PERFORMANCE-BASED LIFE SAFETY ASSESSMENT OF THE FAST GARAGE

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ACKNOWLEDGEMENTS

The study was a group effort of the engineering and administrative staff of Koffel Associates, Inc., Columbia, MD office. The study required the combined efforts of many individuals to develop the design, calculations, modeling, analysis and graphics for the project.

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EXECUTIVE SUMMARY

The Society of Fire Protection Engineers (SFPE) provided three (3) case study specifications from which teams around the world could choose to prepare a performance-based fire safety strategy. The case studies provided were as follows:

- Case Study 1 - Underground Car Park
- Case Study 2 - Production and Storage Building
- Case Study 3 - Shopping Center

The results of the performance-based analysis will be presented at the SFPE 11th International Conference on Performance-Based Codes and Fire Safety Design Methods in Warsaw, Poland on May 23-25, 2016. Each case study specified unique performance objectives, a basic building description, floor plans, and minimum project requirements. Koffel Associates, Inc. has chosen to prepare Case Study 1 - Underground Car Park and has made additional assumptions to complete the performance-based design analysis.


The stakeholders determined that good communication and a team approach were essential to the following building evaluation process:

- Define Project Scope
- Identify Fire Safety Goals and Objectives
- Develop Performance Criteria
- Develop Design Fire Scenarios
- Develop and Evaluate Trial Designs
- Select Final Design
- Prepare Design Documentation

The building owner, insurance company, architectural and engineering firm, local Authority Having Jurisdiction (AHJ), and the fire protection engineer were determined to be the primary project stakeholders. The stakeholder’s fire safety goals and objectives provided the framework to develop design objectives and performance criteria to assess the level of fire safety in the building. The fundamental fire safety goal for the project is to provide life safety for the public, building occupants and firefighters by minimizing fire-related injuries and prevent undue loss of life. The goal will be achieved by meeting the following objectives:

- Safeguard occupants from injury due to fire and smoke until they reach a safe place
- Safeguard fire fighters while performing rescue operations or attacking the fire
- Limit the fire damage to the structure
Additional objectives of the owner are as follows:

- Allow for a row of double-stacked cars to maximize the use of the space
- Provide design with and without sprinkler protection to allow flexibility in construction options and cost

Limiting potential fire and smoke exposure of occupants to hazardous conditions is the primary means for achieving the objectives. It was determined that the fire safety goals for the project and the ICCPC regulatory fire safety objectives were consistent and did not conflict.

Risk factors, use of the building, and magnitudes of each of the design fire scenarios were analyzed to develop a basis for the building design. The building was determined to be a Performance Group II, which is defined by the ICCPC as the minimum design performance level with which all buildings or facilities shall comply.

The design objectives were refined into performance criteria which can be quantified and therefore evaluated. The tenability criteria used was as follows:

- Air temperature 76°C (20 minute exposure)
- Radiant heat flux 2.5 kW/m² (maximum)
- Smoke obscuration 10 m visibility (minimum)
- CO concentration 2000 ppm (20 minute exposure)
- HCN concentration 100 ppm (20 minute exposure)

The limits for tenability criteria were quantified using either conservative maximum tolerable levels or by comparison to a time-concentration exposure curve. The visibility limit of 10 m (32.8 ft) was used due to the wide-open nature of the space. Oxygen depletion was not determined to pose a risk to occupants, as none of the scenarios considered involved under-ventilated fires, where oxygen depletion is a factor.

Design fire scenarios were developed to evaluate the proposed building designs. The design fire scenarios listed below are based on realistic fire situations that could occur in the building.

- Fire in stacked gas engine vehicles involving multiple vehicles
- Battery electric car fire blocking stair in plan lower right corner

Fire modeling was performed using Fire Dynamics Simulator. The physical phenomenon evaluated included temperature, heat flux, gas concentrations, heat-release rate, ventilation, visibility, and detector and sprinkler response times.

Egress calculations were performed using the hydraulic model of emergency egress. The time required for occupant evacuation of certain areas, floors, and the entire building was compared against the available safe egress time for each design fire scenario.

The evaluation was based on the use of the space and the arrangement of architectural features. Six (6) exit stairs are available on each level. The total egress time, including pre-movement time, for the building was determined to be approximately 16.5 minutes, assuming 100% of occupants use the exit stairs. Emergency occupant evacuation by elevator is not available within
the building; however, the stair vestibules act as areas of refuge for occupants with disabilities. In all building areas, the available safe egress time was greater than the required safe egress time.

Trial fire safety designs are potential protection options to meet the fire safety goals and objectives established for the project and are provided below:

- **With Automatic Sprinkler System:**
  - Smoke detection was required to provide early occupant notification to ensure tenable conditions exist during the evacuation.
  - Smoke exhaust system was required to maintain tenable conditions.

- **Without Automatic Sprinkler System:**
  - Smoke detection was required to provide early occupant notification to ensure tenable conditions.
  - Smoke exhaust system was required to maintain tenable conditions at a larger exhaust rate than the sprinkler-protected building trial.

The design fire scenarios, egress calculations, and trial building designs were combined to address the fire safety objectives. By comparing the design fire safety scenarios with the fire safety goals and objectives, it was determined that each objective was adequately met. The objectives were met by the following building design features:

- Training of garage staff for prompt evacuation
- Smoke exhaust system
- Emergency voice/alarm voice communication system
- Fire command center with life safety and utility system controls
- Pressurization of the elevator hoistways and the six enclosed exit stairs
- Building frame provided with 3-hr fire-resistance rated structural frame and 2-hr floor slabs
- Complete, supervised automatic sprinkler system throughout building

In the case of the building not being provided with complete automatic sprinkler protection, a larger exhaust rate is required to maintain tenable conditions during egress.

The building design was compared against prescriptive code requirements to develop a baseline for the building design and an analysis was performed to determine if alternative safety measures were required. The prescriptive code deficiencies followed by analysis is detailed below:

- Dead end greater than 20 ft without sprinkler system or 50 ft with sprinkler system. The dead end at the plan southeast corner of the garage exceeds both of the permitted values.

In the sprinkler system design the combined standpipe/sprinkler system will be connected to the municipal water supply and supplemented by a fire pump to meet the hydraulic demand of the system.

The performance-based process for building design has developed an adequate level of life safety deemed acceptable by the stakeholders without imposing unnecessary constraints on other aspects of the building design as intended. The stakeholders have agreed that the building design meets the fire safety goals, design objectives, and performance criteria thereby ensuring safety to building occupants.
GLOSSARY

Design Fire – A quantitative description of a fire, including growth rate, peak heat release rate, and burning duration, for use in a design fire scenario.

Design Fire Scenario – A set of conditions that defines or describes the critical factors for determining outcomes of trial designs. Conditions include, but are not limited to, the location, duration, size, and development of the fire; building characteristics (e.g., construction ventilation, openings/connections between areas); passive and active fire protection systems; and occupant characteristics.

Fire Dynamics Simulator (FDS) - FDS is a computational fluid dynamics (CFD) model of fire-driven fluid flow developed by the National Institute for Standards and Technology (NIST) located in Gaithersburg, Maryland. The software solves numerically a large eddy simulation form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires.

Fire Hazard – Any situation, process, material, or condition that, on the basis of applicable data, may cause a fire or explosion, or provide a ready fuel supply to augment the spread or intensity of the fire or explosion and that poses a threat to life or property.

Fire Safety Goals – Desired overall fire safety outcome expressed in qualitative terms.

Fire Safety Objective – A requirement of the fire, building, system, or occupants that needs to be fulfilled in order to achieve a fire safety goal.

Flashover – The transition from a growing fire to a fully-developed fire in which all combustible items in the compartment are involved in fire. Gas temperatures of 500 to 600°C (932 to 1112°F) or an incident heat flux at the floor level of 20 kW/m² typically signify the onset of flashover conditions.

Hazard – A possible source of danger that can initiate or cause undesirable consequences if uncontrolled.

Performance-Based Design – An engineering approach to fire protection design based on (1) established fire safety goals and objectives; (2) deterministic and/or probabilistic analysis of fire scenarios; and (3) quantitative assessment of design alternatives against the fire safety goals and objectives using accepted engineering tools, methodologies, and performance criteria.

Performance Criteria – Criteria stated in engineering terms against which the adequacy of any developed trial design will be judged.

Safety Factor – Adjustments made to compensate for uncertainty in the methods, calculations, and assumptions employed in the development of engineering designs.

Stakeholder – A person who has a vested interest (financial or safety related) in the successful completion of the project.

Trial Design – A fire protection system design intended to achieve the stated fire safety goals and expressed in terms that make it possible to assess whether the fire safety goals have been achieved.
1. INTRODUCTION

1.1 Project Background

The Society of Fire Protection Engineers (SFPE) provided three (3) hypothetical case study specifications for a performance-based design for the 11th International Conference on Performance-Based Codes and Fire Safety Design Methods to be held in Warsaw, Poland. The three case study options are as follows:

- Case Study 1 - Underground Car Park
- Case Study 2 - Production and Storage Building
- Case Study 3 - Shopping Center

Koffel Associates Inc. chose to undertake a performance-based design for Case Study 1 - Underground Car Park. The garage is described as a two-story underground car park located under an office or residential building.

The specification also contained the fire and life safety objectives, a basic building description, drawings, and minimum requirements for the project. Koffel Associates, Inc. supplied additional assumptions, as described throughout this report.

Koffel Associates completed a performance-based analysis of the building. Based on the analysis, two proposed Final Designs are provided; one with sprinkler protection and one without, including recommended fire and life safety features to ensure the fire safety goals and objectives are met. The evaluation methods and results of the analysis are documented herein.

1.2 Methodology


The SFPE Guide outlines the steps necessary to evaluate performance-based design options. The following tasks are specified in the Guide and were included in this evaluation:

- Define Project Scope
- Identify Fire Safety Goals and Objectives
- Develop Performance Criteria
- Develop Design Fire Scenarios
- Develop and Evaluate Trial Designs
- Select Final Design
- Prepare Design Documentation

A code analysis was performed to determine prescriptive code requirements based upon the International Code Council (ICC), International Building Code®, 2015 Edition (IBC). The prescriptive requirements were not used as a basis for design, only as a point of comparison to the performance-based design.
2. PROJECT SCOPE

2.1 Project Description

The objective of the project is to undertake a performance-based fire safety analysis and design for a new two-story underground parking garage. The analysis demonstrates that the fire safety goals and objectives are met, provided the recommended fire safety design features contained in Section 7 are implemented.

Due to the hypothetical nature of the case study, several assumptions were made and detailed throughout the report.

2.2 Codes and Standards

The applicable prescriptive building and fire codes are the IBC and the International Fire Code® 2015 Edition (IFC). Although the building will include performance-based design features, a code analysis based upon the prescriptive codes is provided for comparison of fire protection/life safety features to the performance-based features.

The IBC is part of a family of codes published by the International Code Council (ICC). The ICC was formed to create a single building code organization within the United States. Prior to the formation of the ICC, three model building code organizations existed within the United States. Included in the ICC family of codes are the International Mechanical Code®, the International Plumbing Code®, the International Property Maintenance Code®, the International Performance Code, and other codes. The International Performance Code is a performance-based approach to the design of buildings.


2.3 Building Description

2.3.1 Base Building Description

The building is five stories above grade and is a podium-style building consisting of Type IA and Type VA construction.

The new building will be located in Washington D.C. The building is 133 m (437 ft) by 129 m (424 ft) with a total maximum footprint of 17,183 m² per floor, though the individual floors stagger in size. The deck to deck height between stories is 2.7 m (9 ft) per mercantile/business levels and 2.9 m (9.5 ft) per parking garage level.

The building is comprised of Group S-2 (Low-Hazard Storage), Group M (Mercantile), and Group B (Business) occupancies [IBC, Chapter 3]. Levels B2 through B1 will consist of an enclosed parking garage – Group S-2 occupancy. Level 1 will also contain some retail tenant spaces – Group M occupancy. The upper levels will be primarily office space – Group B occupancy.
The building will be designed as a podium with a non-separated mixed occupancy below the separation and Group B above [IBC, 508.3]. A non-separated occupancy will allow the mercantile occupancies and parking garage to be individually classified. However, Level 1 through B2 will have common base-building fire protection systems and the same construction type [IBC, 508.2.3] required for the most restrictive of the occupancies within the building, i.e. the S-2 requirements.

Miscellaneous occupancies that comprise less than 10 percent of floor area are considered accessory occupancy areas [508.2.1]. These occupancies will not affect the base-building systems and construction type [IBC, 508.2.3].

No hazardous materials or processes are anticipated within the building [IBC, 307].

2.3.2 FAST Garage Description

The FAST Garage consists of parking, retail, and offices.

The architectural floor plans are provided in Appendix A. A description of the use of each floor level is detailed in Figure 1 and discussed below:

Levels

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<tr>
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<th>Occupancy</th>
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<td>Offices</td>
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<td>1</td>
<td>Mercantile</td>
</tr>
<tr>
<td>B1</td>
<td>Parking Garage</td>
</tr>
<tr>
<td>B2</td>
<td>Parking Garage</td>
</tr>
</tbody>
</table>

Figure 1 – Occupancy Stacking Diagram

**Level B2-B1** – Level B2 and B1 are underground parking. Level B2 contains space for approximately 318 vehicles, and utilizes two-level stackers along the west wall to maximize space. Level B1 contains space for approximately 295 vehicles. These levels also contain some of the mechanical components of the smoke control system, mechanical areas, an electrical equipment room, and other support spaces.

**Level 1** – Level 1 is located at grade and contains retail areas for lease. Vehicle entry to the underground garage is located at this level remote entrance. All retail areas open into a lobby which egresses to the sidewalk. All retail spaces also have at least one (1) other exit to the exterior. Three (3) 2-hr fire-resistance rated exit stairs, which serve all floors of the building, discharge into vestibules on this level. From the vestibules, occupants have direct access to the exterior. The other three (3) stairs discharge directly to Level 1 where occupants egress through the lobby to the main exit.

**Level 2 through Level 5** – The floors are used solely as office space. Four enclosed exit stairs are located on each floor. Each exit stair is enclosed with 2-hr fire-resistance rated construction.

**Site Plan** – FAST Garage and the associated above-grade building is located on an 8,000 m² open lot in the suburbs of Washington D.C.
2.3.3 Accessibility Features

The building will be accessible in accordance with the 2010 ADA Standards for Accessible Design to account for persons with disabilities.

**Accessible Entrances** – The FAST Garage has a main entrance which will be completely accessible.

**Accessible Means of Egress** – A minimum of one accessible means of egress will be provided from all spaces. An elevator serves each floor as an accessible means of egress. An elevator lobby will be provided on each floor as an area of refuge.

**Accessible Areas of Refuge** – Each floor is provided with egress elevators with a smoke-resistant vestibule which serves as an area of refuge. The area of refuge is designed to minimize the intrusion of smoke by extending the elevator pressurization from the elevator shaft into the space. A wheelchair space of 0.762 (30 in.) by 1.22 m (48 in.) is provided in the areas of refuge. A minimum of one area of refuge for every 200 occupants is provided on Level B2 through Level 15. A two-way communication system is provided in the areas of refuge on each floor.

**Accessible Elevators** – All elevators are equipped for fire service and therefore will be provided with emergency power and emergency operations and signal devices per ASME A17.1 *Safety Code for Elevators and Escalators*.

**Accessible Signage** – Each door to an area of refuge will be provided with tactile signage indicating “AREA OF REFUGE”. Signage will be provided in the area of refuge indicating the following:

- Persons capable of using the exit stair do so as soon as possible, unless assisting others
- Instructions for summoning assistance for the use of exit stairs
- Direction on the use of the two-way communication system

2.4 Stakeholders

The stakeholders involved in the fire protection aspects of the project include the following:

- **Salamander Investment Properties, Inc.** – The Real Estate Investment Trust (REIT) that owns the building and property.
- **CCC Insurance** – The insurance carrier for the building owner covering losses such as property damage, personal injury, and business interruption.
- **Top Class Architects, Engineering, and Interiors, Inc.** – The design firm providing architectural and engineering services, other than fire protection engineering and security services.
- **Washington, D.C.** – Washington D.C. is the Authority Having Jurisdiction (AHJ) enforcing all applicable regulatory codes governing the construction of the project. The District of Columbia Fire Department is the emergency response agency for emergency incidents at the building.
- **Koffel Associates, Inc.** – Koffel Associates is the fire protection engineering and code consulting firm retained for the project.
2.5 Constraints on the Design and Project Schedule

The AHJ required a third party peer review to evaluate the design for compliance with the ICCPC which is included in Appendix G.

The project schedule is as follows:

- Performance-Based Design Report: April 1, 2016
- Schematic Design (SD) Documents (Drawings and Specs): June 15, 2016
- Design Development (DD) Documents: October 11, 2016
- Construction Design (CD) Documents: February 3, 2017
- Permits Awarded: April 10, 2017
- Project Bidding and Bid Award: June 1, 2017
- Start of Construction: August 30, 2017

The stakeholders will meet bi-weekly throughout the design phase of the project to streamline the permit approval process. The District of Columbia also contracted the services of a third-party reviewer for the fire protection aspects of the design. The third-party review will be conducted in accordance with the SFPE Guidelines for Peer Review in the Fire Protection Design Process, 2009 Edition.

3. PRESCRIPTIVE CODE ISSUES

A prescriptive code evaluation was performed based upon the International Building Code, 2015 Edition and is contained in Appendix B. The following prescriptive code deficiencies in the building design were noted:

- Dead end exceeds 20 ft in plan southeast corner of garage. This causes the building to be deficient for the analysis with or without a sprinkler system.
- Sprinkler protection is required throughout the garage, although the design specification calls for an option to omit sprinkler protection.

The performance-based assessment addresses the prescriptive code deficiencies. A summary of how each deficiency was addressed is provided in Section 6.6.

4. GOALS, OBJECTIVES, AND PERFORMANCE CRITERIA

The project stakeholders established fire safety goals, objectives and performance criteria in order to assess the level of fire safety in the building. Goals are the overall desired fire safety outcomes expressed in qualitative terms. Objectives are established which are measurable requirements which must be met in order to achieve a goal. Performance criteria further refine objectives into numerical values which are compared to the results of engineering calculations to judge the trial designs.
4.1 Primary Fire Safety Goals

The fundamental fire safety goal for the project is to provide life safety to the public and building occupants in the event of a fire or similar emergency.

Fire Safety Goal: Provide life safety for the public, building occupants and firefighters by minimizing fire-related injuries and prevent undue loss of life.

The stakeholders agreed that the fire safety goals related to property protection, continuity of business operations, historic preservation, or other purposes were not fundamental to this analysis, and were, therefore, not included.

4.1.1 Primary Fire Safety Objectives

The fire safety goal was refined into several fire safety objectives. The stakeholders have developed the following primary fire safety objectives:

1. Safeguard occupants from injury due to fire until they reach a safe place.
2. Safeguard firefighters while performing rescue operations or attacking the fire.
3. Limit the fire damage to the structure

Additional design feature objectives identified by the building owner and architect and agreed upon by the stakeholders:

1. Provide a row of double-stacked cars to maximize the use of the space.
2. Provide design with and without sprinkler protection to allow flexibility in construction options and cost.

Limiting the potential of occupant exposure to fire, noxious gasses, and other hazardous conditions was the primary means for achieving the objectives. Conditions along the paths of egress must be tenable to allow evacuation or relocation prior to the development of hazardous conditions. Also, the structural integrity of the building, and particularly its egress components, must be maintained until occupants are safely evacuated or relocated.

4.1.2 Regulatory Fire Safety Objectives

The ICCPC contains objectives which must be considered when applying the performance code. The stakeholders evaluated the ICCPC objectives and determined that the following are pertinent to this evaluation:

1. To provide an acceptable level of fire safety performance when facilities are subjected to fires that could occur in the fire loads that may be present in the facility during construction or alteration and throughout the intended life (Sections 602.1 and 1701.1).
2. To protect people during egress and rescue operations (701.1 and 1901.1).
3. To promote safe practices and actions of people and to assure that the actions and practices of people that are components of a design are maintained (Section 1801.1).
4. To provide and maintain means of notification, access, and facilities for emergency operations and responders (Section 2001.1.1).
5. To provide notification of the need to take some manual action to preserve the safety of occupants or to limit property damage (Section 2001.1.2).
6. To protect emergency responders from unreasonable risks during emergencies (Section 2101.1).
7. To ensure reliability of the system necessary to meet the performance objectives of the building, facility, or processes in accordance with the design (Section 401.1).
8. To assist in the selection of appropriate materials and construction systems (Section 402.1).

It was determined that the regulatory objectives detailed above are consistent with the stakeholder primary fire safety objectives.

4.2 ICC Performance Levels

4.2.1 Risk Factors

The ICCPC uses the following risk factors as a basis for the classification of a building into a performance group. The following considerations are used in our analysis:

- **Fire Hazards** – The fire hazards considered, and their associated design fire scenarios, are covered in the Section 6 on Design Fire Scenarios and Trial Building Designs.

- **Length of Occupancy** – Retail and office spaces will only be occupied during specified hours. The parking garage will be occupied at all hours.

- **Sleeping Characteristics** – The building will not contain sleeping occupants.

- **Familiarity** – Occupants on the business occupancy floors will be familiar with the building; however, the occupants of the retail and parking garage occupancies may not be considered familiar with the building.

- **Vulnerability** – The occupants are anticipated to be capable of self-preservation, unless physically disabled and cannot utilize the stairs.

4.2.2 Performance Group

The ICCPC methodology classifies buildings into performance groups using identified risk factors combined with the relative importance of protecting the building to the community. A review of ICCPC Table 303.1 Performance Group Classifications for Buildings and Facilities indicates the building is classified as a Performance Group III due to having an area where more than 300 people can congregate, i.e. the garage levels.

The relative risk rankings assigned were reviewed by and agreed upon by the stakeholders.
### 4.2.3 Maximum Level of Damage to be Tolerated

The maximum level of damage to be tolerated is based upon the Performance Group and the magnitude of the event. Section 5 of this report identifies the design fire scenarios used and a magnitude of the event has been assigned to each scenario. Table 1 below provides a methodology to determine the maximum level of damage to be tolerated.

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<td>HIGH</td>
<td>MODERATE</td>
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<td>LARGE (Rare)</td>
<td>SEVERE</td>
<td>HIGH</td>
<td>MODERATE</td>
<td>MILD</td>
</tr>
<tr>
<td>MEDIUM (Less Frequent)</td>
<td>HIGH</td>
<td>MODERATE</td>
<td>MILD</td>
<td>MILD</td>
</tr>
<tr>
<td>SMALL (Frequent)</td>
<td>MODERATE</td>
<td>MILD</td>
<td>MILD</td>
<td>MILD</td>
</tr>
</tbody>
</table>

**TABLE 1 - MAXIMUM LEVEL OF DAMAGE TO BE TOLERATED BASED ON PERFORMANCE GROUPS AND DESIGN EVENT MAGNITUDES**

Source: Table 303.3. ICCPC, page 13
The various levels of impact in Table 1 are defined as follows:

- **Mild Impact** – A mild impact has no structural damage and all nonstructural systems required for normal and emergency use are fully operational. There is a very low likelihood of life loss and any injuries are minimal in number and nature. The overall damage or property loss is minimal; however, it is recognized that a higher level of injuries may occur in localized areas in close proximity to a fire.

- **Moderate Impact** – A moderate impact has repairable structural damage and the potential for delay in reoccupying the building. Nonstructural systems required for normal uses are fully functional; although, some clean-up and repair may be necessary. Emergency systems remain fully operational. There is a low likelihood of a single fire death and a very low likelihood of multiple fire deaths. Injuries to building occupants are moderate in number and nature. The overall damage or property loss is moderate in cost and extent.

- **High Impact** – A high impact has significant, although repairable, structural damage and a significant delay in reoccupying the building is expected. Nonstructural systems may be significantly damaged and inoperable. Emergency systems may be significantly damaged, however remain operational. There is a moderate likelihood of a single fire death and a low likelihood of multiple fire deaths. Injuries to building occupants are moderate in numbers and nature. Overall damage may be localized to the fire and is generally significant.

- **Severe Impact** – A severe impact has substantial structural damage without structural collapse. Repair is not technically feasible and the building cannot be reoccupied. Nonstructural systems may be completely nonfunctional and emergency systems may be substantially damaged and non-operational. There is a high likelihood of single fire death and a moderate likelihood of multiple fire deaths. Injuries to building occupants are high in number and significant in nature. Overall damage or property loss is a total loss.

The stakeholders reviewed the maximum tolerable extent of damage permitted by Table 1 and determined that the potential outcomes were acceptable.

**4.3 Specific Performance Design Criteria**

Performance criteria refined the design objectives into values against which the performance of proposed design approaches were evaluated. Numerical values that can be evaluated with computational analysis techniques were proposed where the objectives could be quantified.

Adverse life safety effects due to fires can result from exposure to elevated temperatures, toxic and irritant compounds, reduced oxygen levels, and visible smoke particulate. Effects can be "instantaneous" if an individual is exposed to very high temperatures or high concentrations of combustible products and can result in incapacitation or death within seconds. Alternatively, adverse human response can be "dose" related, i.e., an accumulated exposure over a period of time. However, visibility distance is typically the first hazard parameter to reach an untenable condition. Visibility was found to be the governing factor in this analysis.
4.3.1 Tenability Criteria Used

The following tenability criteria and associated limits were considered during the fire modeling process:

- Air temperature: 76°C (169°F) (20 minute exposure)
- Radiant heat flux: 2.5 kW/m² (maximum)
- Smoke obscuration (soot visibility): 10 m (3.05 ft) visibility (minimum)
- Carbon monoxide concentration: 1,400 ppm (20 minute exposure)
- Hydrogen cyanide concentration: 100 ppm (20 minute exposure)

Several criteria were considered for tenability analysis during fire modeling. The major criteria analyzed were temperature, radiant heat flux, and smoke obscuration. Secondary considerations included the concentrations of the major toxic gases present in a fire. The limits for these criteria were quantified using either conservative maximum tolerable levels or by inspection of a time-concentration exposure curve for 20 minutes, allowing reasonable time to escape from the exposure area.

Exposure to heat from fire presents a number of difficulties for fire victims. The maximum pain tolerance for humans occurs at 120°C. At this temperature, they will become incapacitated due to hyperthermia, rapid blood temperature rise, and skin burns. Steam, which is produced by fires in areas of high humidity, has been found to cause respiratory burns at a temperature of 100°C as hot gases are inhaled.

The maximum air temperature allowed for tenability was selected to be 76°C. For a constant exposure temperature of 76°C, the resulting time to incapacitation is expected to be 20 minutes, based on Purser’s time/temperature relationship noted in Figure 3 below. Air through which occupants must egress must not exceed the time/temperature values from the curve below. If the temperature never exceeds 76°C, occupants will have a minimum of 20 minutes to escape the exposure area.

![Figure 3 – Time tolerance for exposure to convected heat](image-url)
The maximum tenable radiant heat flux is 2.5 kW/m$^2$. Exposure below 2.5 kW/m$^2$ can be tolerated for 30 minutes or more$^{20}$. This maximum limit is based on exposure to bare skin which accounts for areas of the body that are not covered by clothing. Exposure above the 2.5 kW/m$^2$ results in second degree burns in less than two minutes. Extreme pain of this magnitude can result in shock and incapacitation, preventing victims from being able to escape or delaying egress.

The general design limit for visibility in large enclosures featuring transient occupants who are not expected to be familiar with the layout of the building and means of egress is 10 m (32.8 ft). For smaller enclosures and/or those enclosures in which the occupants are expected to be non-transient and/or more familiar with the layout of the space, the visibility criterion is reduced to 5 m (16.4 ft). The visibility limit is decreased to 5 m (16.4 ft) in smaller enclosures because occupants are expected to be familiar with their surroundings and have less distance to travel in order to escape$^{20}$. As smoke accumulates in a compartment, occupants may be prevented or deterred from using escape routes if visibility drops below these levels.

In consideration of the various toxic gases produced as byproducts of the combustion process, CO is the most significant, as it can cause incapacitation at very low concentrations. CO is present in all fires at high concentrations, and is the most common cause of death due to inhalation of combustion byproducts. CO will ultimately cause asphyxiation, but upon inhalation can immediately cause confusion that can delay an occupant’s egress. Purser references a CO concentration of 1,400 ppm for incapacitation after up to an hour of exposure for smaller adults and children$^{20}$. This is a conservative limit for CO, as it accounts for a large population of people, who may be performing light activity and allows adequate time for egress before the onset of confusion.

HCN is another major asphyxiant gas. HCN in low concentrations can be tolerated with minimal side effects, while in high concentrations incapacitation can be rapid and without warning. Effects of HCN concentrations of less than 80 ppm can be tolerated for periods of up to an hour. The effects of HCN at concentrations of 180 ppm can cause incapacitation in minutes. For an exposure time of 20 minutes, the onset of incapacitation can occur for concentrations above 100 ppm.

Other considerations, such as O$_2$ depletion and the effect of CO$_2$ may be concerns for tenability in some fires. Oxygen levels may be of concern in areas which are susceptible to under ventilation, which is not the case for the scenarios modeled. While CO$_2$ levels are expected to increase with fire duration, they are not expected to have a significant impact on toxicity calculations or to supersede the effects of CO. The severity of CO and HCN inhalation from toxic gases suggests that the incapacitation concentrations of CO and HCN would provide sufficient conservative tenability criteria for this application.

### 4.3.2 Structural Criteria Used

The building construction will be consistent with IBC Type IA construction for the parking garage and retail spaces below the 2-hr fire-rated podium and Type VA construction for the office spaces. The IBC construction types are determined based on performance criteria found in ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials*. This standard uses a standard time-temperature curve (fire curve) to establish a common fire exposure for determining the fire-resistance of materials and structural assemblies. The ASTM
E119 fire curve is a logarithmic curve and is consistent with the International Standards Organization standard time-temperature curve, ISO 834.

Type IA and Type VA construction in the podium building is justified by the requirements of the IBC. The 2-hour fire-resistance rating, as defined by ASTM E119, will provide sufficient protection of the structure for the anticipated fire exposures associated with the building.

4.4 Reliability Analysis

A critical component of a performance-based design includes an analysis of the reliability of each fire protection system. Two types of reliability must be considered for fire protection systems; operational reliability and performance reliability. Operational reliability assesses the probability that a system will activate or operate during a fire event. Performance reliability assesses the likelihood that if the system operates, the fire protection goal will be achieved. This risk analysis can assist in the creation of mitigation strategies to ensure that performance goals are achieved in the event of system failure. A brief reliability analysis and an assessment of strategies for preventing failure and mitigating risk have been provided for several building systems.

Automatic Sprinkler System

Sprinkler systems are intended to minimize the impact of fire by controlling fire size. An NFPA report on sprinkler operation cites the operational reliability of sprinklers in an office fire as 80.6% and in retail as 84.9%. No specific data was provided for parking garages; however storage occupancies had a reliability of 84%\(^3\). This data does not account for buildings which were reported as having sprinklers, but sprinklers were not present in the area of fire origin. It is also not segregated by type of sprinkler. The reliability of a sprinkler system in a fully sprinkler protected building with quick response sprinklers can be expected to be higher than the values provided. Using the criteria set by the ICCPC performance table (Table 1), this would be considered a less frequent risk, requiring that only a mild impact be a result of system failure.

Several fire design scenarios modeled the impact of sprinkler system operational failure. In general, sprinklers were required to control the fire in order to maintain tenable conditions. Based on the previously noted reliability, a sprinkler system in a typical building would not provide the necessary operational reliability. Therefore, strategies for preventing sprinkler system operational failure are required. Sprinkler systems will undergo commissioning testing before the building is occupied. Valves will be locked in the open position and will be equipped with tamper switches. Tamper switches will send supervisory signals to the fire command center and an off-site monitoring station. Periodic testing and inspection of the sprinkler system will be provided per NFPA 25: Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems, 2014 Edition. The rationale for these strategies is that in occupancies where sprinkler systems are rigorously tested and documented, operational reliability of as high as 99.5% can be seen\(^3\). While these preventative measures would not eliminate risk, the reliability of the system should be improved enough to consider sprinkler failure a rare event, allowing for the moderate impact modeled in fire design scenarios.

Data on performance reliability of sprinklers is more subjective, as the primary goal of a sprinkler system is suppression, rather than extinguishment. Performance data for fires which resulted in full extinguishment by sprinkler systems is as follows: 18.7% for offices, 20.9% for department stores, and 33.3% for storage occupancies\(^3\). However, data is not available for the
percentage of fires in which sprinklers operate which are controlled to the extent that they can be manually extinguished. The performance reliability of the sprinkler system will be mitigated by trained staff, instructed in the use of manual fire extinguishment and fire department response in cases of larger fires.

Fire Alarm System

The operational reliability of a fire alarm system is the probability of fire alarm activation and occupant notification in a fire event. A literature search found an operational reliability of 71.1% in office and retail buildings and of 68.2% in storage occupancies. Based on the analysis in Table 1, this system would fall under the frequent or less frequent failure occurrence, requiring that only a mild impact be the result of system failure. Failure of a fire alarm system has the potential to result in loss of life, which is not consistent with mild impact. Strategies to increase the reliability of the systems must be developed.

Similar to sprinkler system reliability, occupancies which experienced more vigorously tested systems experienced a reliability of up to 87%. The fire alarm system will be installed and maintained per NFPA 72. Trouble signals will report to the building fire alarm control panel to alert personnel to system failure. A fire watch by security personnel will also be implemented to minimize the possibility that a fire will go undetected. Through these strategies, the reliability of the fire alarm system will be increased, and the impacts of a failure will be minimized.

The performance reliability of a fire alarm system is based on a system’s success in encouraging occupant evacuation in the event of a fire. Limited quantitative data is provided on this subject. The minimization of false alarms through inspection and testing, as well as the use of voice evacuation, will be employed to improve the occupant evacuation response times. Additionally, training will be provided to staff to increase the awareness of evacuation procedures, including providing assistance in the event of a fire.

Fire Barriers/Passive Fire Protection

Although a qualitative analysis of fire barrier reliability is not available, common failures of fire barriers will be addressed through the implementation of a building management program. The building management program will address fire-rated door maintenance, penetrating items in fire-rated construction, and a contractor permitting process. Fire-rated doors will be inspected on a yearly basis for compliance with NFPA 80, *Fire Doors and Other Opening Protectives*. Building policy will prohibit items that do not serve the stair or elevator shaft from penetrating the enclosure. The building permitting process will require contractors in the building to undergo training to provide information about the location of any fire-rated barriers and proper technique for firestopping any penetrations created. Contractors will be required to photograph all penetrations created to document location of said penetrations as well as installation of appropriate firestopping assemblies.

5. DESIGN FIRE SCENARIOS

Brief Description of Design Fire Scenarios:

The following design fire scenarios, which are referenced in NFPA 1, *Uniform Fire Code*, have been used to evaluate the proposed building design. These scenarios are representative of realistic fire situations that could potentially occur in the building. The scenarios take into
consideration a number of variables including the development, size, and burning duration of the potential fires, tenability conditions for occupants, and the reliability of the fire protection systems to be used in the building.

Each of the following design scenarios are analyzed twice, once with the building having sprinkler protection and once without. The design scenarios each address multiple design fire scenarios suggested by NFPA 1. For more detail regarding the scenarios listed below, refer to Section 6.4 of this report.

**Scenario 1 – Fire in Stacked Gas Engine Vehicles Involving Multiple Vehicles**

*Scenario 1A. Building is equipped with a sprinkler system:* This scenario is occupancy specific to the garage space and its typical fuel loads. The double-stacked car row allows a maximum amount of fuel to be consolidated within the typically unoccupied garage. This fuel configuration will cause an ultra-fast fire in a normally unoccupied space. By utilizing a sprinkler system within the garage, this type of fire can controlled until the fire department is able to begin manual fire extinguishment operations.

*Scenario 1B. Building is not equipped with a sprinkler system.* By running the same scenario without assuming an active sprinkler system, the true hazard of the fire is revealed. It becomes clear that a smoke exhaust system is required to ensure tenable egress is available for the appropriate amount of time.

**Scenario 2 – Battery Electric Car Fire Blocking Stair in Plan Lower Right Corner**

*Scenario 1A. Building is equipped with a sprinkler system.*

*Scenario 1B. Building is not equipped with a sprinkler system.*

6. **PERFORMANCE-BASED ANALYSIS**

6.1 **Methodology**

The design fire scenarios, egress calculations and trial building designs were evaluated holistically to address the fire safety objectives detailed in Section 4.1 of this report. Quantitative analyses, including computer fire modeling and egress calculations, were used to determine if the performance criteria were met for each scenario.

Computer fire modeling was performed using Fire Dynamics Simulator. SFPE’s *Guidelines for Substantiating a Fire Model for a Given Application, 2011 Edition* was used to aid in the choosing of an appropriate modeling technique. The physical phenomenon evaluated included smoke layer temperature, heat flux, gas concentrations, heat release rate, ventilation, visibility, and detector and sprinkler response times. The large compartment created by the interconnection of Level B1 and B2 by unenclosed floor openings has a complicated and dynamic geometry and a mechanical smoke exhaust system. For these reasons, a computational fluid dynamics (CFD) field model was deemed most appropriate for evaluating the performance of building systems in each of the design fire scenarios.
Detailed egress calculations were compared against each design fire scenario. The building design was modified, as necessary, when hazard development times did not allow for safe egress times in accordance with the performance criteria set forth in Section 4.3 of this report.

The egress modeling was performed using the hydraulic model of emergency egress, as outlined in the SFPE Engineering Guide, *Human Behavior in Fire*.  

6.2 Timed Egress Analysis

Egress calculations were performed to determine the time it would take for occupants to fully evacuate the building. The garage portion of the building is provided with the following egress components: six (6) enclosed egress stairs.

Pre-Movement Time

Pre-movement time is the period of time from the initial perception of an unusual cue until the person makes the decision to start evacuation. Pre-movement time was determined to be composed of the time from fire alarm initiation to the time it takes the occupants to respond and begin evacuation.

The greatest time from the start of fire development to the activation of a smoke detector in any scenario was determined by modeling to be 30s. For a new fire alarm system, NFPA 72®, National Fire Alarm and Signaling Code, 2013 Edition Section 10.12.1 requires a maximum of 10s from time of smoke detector activation until initiation of fire alarm. Thus, the time to fire alarm initiation is 40 seconds or 0.67 minutes.

The time it takes the occupants to respond will vary depending on the use of the space. Occupants throughout the building will be alert and awake upon fire alarm initiation. Employees (store, garage, or office) in these areas will be very familiar with the layout of the building and will respond faster to the fire alarm system. Building staff in retail and garage areas will undergo special training to learn how to guide occupants to an exit during an emergency. The constant presence of trained building staff significantly reduces pre-movement times in these areas. To be conservative and account for a delay in trained staff action, a response time of 2 minutes, or 120 seconds, was assumed for all areas of the building. Thus, the pre-movement times can be conservatively estimated as **160 seconds** or **2.67 minutes** for all areas. These times will be added to all of the travel times to determine the total egress time.

Egress Calculations

Egress calculations were performed based on the occupancy classifications of each floor to determine the total required egress time for the building. The SFPE Engineering Guide, *Human Behavior in Fire*, was used to calculate the egress time for the building. The calculations are detailed in Appendix F, Egress Hand Calculations. The number of occupants, per floor, was calculated using NFPA 101®, *Life Safety Code*® (LSC), 2015 Edition occupant load factors. The resulting occupant loads are as indicated in Table 2 below:
Table 2 – Occupant Loads

<table>
<thead>
<tr>
<th>Level</th>
<th>Area (sq m)</th>
<th>Occupancy</th>
<th>Number of Occupants per Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>14,473</td>
<td>Parking</td>
<td>778</td>
</tr>
<tr>
<td>B2</td>
<td>14,473</td>
<td>Parking</td>
<td>778</td>
</tr>
</tbody>
</table>

All floors in the building above the level of exit discharge have access to a minimum of four (4) enclosed exit stairs. All floors below the level of exit discharge have access to six (6) enclosed exit stairs. The following egress calculations assume that Levels B1 and B2 contain 778 occupants to address the potential for maximum occupants within the parking garage in order to provide the most conservative estimate.

When calculating the total egress time for the occupants to leave the building, a number of factors have to be taken into account. These are as follow:

- Time to reach exit door
- Maximum flow time
  - Flow into stair through door
  - Flow down the stair
- Travel time from stair discharge to exit

The detailed calculations, as well as an explanation of calculation methods, are provided in Appendix B. The elevators are not equipped for occupant evacuation so all occupant evacuation takes place via the stairs. These calculations resulted in an egress time of approximately 14.2 minutes.

Occupants with Disabilities and Impairments

All building occupants are expected to be alert and capable of self-preservation. However, a small percentage of occupants could have a disability which impedes their ability to egress. The potential for occupants with disabilities exists throughout the building, as all occupants have access to the upper floors by means of elevators. The use of areas of refuge throughout the normally occupied floors of the building provides protected area for those with disabilities.

The project stakeholders are aware of the needs of occupants with disabilities during a building evacuation. Staff training and awareness will partially address the issue, in addition to the fire department awareness of areas of refuge.

6.3 Trial Designs

Trial fire safety designs are protection options that could be used to meet the fire safety goals and objectives established for the project. The following primary trial designs were evaluated using fire modeling and egress calculations:
1. Smoke detection – The benefits of smoke detection were evaluated to provide early occupant notification of a fire. It was determined through the analysis that early detection and notification were essential to ensure tenable conditions were maintained during egress times.

2. Sprinkler protection – The effect of sprinkler protection throughout the building was evaluated. Sprinkler protection was modeled to control fire development, rather than extinguish the fire.

3. Smoke management system – The benefits of providing mechanical smoke exhaust were evaluated. Several exhaust and make-up air configurations were modeled and the effects on smoke movement and tenability were quantitatively analyzed and compared. It was determined that a smoke evacuation system was required to maintain tenable conditions for each of the Design Fire Scenarios and that the selected system provided the highest available safe egress time (ASET) in the protected space.

Additional trial designs and evaluations were conducted, as necessary, as described in Sections 6.4 and 6.5. The chosen Final Design is summarized in Section 7.

### 6.4 Evaluation of Fire Scenarios

**Overview**

The scenarios described below were modeled using FDS (Fire Dynamics Simulator), a computational fluid dynamics model created and distributed by NIST. A basic model (Figure 1) was constructed using third party graphical user interface software (Pyrosim) and the floor plans provided in the case study specifications. The floor slabs, including the multiple vertical openings created by the ramps from the lower level to the exterior, were modeled based on measurements taken from AutoCAD files the design team produced using the case study specifications. Slab-to-slab height of 3 m, as specified in the case study specifications, was utilized. Holes were used to create openings for doors and to create the horizontal entrances to the parking structure through the “ground slab.” Various building characteristics and components were modeled independently as necessary for the various scenarios. Flame spread and fire growth were considered directly in the specification of design fire heat release rates, rather than by specifying material properties and simulating the burning of combustibles.

![Figure 1 – Basic Building Model](image)

This basic model was then modified to create multiple fire scenarios. The compartment geometry, fire location, heat release rate, material properties, and other variables were modified as necessary to simulate the desired characteristics of the fire scenario. Heat release rate data was
obtained from reliable sources and, in some occasions, modified using conservative engineering judgement. A soot yield of 0.05 g/g was specified for all scenarios to represent the type of smoke expected from cellulose materials and many plastics. This value was found to generally provide the closest, yet conservative, agreement with the experimental measurements of smoke density in one study. Scenarios were run both with and without sprinkler activation, as the design required both sprinkler protected and non-sprinkler protected scenarios to be taken into account. When sprinkler protection was used, it was assumed to control a fire if a sprinkler activated in a scenario, as opposed to suppressing the fire, as this is a more conservative approach. This was done by adjusting the size and growth rate of the design fire. Where suppression was not used, all scenarios were run with an actual simulation time of 900s as this was sufficient to analyze tenability for the duration of required egress time. A grid resolution consisting of 1 m cubes was used for the majority of the simulations. A finer grid resolution would be desirable; however, significantly finer resolutions were prohibitively computationally intensive. Grid convergence was not analyzed due to time constraints, but would be an important consideration.

**Tenability in FDS**

A fundamental issue is frequently encountered when performing this type of fire modeling. As the capabilities of FDS are still somewhat limited, a systematic approach to extracting applicable data needs to be established in order to provide acceptable comparisons between the actual data that can be obtained from FDS and the tenability limits described previously, which can be dependent on many variables. For simplification and reliability, a select few criteria were used to assess tenability.

Slice files were specified at 2.0 m (6.5 ft) above the floor on both levels of the model to examine temperature exposure. This data is expected to be highly reliable. In a fire scenario, smoke and buoyant heat rises to the highest point in an enclosure and then descends toward the floor. A thermal gradient exists from ceiling to floor in which the temperature decreases as distance to the floor decreases. It can be reasonably expected that if the temperature at 2.0 m (6.5 ft) above the floor reaches a certain value, the temperature above 2.0 m (6.5 ft) is greater and the temperature below is lower. Hence, it is only pertinent to analyze the temperature at the expected upper average height of the occupants (2.0 m (6.5 ft)) in order to characterize the level of safety with regard to direct thermal exposure. A maximum temperature criterion of 76°C (169°F) was selected, as this is the maximum temperature an occupant is expected to be capable of withstanding for a conservative duration of 20 minutes (see section 4.3.1).

Slice files were also specified at 2.0 m (6.5 ft) above the floor on each level of the model to examine visibility. This is also a very reliable and useful property to be analyzed for tenability analysis. Three parameters can be specified in FDS to control smoke production and visibility. Two of these are the mass extinction coefficient and the visibility factor. The default value for the mass extinction coefficient was used, as this is the suggested value for flaming combustion of cellulose materials and plastics. The default value for the visibility factor was also used, as this is a constant that is characteristic of the object being viewed through the smoke and is not important when comparing the visibility at one point in the 2.0 m (6.5 ft) z-plane to another. The third parameter specified in FDS to control smoke output and visibility is the soot yield. As mentioned previously, a value of 0.05 g/g was specified for all design fires.

The criterion used for minimum visibility was 10 m (32.8 ft) for all scenarios, as all of the scenarios involved large areas where occupants would be expected to travel a maximum of 67 meters to reach an exit. An additional inherent benefit to using this specific visibility
criterion is that the levels of asphyxiant gases occupants are exposed to in these visibility ranges are most likely not capable of causing incapacitation when the exposure duration does not exceed 30 minutes\textsuperscript{20}. Hence it is reasonable to assume that for the fire models performed, where the typical duration of exposure is on the order of only several minutes, the occupants would not be exposed to fatal levels of asphyxiant gases if the visibility criteria are not exceeded.

Oxygen concentration was not considered due to time constraints of the project. Due to the high volume of fresh air being supplied as make-up air for the smoke exhaust system, occupants are highly likely to be incapacitated by other conditions before the oxygen concentration becomes untenable. In addition to the fact that the previously described visibility criterion provides a relatively accurate approximation regarding exposure to asphyxiant gases, carbon monoxide levels were not examined, because the algorithm used by FDS to predict CO levels does not predict the CO concentration of exhaust gases and is of little use, unless the fire is severely underventilated\textsuperscript{18}.

For final analysis, data output by FDS was compared to the tenability criteria in order to obtain the available safe egress time (ASET). Next, the ASET was compared to the required safe egress time (RSET). If the available time was not sufficient, the building design was modified and the scenario was re-simulated.

**Simulations**

Although multiple simulations and iterations were run, only several will be discussed, as there were multiple iterations that yielded unremarkable results. All simulations had fires on the lower levels as the occupants on this level would have the longest egress time. In addition, fire combustion products produced on this level would affect occupants on both levels whereas a fire on the upper level (still below grade) would only negligibly affect occupants on the lower level due to the buoyancy of the combustion products. All simulations analyzed various types and locations of car fires as these are the most conservative (dangerous) scenarios that would be likely to occur in a parking garage. Because a car fire from a traditional car would likely have a higher heat release rate than that of an electric vehicle, the more conservative 8MW was used as a baseline fire size.

**Simulation 1 – Car fire in the southeast corner of the lower level**

In the first simulation, an 8 MW fire was placed in the southwest corner of the lower level to represent a car in the corner of the parking garage on fire. The fire was prescribed as a fast $t^2$ fire with an $\alpha$ value of 150 seconds. The alpha value determines how quickly a fire grows to its expected maximum size. The intent of this simulation was to derive a baseline for the time it would take to activate a sprinkler system if there was one provided in the building. Heat detectors were placed throughout the space with an RTI of 50, similar to the anticipated RTI of a standard-response sprinkler. Although the heat detector does not actually suppress the fire when it activates, its activation time can be used to determine how quickly the sprinkler activates and how large the fire would be at the time of sprinkler activation. It was determined that the fire had grown to 3.6MW after 99 seconds when the heat detector activated. Because it is presumed that the fire size will not continue to grow after sprinkler activation, these numbers were used in subsequent scenarios to simulate the same fire load with sprinkler activation. As could be expected with these parameters, the space became untenable quite quickly, resulting in the need for additional fire protection features.
Simulation 2 – car fire in southeast corner with sprinkler protection

In this simulation, the tenability of the space was tested based on the expectation of a sprinkler system activation. The results from the previous scenario were used to create a 3.6 MW fire with an $\alpha$ value of 99. This effectively simulates a fire growing to maximum size of 3.6 MW at a $t^2$ rate in 99 seconds. Shown below in Figure 2 is the heat release rate graph showing the heat release rate curve. Even with the water based suppression system, it was determined that the space became untenable quickly for safe egress of occupants. It was clear that additional life safety features, specifically smoke exhaust, would be required.

![Figure 2 – HRR Curve](image)

Simulation 3 – Car fire in southeast corner with smoke control

At this stage it was determined that the more conservative approach would be to continue the simulations without sprinklers, as the design brief called for a scenario where sprinklers were not provided in the building. This lead to the simulation having the same parameters as Simulation 1 except with the addition of a smoke exhaust system and fresh air intake from the exterior. The makeup air was placed at the end of the section in the southwest side of the building. This was done to artificially deter smoke from traveling down this corridor. The strategy was to provide an opposed airflow approach that would prevent smoke originating outside of the dead-end from migrating into the dead-end. Initially, 24 m$^3$/s of exhaust was provided at two locations in the west and north walls of each garage level, with make-up air being provided with simple openings to the building exterior located at the vehicle ramps or at the end of the dead-end to the southeast of the garage. The simulation yielded better but albeit similar results to the tenability characteristics of the previous simulation in that the space became untenable prior to the safe egress of occupants.
Simulation 4 – Car fire in southeast corner with increased smoke control.

The same parameters from simulation 3 were used for this simulation except the exhaust air rate was doubled. Instead of natural opening make-up air, a supply fan was added for makeup air at 85% of the exhaust rate. The intent was to determine the rate that would be necessary to exhaust the combustion products and allow occupants to safely egress the facility. With the upgraded smoke control system, the products of combustions were controlled and were isolated to the corner of the building of origin. Shown below in Figure 3 is the Smokeview slice file at 2.0 m showing the soot visibility at 635 seconds.

![Figure 3 – Soot Visibility at 2 m](image)

Simulation 5 – Car fire centrally located in building with increased smoke control

In this simulation the fire location was changed to be more centrally located in the building, in order to test the robustness of the smoke exhaust system with respect to fire location. The first iteration yielded results showing that most of the garage was untenable after about 6 minutes. Shown below in Figure 4 is the Smokeview slice file of soot visibility at 2 m. As a result, additional exhaust and supply fans were added on opposite sides of the garage. With the increased amount of exhaust and supply fans, it was determined that the fire could be contained within the region of the garage where it originated. Because of time constraints, an exact smoke exhaust system could not be determined, however it is assumed that by adding additional supply and exhaust fans and increasing the size of those fans, tenable conditions could be maintained for the required safe egress time. With the assumption that sprinklers will only contain the fire, the increased smoke exhaust system is needed regardless of the presence of sprinklers.
Simulation 6 – Car fire near stair with increased smoke control

In this scenario the design fire location was moved near the exit stair at the plan southeast of the garage, and the entrance to the dead-end section. The results from this simulation were the same as the above scenario with the fire in the center of the building. The fire is constrained to the region of the garage where it originated. Shown below in Figure 5 is the Smokeview slice file showing the soot visibility at 2 meters. Again, an exact smoke control system could not be designed, but it can be assumed that with adding additional supply and exhaust fans the entire space would remain tenable.
6.5 Evaluation of Fire and Life Safety Goals

The design fire scenarios were compared to the fire and life safety goals to ensure that each objective was adequately met. A trial design was considered an acceptable design option if the fire safety goals and objective were met. Evaluations of the primary fire safety objectives, as described in Section 4.1, are summarized below:

**Fire and Life Safety Goal 1**

Fire and Life Safety Goal 1 states, “safeguard occupants from injury due to fire until they reach a safe place.” During a fire event, occupants throughout the building will migrate to the nearest means of egress and travel to Level 1, where they will exit the building.

Vertical travel within the garage is accomplished via six enclosed exit stairs. Early evacuation can be initiated by staff or by means of the emergency voice/alarm communication system. Activation of the alarm system will be by manual means, sprinkler activation, or smoke detection. Sprinkler protection and mechanical smoke exhaust systems maximize the time that tenable conditions are maintained for safe egress from the building.
Fire and Life Safety Goal 2

Fire and Life Safety Goal 2 states, “safeguard firefighters while performing rescue operations or attacking the fire.” A fire command center will be provided containing controls for all utility systems relevant to fire safety detailed in Section 7.2. The fire-resistance rated construction elements provide good baseline protection for firefighters, although protection is improved by several enhancements to the building design. Most notably, the automatic sprinkler system will control or suppress fires, if a system is provided. A fire service access elevator serving all floors is provided for firefighter operations and will be pressurized to limit smoke migration. Additionally, the automatic smoke control system in the garage will help to maintain good visibility if a fire were to occur in the garage levels.

Fire and Life Safety Goal 3

Fire and Life Safety Goal 3 states, “limit the threat to the structure.” The building design provides the most robust construction type typically found in modern non-super high-rise construction (i.e. less than 128 m [420 ft]).

6.6 Addressing Prescriptive Deficiencies

FAST Garage has minimal deficiencies when compared to the prescriptive requirements for a building of its type, however these deficiencies are addressed with performance-based alternatives. The following summarizes how each prescriptive deficiency noted in Section 3 is addressed:

1. Dead-end – The provision of a smoke control system maintains tenable conditions within the dead-end area allowing ample time for occupants to reach the exit stair.
2. Sprinkler protection – in the event the building owner exercises the option to omit sprinkler protection, the emergency voice/alarm communication system and the smoke control system work to maintain tenable conditions for a sufficient time to allow safe egress.

7. FINAL DESIGN DOCUMENTATION

7.1 General

FAST Garage was designed with several performance-based features that exceed or provide an acceptable alternative to the prescriptive requirements of the IBC. Overall, the proposed Final Design adequately meets the fire safety objectives:

- Safeguard occupants from injury due to fire until they reach a safe place
- Safeguard fire fighters while performing rescue operations or attacking the fire
- Limit the fire damage to the structure

7.2 Fire Protection Features

As a result of this performance-based design, it was determined that the FAST Garage must be constructed with the following fire protection and life safety features:
**Construction** – The garage and all construction below the podium separation is constructed of steel and pre-cast reinforced concrete. The construction type is consistent with the IBC Type IA (protected non-combustible) construction. The primary structural frame and all load bearing walls have a 3-hour fire-resistance rating. Floor construction and associated secondary members have a 2-hour fire-resistance rating.

**Means of Egress** – The garage is provided with six stairs. Each of the stairs is provided with a 2-hour fire-resistance rated enclosure. The enclosed exit stair discharges directly to the exterior of the building.

**Automatic Standpipe/Sprinkler Systems** – If the building owner chooses to provide sprinkler protection, the building would be provided with a combined automatic Class I standpipe system connected to the sprinkler system, which would be connected to the municipal water supply and supplemented by a fire pump to meet the hydraulic demand. A 161mm (6 in.) manual wet standpipe would be provided in each of the enclosed stairs, and a 63.5mm (2.5 in.) hose connection would be provided on each primary floor landing within each of the enclosed stairs in the parking garage.

The sprinkler system will meet the requirements of NFPA 13, *Installation of Sprinkler Systems*, and the standpipe system will meet the requirements of NFPA 14, *Installation of Standpipe and Hose Systems*.

**Fire Alarm, Detection, and Communication System** – An emergency voice/alarm communication system will be provided throughout the garage in accordance with NFPA 72, *National Fire Alarm and Signaling Code*. Manual pull stations will be located on every floor at the entrance to each enclosed stair.

A smoke detection system will be provided throughout the garage to activate the automatic smoke exhaust system. Smoke detectors will be of the photoelectric type. Smoke detectors will be located in all normally-unoccupied spaces throughout the building. Smoke detectors will also be located in each elevator lobby and elevator machine room for Phase I elevator recall. The elevator machine rooms will have heat detectors supervised by the fire alarm system.

Activation of the fire alarm system in the garage area will automatically activate the smoke exhaust system serving the garage. The status of the smoke control systems will also be monitored by the fire alarm system.

Notification devices will include speakers throughout the facility and ADAAG-approved strobes. Automated voice announcements will be broadcast over the fire alarm system in the event of fire alarm system activation. Total evacuation will be provided due to the connected nature of the building. Live voice announcements at the system microphones will override the automated announcement.

Alarm, supervisory, and trouble signals will be automatically transmitted to an off-site central station (Capitol City Alarms, Inc. 1-800-555-9999). Capitol City Alarms will automatically notify the fire department.
Smoke Exhaust – A mechanical smoke exhaust system will be provided in the garage to ensure tenable conditions are maintained throughout the duration of egress. Fire modeling results show that a smoke exhaust system will significantly increase the available safe time for egress (ASET) in the garage area.

Although case study time constraints precluded determining the exact amount of smoke exhaust optimal for each building design scenario, CFD modeling was utilized to determine that smoke exhaust does have a significant positive impact on the extension of available safe egress time throughout the garage. Input variables included the fire heat release, ceiling height, plume width, smoke density, maximum make up air velocity, and other important parameters.

Activation of the smoke exhaust system will be accomplished by sprinkler system water flow or smoke detection within the garage. Activation of two smoke detectors within the garage will activate the system. Alternatively, manual activation by a fire warden or security personnel will be permitted to initiate the smoke exhaust system. The emergency voice/alarm communication system will also be activated.

The exhausted smoke will be ducted to grade level at the building exterior in areas remote from exit discharge. Smoke exhaust equipment will be listed to withstand the elevated temperatures expected in a fire scenario.

Emergency Power – A secondary power system will be required due to the smoke control system and the accessibility upgrades to the elevators. A generator will provide emergency power automatically activated within 10 seconds of normal power interruption. The generator will be located on the building exterior. The generator will be fueled by natural gas and will have capacity to serve the smoke control systems, elevators, and the other critical building systems (i.e. emergency lighting, fire alarm, fire pumps, etc.) for not less than 4 hours.

Elevators – All elevator hoistways will be enclosed in 2-hour fire-resistance rated construction and will be pressurized. The elevators will have Emergency Fire Department Service and Recall and will have a primary (Level 1) and secondary (Level 2) level of recall. The elevator machine rooms are located in the garage levels.

Public Address System – The emergency voice/alarm communication (EVAC) system described below will also be used as a public address system throughout the building. Utilizing the EVAC system as a paging system will ensure system reliability in the event of an emergency. System repair and maintenance is more likely due to its use for paging.

Fire Alarm Control Panel – The fire alarm control panel will have an integrated voice communication capability. Microphones will be provided at the fire alarm control panel.

Portable Fire Extinguishers – Portable fire extinguishers will be placed throughout the building. Multi-purpose dry chemical extinguishers will be placed throughout the garage, in accordance with NFPA 10, Portable Fire Extinguishers.

Staff Training – Staff will be trained on how to facilitate the evacuation of occupants and on the Fire Emergency Plan. The emergency/voice communication system will be used to facilitate egress. Floor wardens will be assigned to each office floor to notify occupants of an emergency and initiate movement. All building employees in the retail tenant areas will be trained to gather
all occupants and escort them to the nearest available exit. Garage staff is also trained on how to effectively get people out of the building, in the event the voice evacuation system is not functional.

**Retained Prescriptive Requirements** – In addition to the performance-based and prescriptive solutions described above, the following fire protection features will meet the prescriptive requirements of the applicable codes:

- Handrails and guards will be provided, as required, to the proper heights and dimensions.
- Doors will be installed and constructed, as required, including fire exit hardware, panic hardware, ease of use, and force required to open.
- Stairs will comply with code with respect to dimensional uniformity, construction type, walking surface, protection of penetrations/openings, etc.
- Ramps and lifts will be installed to facilitate persons with disabilities.
- Impediments to the means of egress will be prohibited, such as doors chained shut, locking of egress doors, storage in stairs, etc.
- Illumination of the means of egress will be provided.
- Emergency lighting will be provided.
- Marking of the means of egress will be provided.
8. REFERENCES


APPENDIX B

Egress Hand Calculations
Egress Hand Calculations

Hand calculations were performed to determine the time it would take for occupants to fully evacuate the garage via the stairwells. All velocity and specific flow factors used in hand calculations are referenced from the SFPE Design Guide “Human Behavior in Fire” pages 28-32.

Egress Calculations for Stair

The first portion of the egress calculation used comes from the SFPE Engineering Guide, Human Behavior in Fire. The number of occupants, per floor, was calculated using NFPA 101®, Life Safety Code®, 2012 Edition, occupant load factors as follows:

<table>
<thead>
<tr>
<th>Function of Space</th>
<th>Occupants Load Factor (sq m per person)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parking Garage</td>
<td>18.6 gross</td>
</tr>
</tbody>
</table>

Based on these occupant load factors, the occupancy classifications of the various levels, and the assumptions of space planning that were made, the following occupant loads per floor were determined:

<table>
<thead>
<tr>
<th>Floor</th>
<th>Area (sq m)</th>
<th>Occupancy</th>
<th>Number of Occupants per Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14,473</td>
<td>Parking</td>
<td>778</td>
</tr>
<tr>
<td>2</td>
<td>14,473</td>
<td>Parking</td>
<td>778</td>
</tr>
</tbody>
</table>

TABLE B1 – OCCUPANT LOADS

The primary concern when it comes to protecting occupants in this building is being able to protect them from a fire scenario that would take place on either floor of the garage, affecting both simultaneously. Phased evacuation is not applicable thus an alarm would ring on both floors of the garage. Both floors are assumed to have identical floors plans and have access to 6 exit stairs.

Time to Reach Exit Door- Garage Floor 2

Garage Level 2 is a typical parking floor. It has a maximum occupant load of 778 people. There are six exit stairwells on this floor that will be used for egress. It must first be determined how long it will take the first occupant to reach an exit stairwell. A mean level walkway travel velocity of 1.40 m/s is used. The greatest possible distance an occupant can travel is from the corner of the garage to a stairwell, which is 67 m. Thus,

\[ T_{\text{stair \rightarrow exit}} = \frac{d}{v} = \frac{67 \text{ m}}{1.40 \text{ m/s}} = 48 \text{ s} \]
Maximum Flow Time - Level 2

It is then necessary to calculate the time for occupants to move through the stairwell door and onto the stairs. The control element, either the door or the stair, must be determined. The time to move through the door is given by,

\[
T_{\text{door}} = \frac{P}{F_{s,max} W_e} = \frac{130}{(1.32 \text{ persons/} s \cdot m)(0.8 \text{m} - 2 \times 0.15 \text{m})} = 197 \text{s}
\]

where \( P \) is the total number of people per exit, 778 persons divided by six total exits. \( F_{s,max} \) is the maximum specific flow per meter of effective width for corridors, aisles, ramps, and doorways\(^1\). \( W_e \) is the effective boundary layer width, found by subtracting 150 mm\(^1\) from each side of the 0.8m wide stair door. In similar fashion the following equation describes the time for an occupant to move past a point on the exit stair.

\[
T_{\text{stair}} = \frac{P}{F_{s,max} W_e} = \frac{130}{(1.16 \text{ persons/} s \cdot m)(0.8 \text{m} - 2 \times 0.15 \text{m})} = 224 \text{s}
\]

The occupant movement up through the stair is the egress control element. It will take the occupants more time to move up the stairs than to get through the stair door. Based on the equations above, the time for all of the occupants on Garage Level 2 to enter the stair is 272 seconds.

Time to Enter the Stair - Remaining Floors

The approach outlined above is the same for both floors.

The calculation was broken up into the time it would take an occupant to travel to the stair door, and then for the last person to go through the exit stair door. The following table summarizes the times for all of the occupants on each floor to enter the stair.

<table>
<thead>
<tr>
<th>Floors</th>
<th>Occupant Load</th>
<th>Distance to Stair (m)</th>
<th>( T_{\text{to stair door}} )</th>
<th>( T_{\text{through stair door}} )</th>
<th>( T_{\text{floor total}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>778</td>
<td>67</td>
<td>48</td>
<td>224</td>
<td>272</td>
</tr>
<tr>
<td>2</td>
<td>778</td>
<td>67</td>
<td>48</td>
<td>224</td>
<td>272</td>
</tr>
</tbody>
</table>

\( \text{TABLE F2 - EGRESS TIME FOR LAST OCCUPANT TO ENTER STAIR} \)
Travel Time Up Stairs

The floor-to-floor travel distance must be determined. This is obtained using an assumed stair tread and riser lengths, the distance between each floor slab, and the Pythagorean Theorem. In this building, the stairs use a 178 mm (7 in) riser and 280 mm (11 in) tread and the floor-to-floor height is 2.9 meters. Based on the total 5.8 m of vertical decent required and the known dimensions of the stair treads, the diagonal travel distance is calculated to be 10.79 m (35.4 ft). In addition, the horizontal distance of along the length of the stair (along the landings) must also be traversed.

The final equation is:

\[ T_{stairs} = \left( \frac{d}{v_{stairs}} \right) + \left( \frac{d}{v_{landings}} \right) = \left( \frac{10.79\ m}{0.70\ m/s} \right) + \left( \frac{15.3m}{1.40\ m/s} \right) = 27\ s \]

It should be noted that the travel speed on stairs is slower than the travel speed on level components.

Total Egress Time

The final flow speed is determined using the total number of people in the building. There will be 1556 occupants in the building served by 6 exit stairs. Occupants will be distributed equally between all stairs, with each stair serving 259 occupants.

The evacuation time of the entire building can now be determined using the following equation:

\[ T_{total} = T_{unit \rightarrow stair} + T_{stair} + T_{exit} + T_{outside} \]

The time to reach the exit stair varies for each occupancy. The following calculation represents the time for the last occupant to egress from Floor B2 of the building through the stair door, down the stair, and through the exit door.

\[ T_{unit \rightarrow stair} = 272\ s \]
\[ T_{stair} = 27\ s \]
\[ T_{exit} = \frac{P}{F_{s,max} W_e} = \frac{259\ persons}{(1.32\ persons/m) (0.8\ m - 2 \times 0.15\ m)} = 392\ s \]

Where \( P \) = Total people through each exit stair
\( F_{s,max} \) = specific flow through door
\( W_e \) = effective width of stair

It shall be noted that the limiting factor of the egress route was the door leading into the exit stair (\( T_{through\ door} \)). For an entire building evacuation using six exit stairs, the total travel time will be 691 seconds, or approximately 11.5 minutes. This time must be added to the pre-movement time. A conservative estimate of 160 seconds for pre-movement has been added to the egress time. Therefore, the most conservative estimate of total egress time from the building is the pre-movement time plus the total travel time or 14.2 minutes total.

The pre-movement times are discussed in the report.