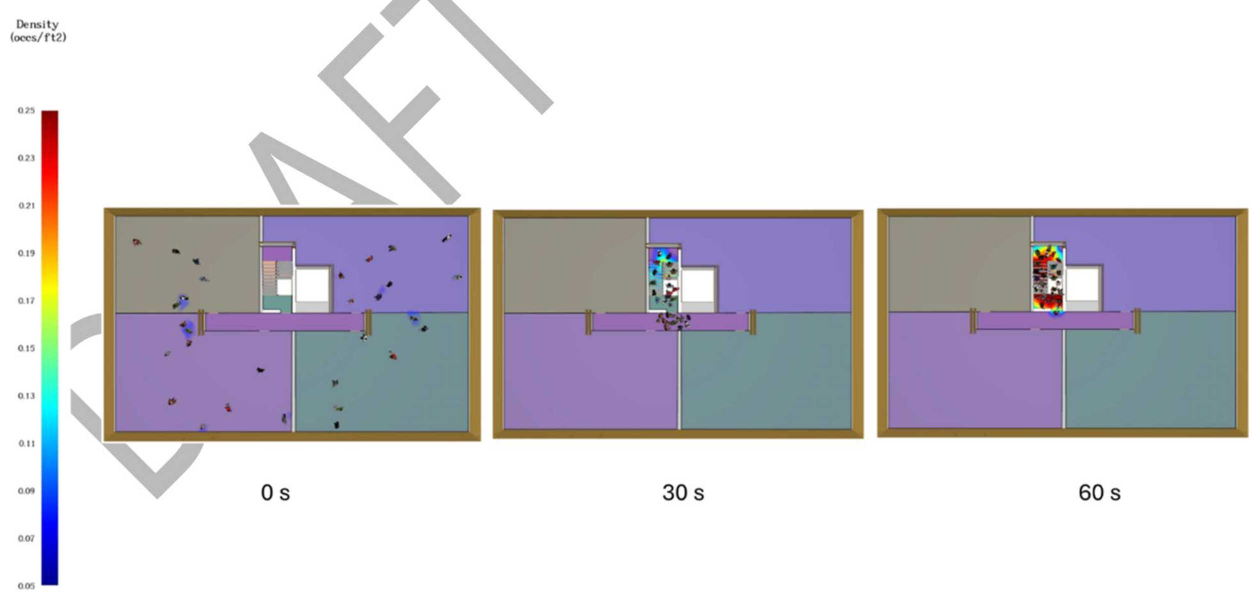


Fig.30 Egress model results of the fire floor in the 6,000 sf building

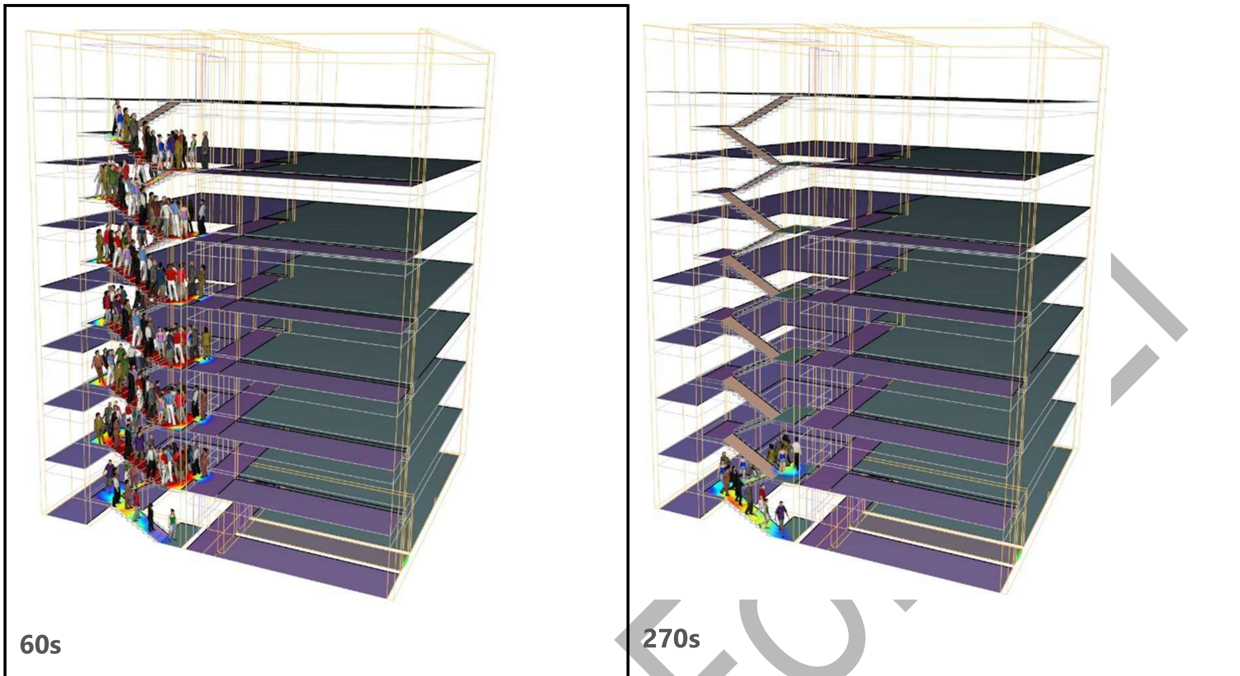


Figure H25. Egress model of 6,000 sf building at 60 and 270 seconds.

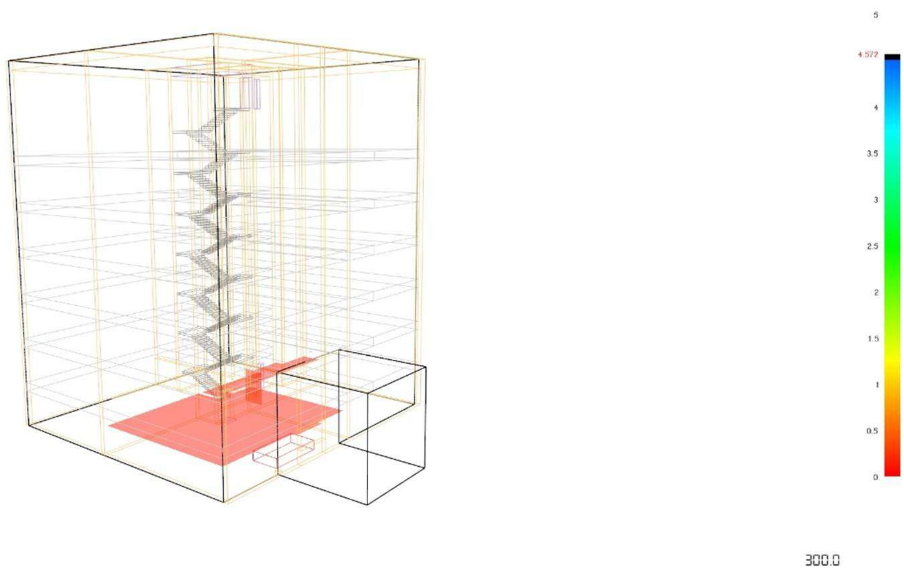
4,000 Square Foot Building Results

Fire Modeling Results

The fire modeling results for all scenarios in the 4,000 square foot building indicated that visibility within occupiable spaces was reduced below 15 feet (the selected tenability criteria) prior to increased temperatures or carbon monoxide concentrations exceeded their respective tentability thresholds. Therefore, visibility was determined to be the limiting factor when determining the ASET for each scenario. Visibility, temperature, and carbon monoxide concentration were each measured at an elevation six feet above the walking surface of the fire floor.

Scenario 3-1

Visibility was reduced below the tenability criterion of 15 feet in 100% of the fire floor corridor within 120 seconds (Figure H26).



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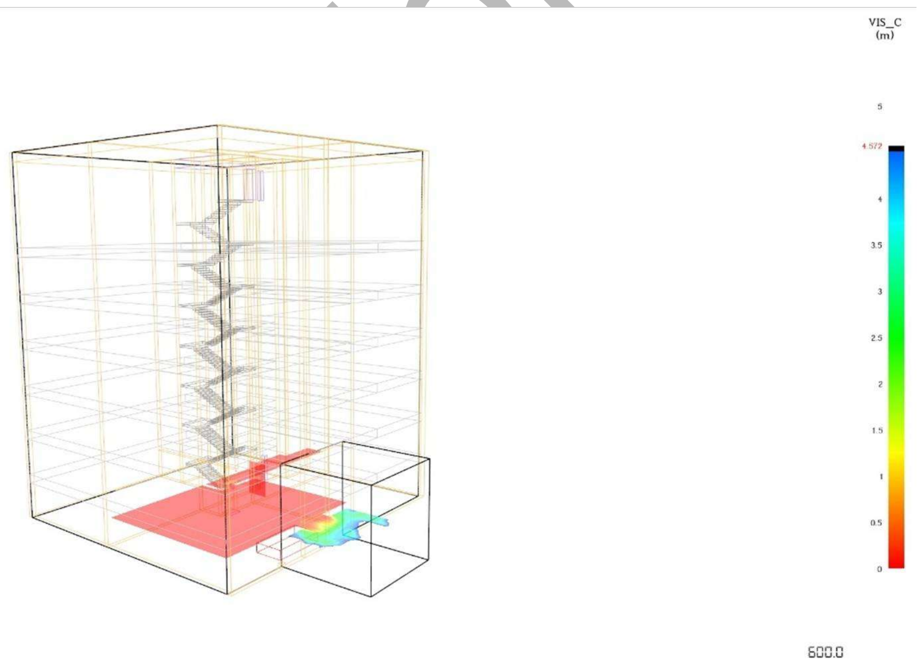


600s

Figure H26. FDS results of the 4,000 sf building with stairway door closed. (Visibility tenability criterion: 15 feet).

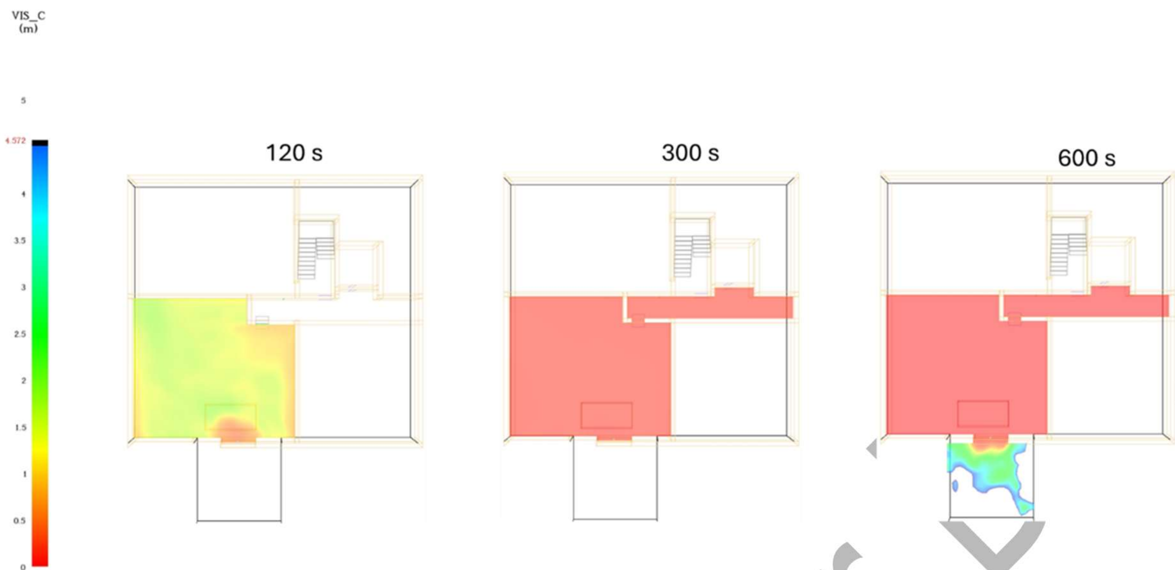
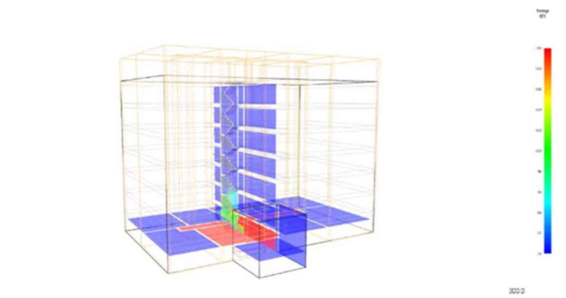
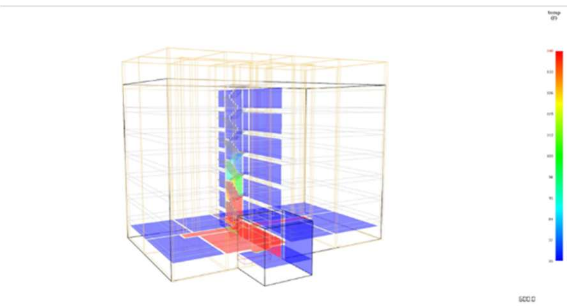


Figure H27. FDS results of the fire floor in the 4,000 sf building with stairway door closed. (Visibility tenability criterion: 15 feet).

Temperature was increased above the tenability criterion of 140°F in 100% of the fire floor corridor at 180 seconds. CO concentration was increased above the tenability criterion of 600 ppm in 100% of the fire floor corridor at 180 seconds.

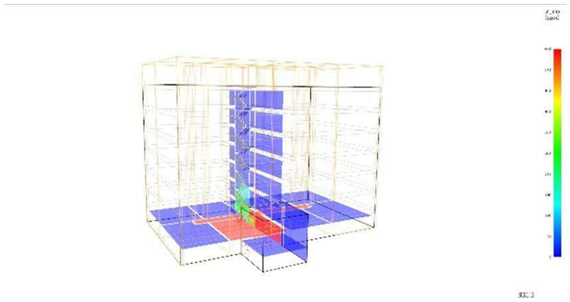


300s

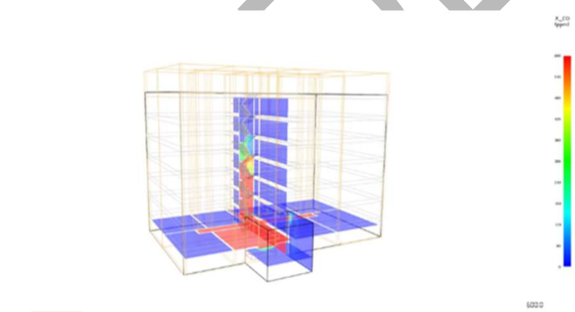


600s

Figure H28. FDS temperature results of the 4,000 sf building with stairway door closed. (Temperature tenability criterion: 140°F)



300s

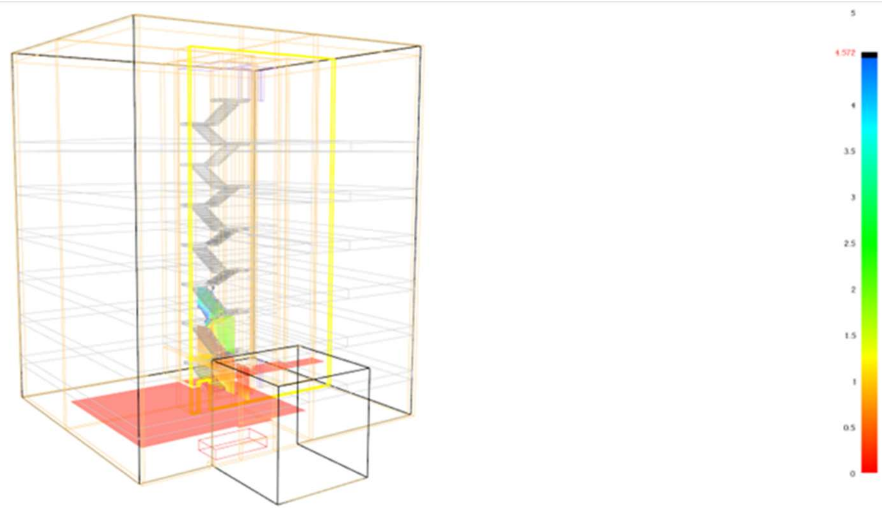


600s

Figure H29. FDS carbon monoxide concentration. results of the 4,000 sf building with stairway door closed. (CO concentration tenability criterion: 600 ppm)

Scenario 3-2

Visibility was reduced below the tenability criterion of 15 feet in 100% of the fire floor corridor within 120 seconds (Figure H30).



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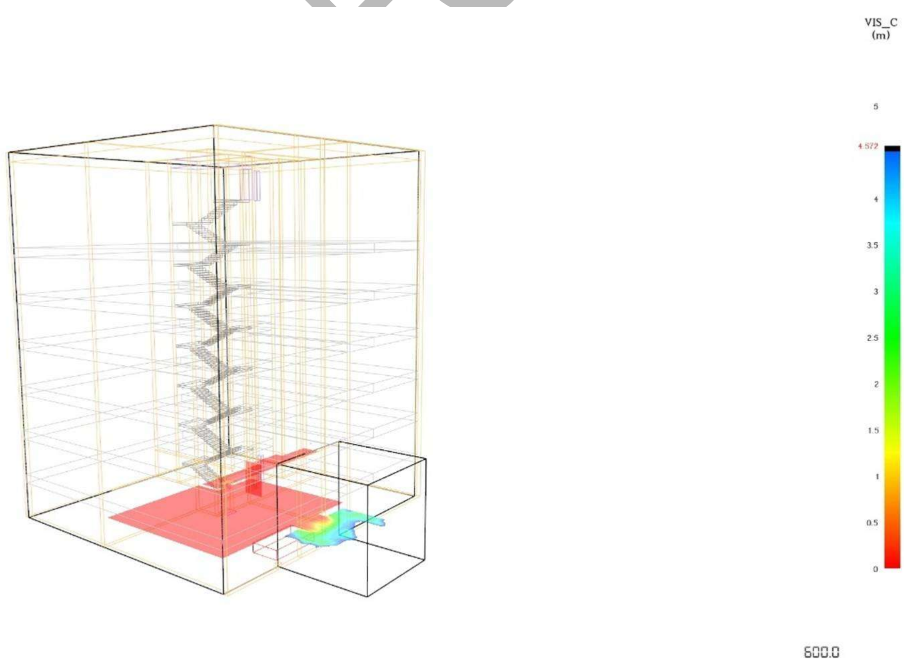


600s

Figure H30. FDS visibility results of the 4,000 sf building with stairway door open on the fire floor. (Visibility tenability criterion: 15 feet).

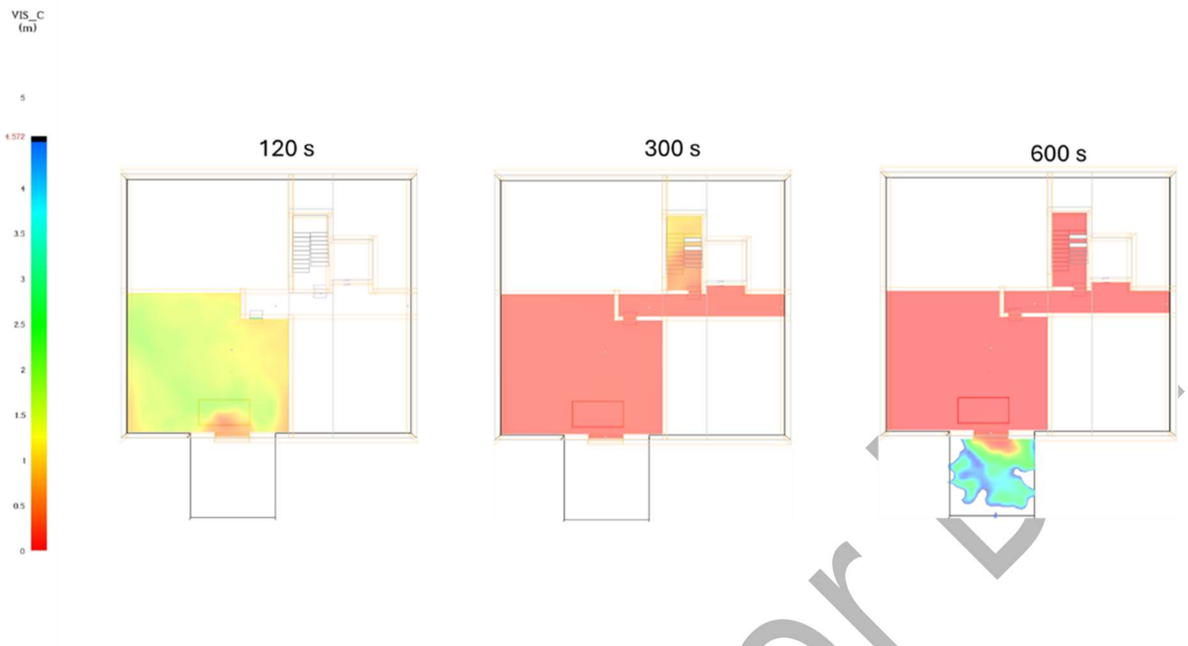
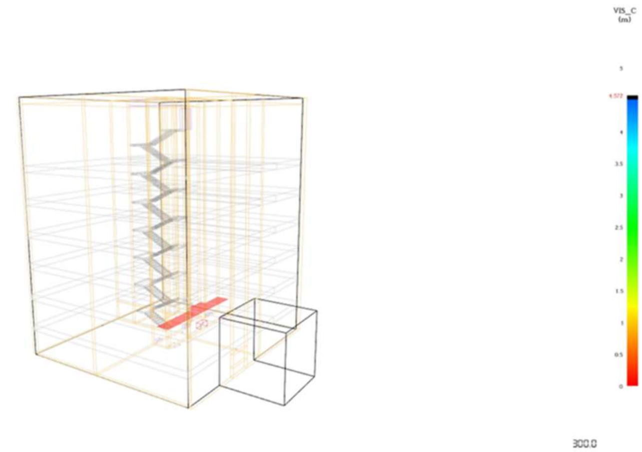


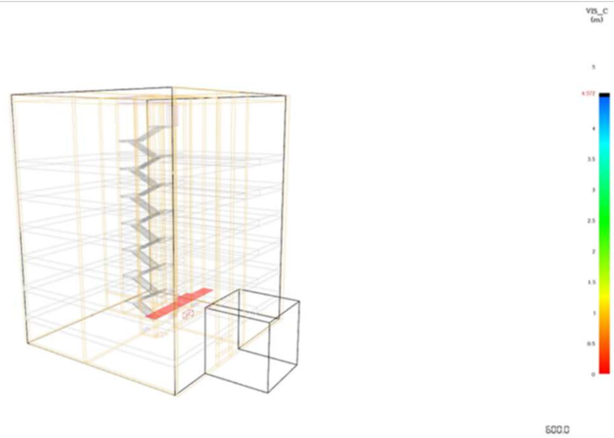
Figure H31. FDS visibility results of the fire floor in the 4,000 sf building with stairway door open on the fire floor. (Visibility tenability criterion: 15 feet).

Scenario 3-3

Visibility was reduced below the tenability criterion of 15 feet in 100% of the fire floor corridor within 30 seconds (Figure H32).



300s



600s

Figure H32. FDS visibility results of the 4,000 sf building with e-bike fire in corridor. (Visibility tenability criterion: 15 feet).

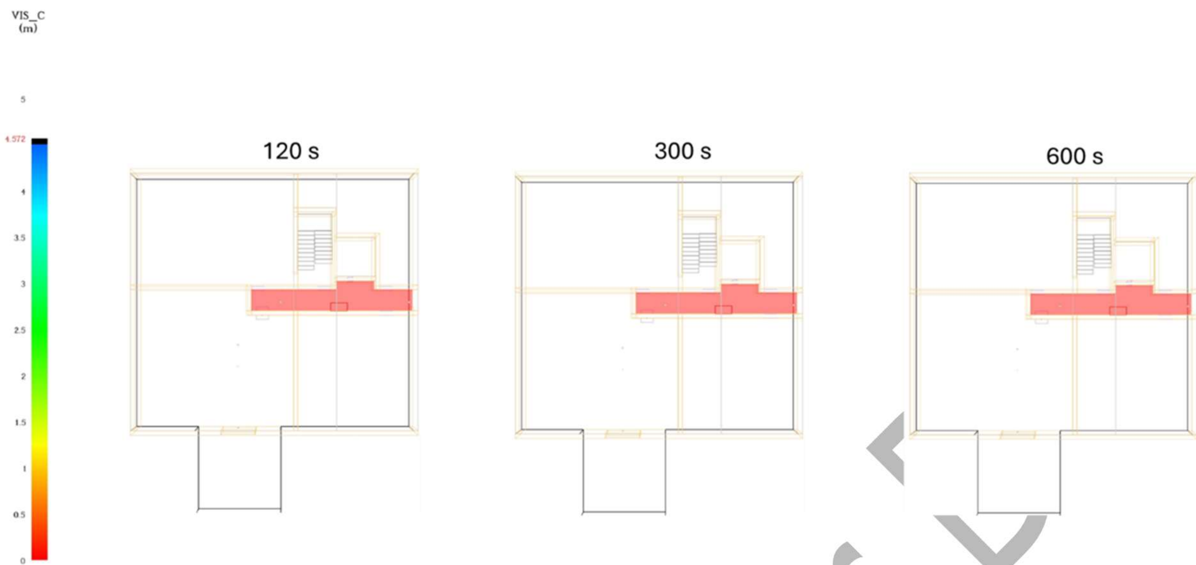


Figure H33. FDS visibility results of the fire floor in the 4,000 sf building with e-bike fire in corridor. (Visibility tenability criterion: 15 feet).

Egress Modeling Results

The occupant load on each floor is approximately 20 people. The movement time required to complete egress of the fire floor is approximately 20-30 seconds. The movement time required to complete egress of the entire building is approximately 210 seconds.

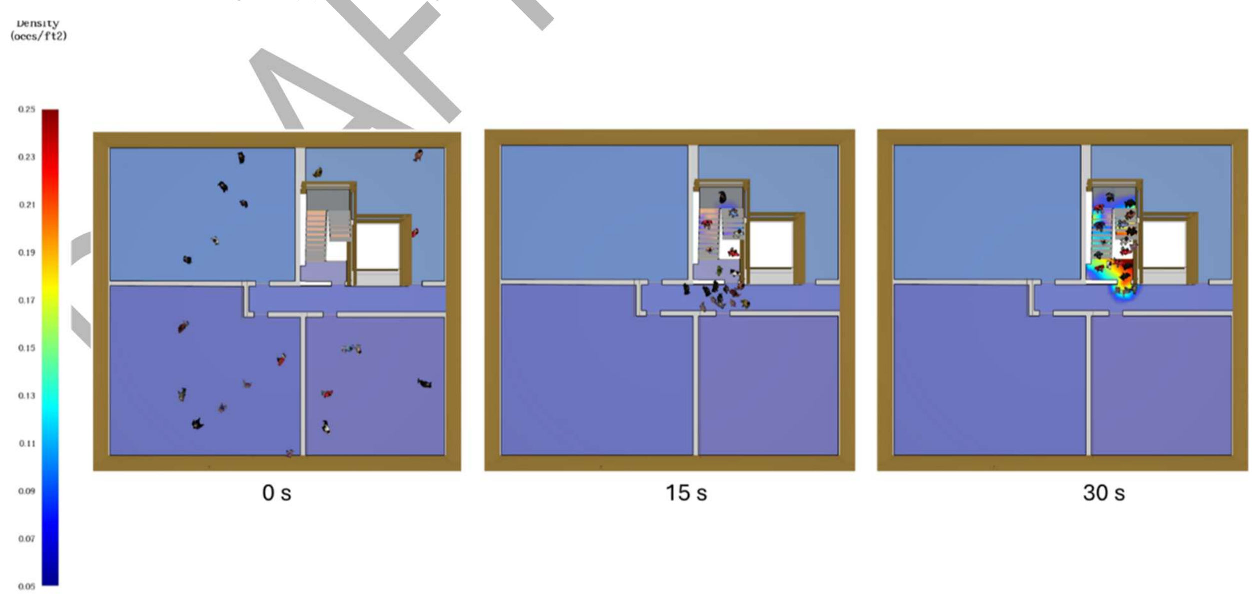


Figure H34. Pathfinder results of the fire floor in the 4,000 sf building

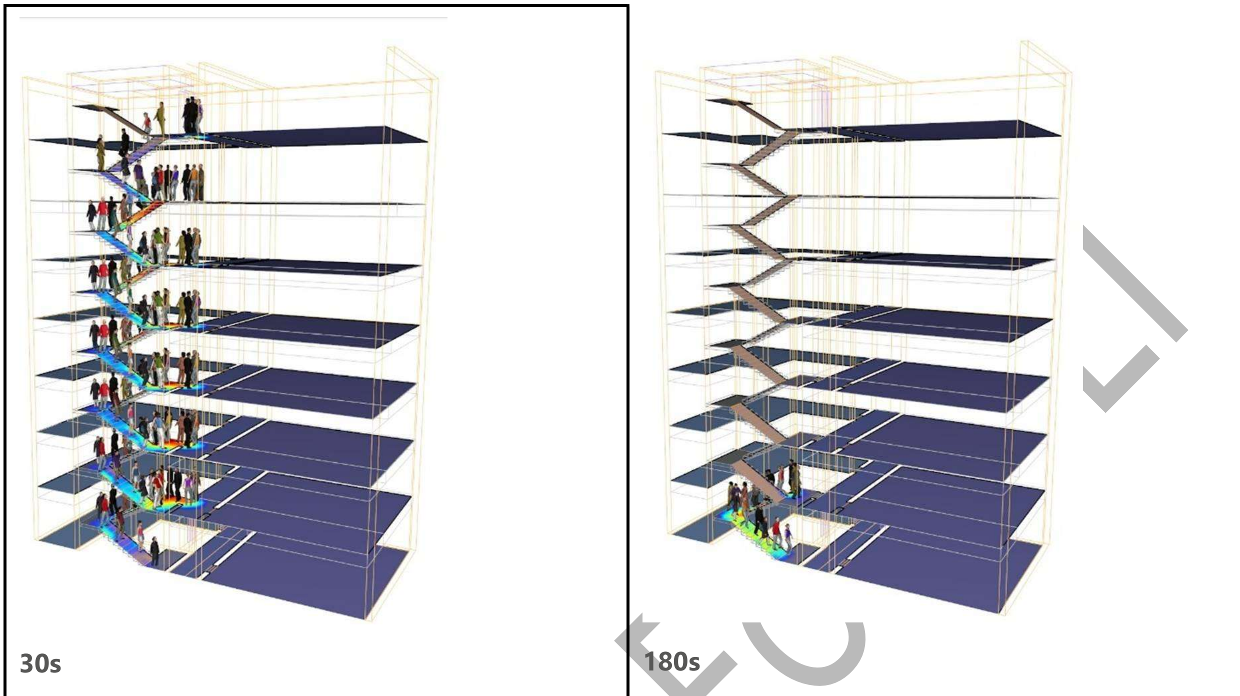


Figure H35. 4,000 sf building egress model at 30 and 180 seconds.

APPENDIX I– UNCERTAINTY DISTRIBUTIONS

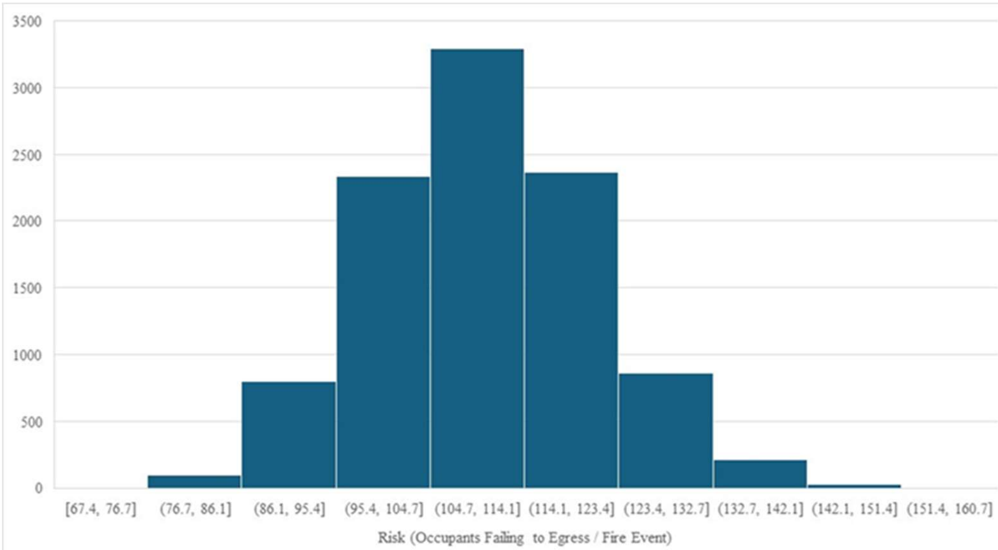


Figure I1. Uncertainty Distribution for Building 1 Dwelling Unit Fire

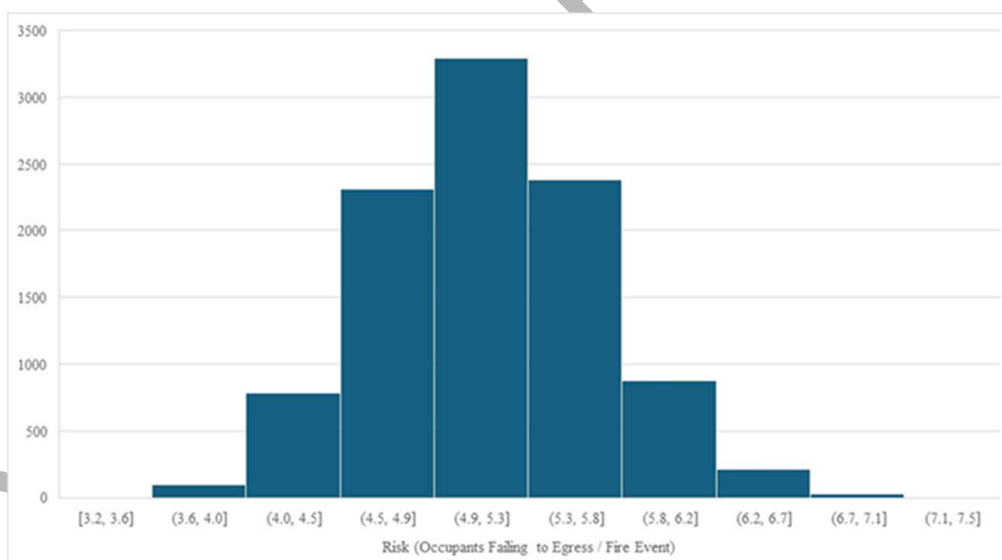


Figure I2. Uncertainty Distribution for Building 2 Dwelling Unit Fire

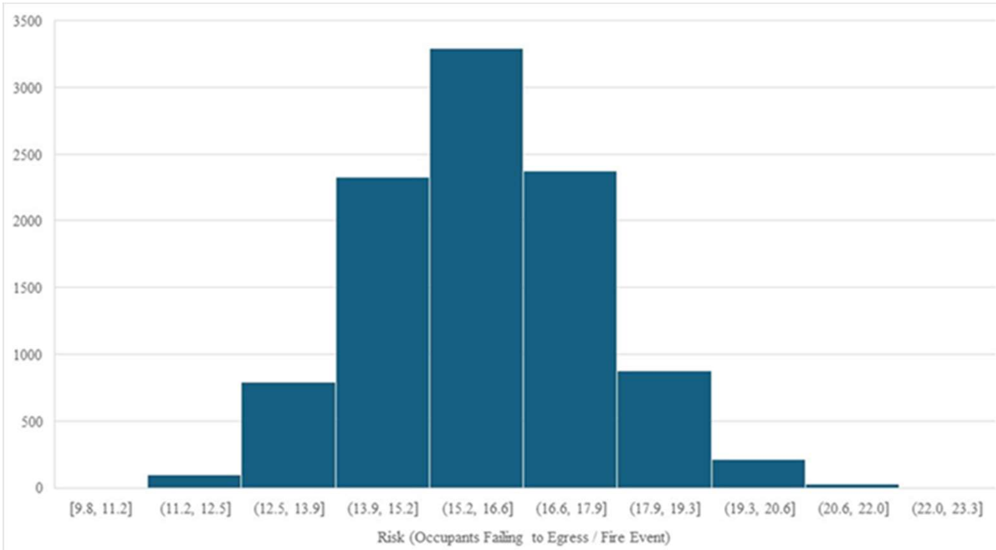


Figure I3. Uncertainty Distribution for Building 3 Dwelling Unit Fire

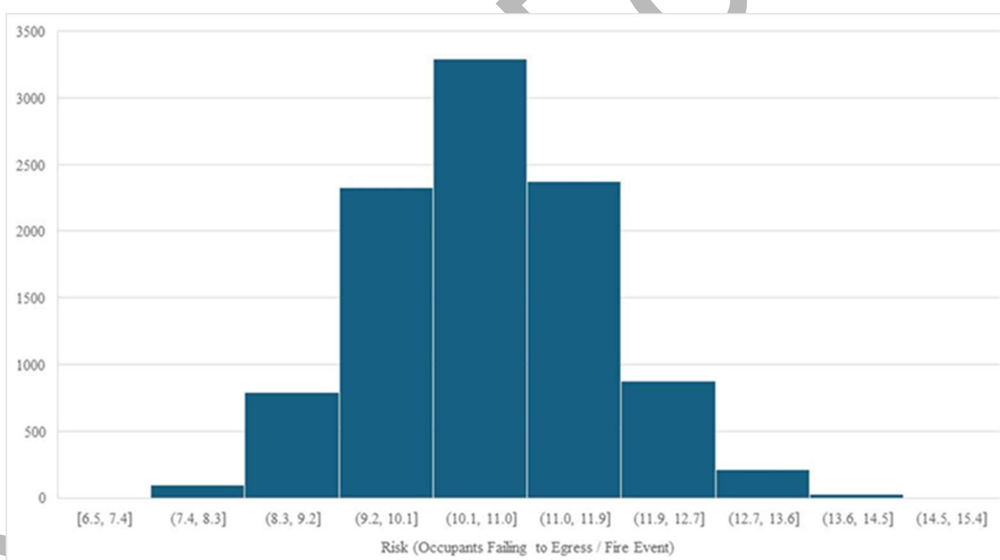


Figure I4. Uncertainty Distribution for Building 4 Dwelling Unit Fire

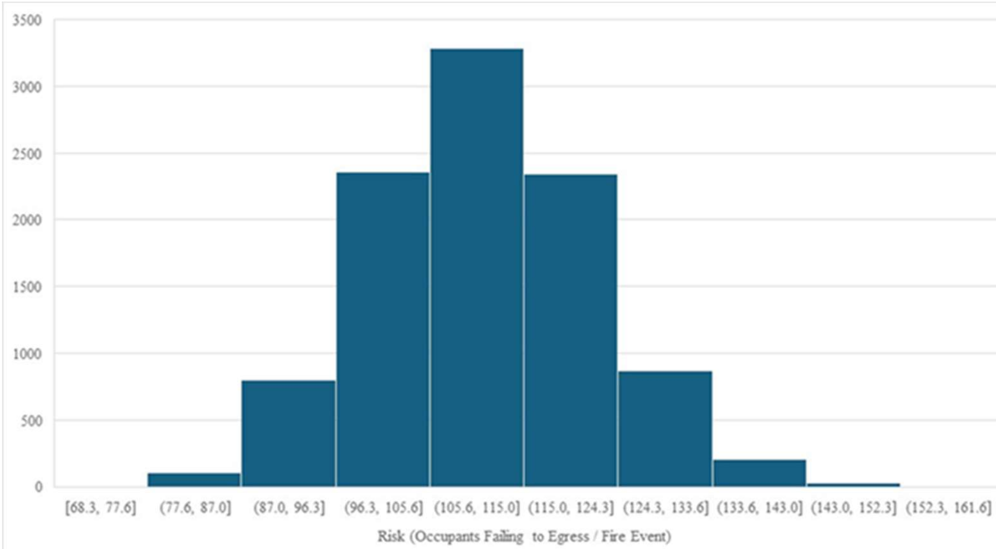


Figure I5. Uncertainty Distribution for Building 1 Corridor Fire

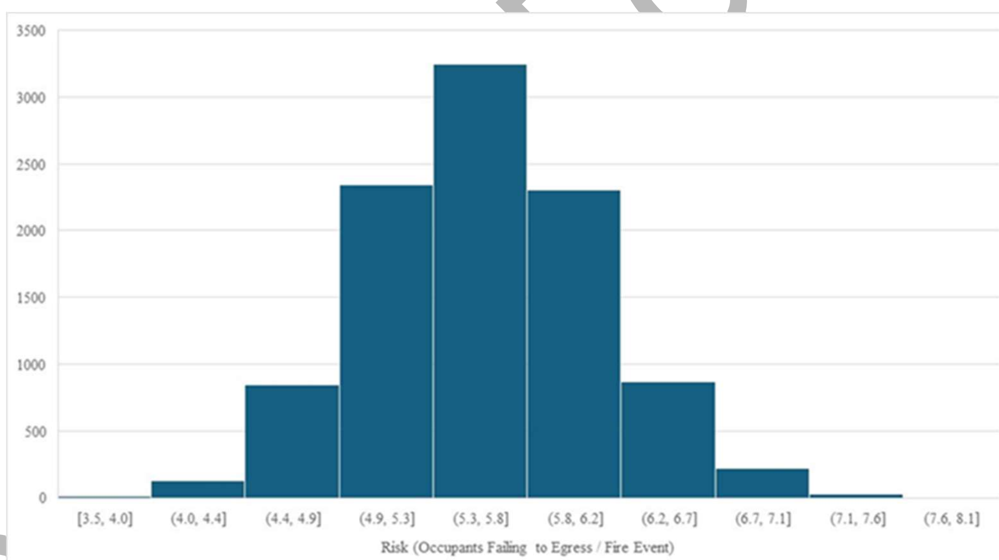


Figure I6. Uncertainty Distribution for Building 2 Corridor Fire

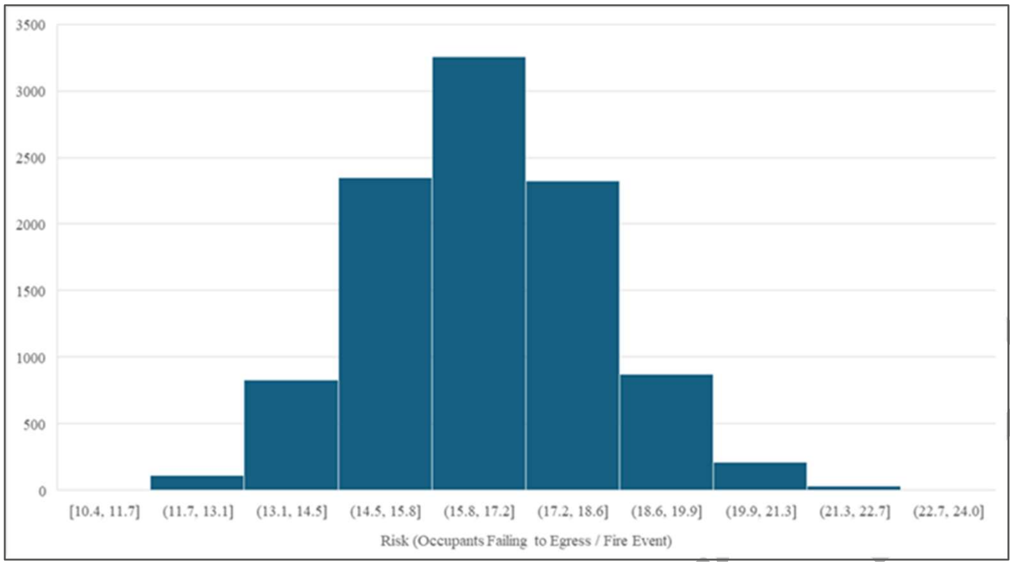


Figure I7. Uncertainty Distribution for Building 3 Corridor Fire

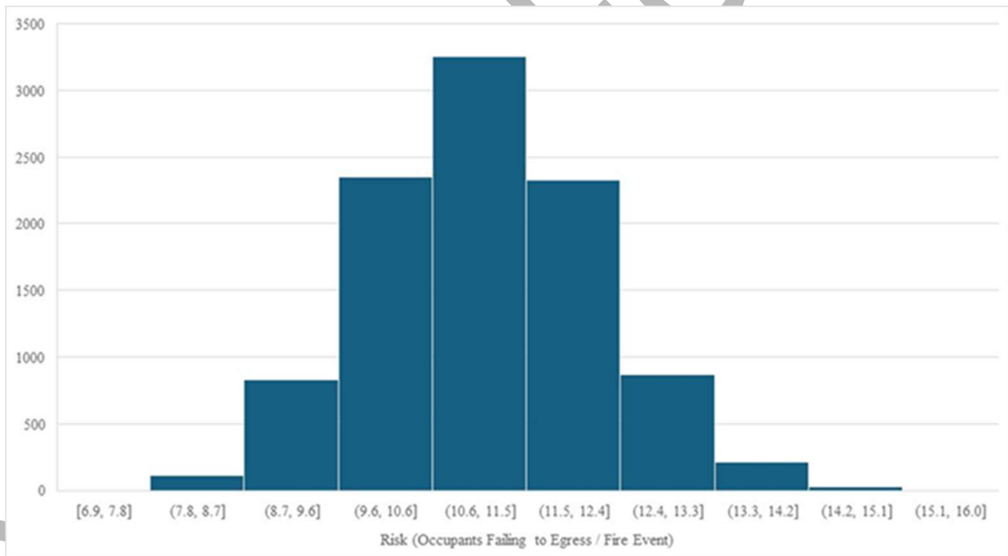


Figure I8. Uncertainty Distribution for Building 4 Corridor Fire

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