Report

H5 TIMED EGRESS ANALYSIS

Performance-Based Design Study for Increasing the Maximum Exiting Distance for a Generic Semiconductor Fabrication Facility

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List of Acronyms

ASET	Available Safe Egress Time
CFD	Computational Fluid Dynamics
ERT	Emergency Response Team
EWFD	Early Warning Fire Detection
FDS	Fire Dynamics Simulator
FFU	Fan Filter Unit
FOUP	Front Opening Unified Pod
HRR	Heat Release Rate
IBC	International Building Code
NIST	National Institute of Standards and Technology
PP	Polypropylene
RMF	Raised Metal Floor
RSET	Required Safe Egress Time
SIA	Semiconductor Industry Association
SOP	Standard Operating Procedure

Executive Summary

Background

Current egress requirements per the 2018 International Building Code (IBC) Table 1017.2 are that the minimum travel distance for H5 occupancies is 200 ft. This study was performed to evaluate the feasibility of increasing the minimum distance to 300 ft while ensuring that the life safety intent of the IBC is met. A performance-based approach was used where the Pathfinder people movement model was utilized to calculate required safe egress times (RSET) and the Fire Dynamics Simulator (FDS) was utilized to evaluate tenability conditions that would result from the design fire.

Bounding facility design parameters were selected based on input from the Semiconductor Industry Association (SIA) Fire and Building Standards Committee to develop minimum requirements for a generic fabrication facility (fab). These parameters were used as inputs for the computer modeling that was performed and include:

+ Minimum fab width of 300 ft;
+ Minimum fab area of 220,000 SF;
+ Flow-through fab (ballroom design);
+ Minimum distance between raised metal floor (RMF) and the Filter Ceiling of 16 ft;
+ Minimum (supply) ventilation rate of 20 cfm/SF (with a minimum 25% fan filter unit (FFU) coverage over the fab); and
+ Ventilation must remain running at full capacity during egress.

Performance Criteria

Performance objectives were selected for the generic study to ensure that occupants would not encounter untenable conditions during the period of egress. Visibility, thermal exposure, and smoke toxicity are the commonly used tenability parameters for egress studies. Table 1 summarizes the threshold criteria that were used in the study.

Table 1. Summary of Performance Criteria for Egress Study

Parameter	Performance Criteria[1]
Visibility distance	At least 33 ft (10 m) to illuminated object while en route to exit; At least 10 ft (3.3 m) to illuminated object while in exit queue
Temperature	Less than 76 °C (169 °F)[2]
Toxic Gas (measured as Carbon Monoxide concentration)	Less than 600 ppm[3]

[1] All values measured at 6 ft (1.8 m) above floor [Yamada & Akizuki, 2016]

[2] Based on 20 minute exposure before incapacitation [Purser & McAllister, 2016]

[3] Concentration levels of approximately 600 ppm can affect cardiac function for some individuals [Purser & McAllister, 2016]

Design Fire Scenario

The design fire scenario was based on a flammable liquid spill that ignites and spreads to a process tool. The resulting heat release rate profile was developed based on a generic tool size, the spacing between tools, and a fuel load limit of 1 lb/ft^2 of non-FM 4910 plastic. This information was used to model the fire development for a worst-case tool, and the ability for fire to spread to adjacent tools either in the same row or across the bay or chase.

A maximum heat release rate of 20 MW was calculated for each tool with potential spread to 2 adjacent tools in the time period of evacuation. At any given time, no more than 2 tools would be burning at this steady-state heat release rate of 20 MW each, for a total of 40 MW. Rather than crediting the decay and growth periods that would occur during the time period of tool fire spread, an ultra-fast growing fire that reaches a steady-state value of 40 MW was used to provide a conservative bound for the tool fire scenario (see Figure 1).

Three fire locations (center, southwest corner and west wall locations) were evaluated to examine the effect of location on smoke spread dynamics and the RSET values resulting when a reduced number of exits are available.

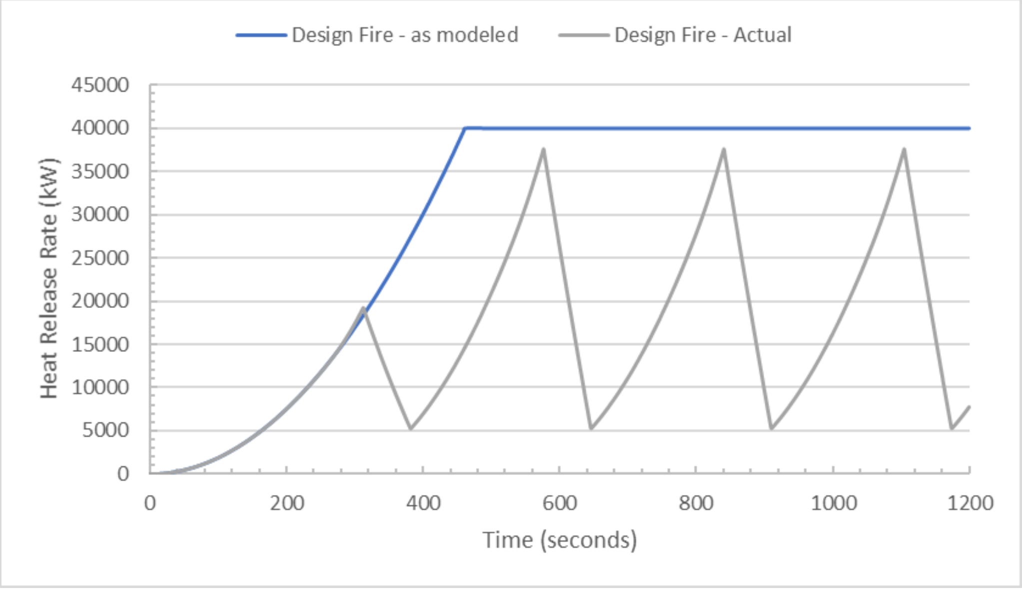

Figure 1. Heat release rate profile for tool design fire scenario

Summary of Egress Times

RSET values were determined by summing the detection, warning, premovement and travel times required to travel to an exit stair and enter the vestibule. The detection time was identified using FDS model data for smoke detection and sprinkler activation, while allowing for the collective 100 second delay specified in NFPA 72. Literature data were used to select a conservative premovement time. Travel times were determined by Pathfinder assuming that 96.6% of building occupants travel unimpeded and 3.4% of building occupants require the use of crutches or a cane. These times are summarized in Table 2.

A safety factor of 1.5 was applied to the evacuation times incorporating the methodology in IBC Section 909.4.6 for smoke control systems. As shown in Table 2, RSET values ranged between 10.9 and 15 minutes, with longer values corresponding to the southwest corner and west wall fire scenarios where an exit is closed for at least part of the egress time period. The largest RSET value resulted for the west wall fire location where all of the exits are initially available for use, but at 380 seconds, one exit is blocked due to diminished visibility conditions, requiring that occupants in the queue travel to another exit.

Table 2. Summary of Required Safe Egress Time Results

Event	*Center Fire No Exits Closed (seconds / minutes)*	*Southwest Corner Fire One Exit Closed (seconds / minutes)*	*West Wall Fire One Exit Closed at 380 seconds (seconds / minutes)*
Detection	215 / 3.6	215 / 3.6	215 / 3.6
Warning	10 / 0.2	10 / 0.2	10 / 0.2
Pre-movement delay	30 / 0.5	30 / 0.5	30 / 0.5
Travel time	256 / 4.3	385 / 6.4	250 / 4.2
Evacuation time	**511 / 8.5**	**640 / 10.7**	**678 / 11.3**
RSET	**655 / 10.9**	**847 / 14.1**	**904 / 15.0**

Summary of Fire Modeling

FDS models were constructed for the three fire locations, incorporating sprinkler activation to examine mixing effects but not suppression effects. Model results showed that visibility is the limiting tenability parameter where smoke spreads radially from the fire location but never fills the entire fab. Rather, a steady-state condition is reached for each scenario where the smoke generation rate is balanced with the ventilation rate. For each fire location, the visibility at 6 ft above the floor will exceed 100 ft in approximately 30-50% of the fab when the steady-state condition is reached.

A sensitivity study was performed to determine if the model results are dependent on FFU coverage, ventilation rate/SF, FFU capacity, FFU dimensions, tool size, and tool height. With the exception of FFU coverage, it was determined that these parameters do not have a significant impact on the spread of smoke, heat and toxic gases in the fab. Smaller regions of smoke spread will result when the FFU coverage is greater than 25%. It was concluded that the available egress time is sufficient for occupants to exit the fab safely.

Conclusions

Based on these results, Jensen Hughes finds that an egress distance of 300 ft in a generic H5 fabrication design will meet the intent of the IBC where safe egress conditions exist, provided that the minimum design parameters for building width, square footage, ceiling height, and ventilation rate are met. Therefore, the increased travel distance of 300 ft (91.5 m) is acceptable and will not impact the safety of occupants in the event that emergency evacuation during a fire is necessary.

1.0 Introduction

Current egress requirements per 2018 International Building Code (IBC) Table 1017.2 state that the minimum travel distance for H5 occupancies is 200 ft. A study was performed to determine if there are conditions for semiconductor fabrication facilities where the minimum requirements could be increased to 300 ft while ensuring that the egress time is sufficient for occupants to exit safely. This study used a performance-based approach where the Pathfinder egress model was utilized to calculate Required Safe Egress Times (RSET) and the Fire Dynamics Simulator (FDS) was utilized to evaluate tenability conditions that would result from the design fire.

In order to perform this analysis, minimum fab design values were defined:

+ Minimum fab width of 300 ft;
+ Minimum fab area of 220,000 SF;
+ Flow-through fab (ballroom design; bay / chase design was not evaluated and this study is not applicable);
+ Minimum distance between raised metal floor (RMF) and Filter Ceiling of 16 ft;
+ Minimum (supply) ventilation rate of 20 cfm/SF (at least 25% fan filter unit (FFU) coverage); and
+ Ventilation must remain running at full capacity during egress.

These values were determined using input from the SIA Fire and Building Standards Committee. Based on the design parameters, a generic semiconductor fabrication facility, or fab, was developed and used as a basis for this evaluation.

2.0 Background

2.1. APPROACH

The following steps were used to develop this study and are discussed further in the sections noted:

1. **Development of Egress Study Parameters:** Assumptions and modeling parameters were identified for the purpose of constructing the fire and egress models (Section 2.3).
2. **Development of Performance Criteria:** Performance criteria for tenability measures were identified for evaluating if safe conditions will be maintained in the event that a fire occurs in the fab and evacuation is necessary (Section 2.4).
3. **Development of Design Fire Scenario:** Combustible fuel loading in the facility was evaluated and a worst-case design fire scenario was developed (Section 3).
4. **Determination of Required Safe Egress Times:** The Pathfinder people movement model was used to construct models for the generic fab and calculate Required Safe Egress Times (Section 4)
5. **Comparison of RSET Values with Fire Model Results:** The tenability conditions resulting from the design fire scenario were modeled using the Fire Dynamics Simulator Version 6.7.4, a computational fluid dynamic (CFD) model [McGrattan et al., 2020]. The conditions at RSET times were evaluated to determine if sufficient time exists for safe egress (Section 5).

2.2. GENERIC BUILDING DESIGN

The generic semiconductor fabrication facility was modeled as a 3-level structure with Utility, Subfab, and Fab levels, each with identical footprints. A plan view for the Fab level is shown in Figure 2-1. Six exits are spaced evenly around the building perimeter such that the egress travel distance is 300 ft.

The Fab level consists of two areas separated by a Filter Ceiling, located at a height of 16 ft above the RMF, which is constructed of a combination of blank ceiling panels and fan filter units. Process tools are located below the Filter Ceiling and the Interstitial area is located above the Filter Ceiling. The process tools are arranged in rows with a “chase” on the back side of the tool and a “bay” on the front side of the tool. Chases are used for accessing the tools for maintenance operations and are not designated as egress paths. Bays are used for loading material into the tools and are designated as egress paths.

Fire modeling was conducted for the Fab level only, while egress modeling included each level. For simplicity, the fab was modeled using a single generic tool type and a uniform layout. In reality, many different types of tools are utilized in semiconductor fabrication facilities with various layouts. Additional models were run to determine if the results are sensitive to these parameters.

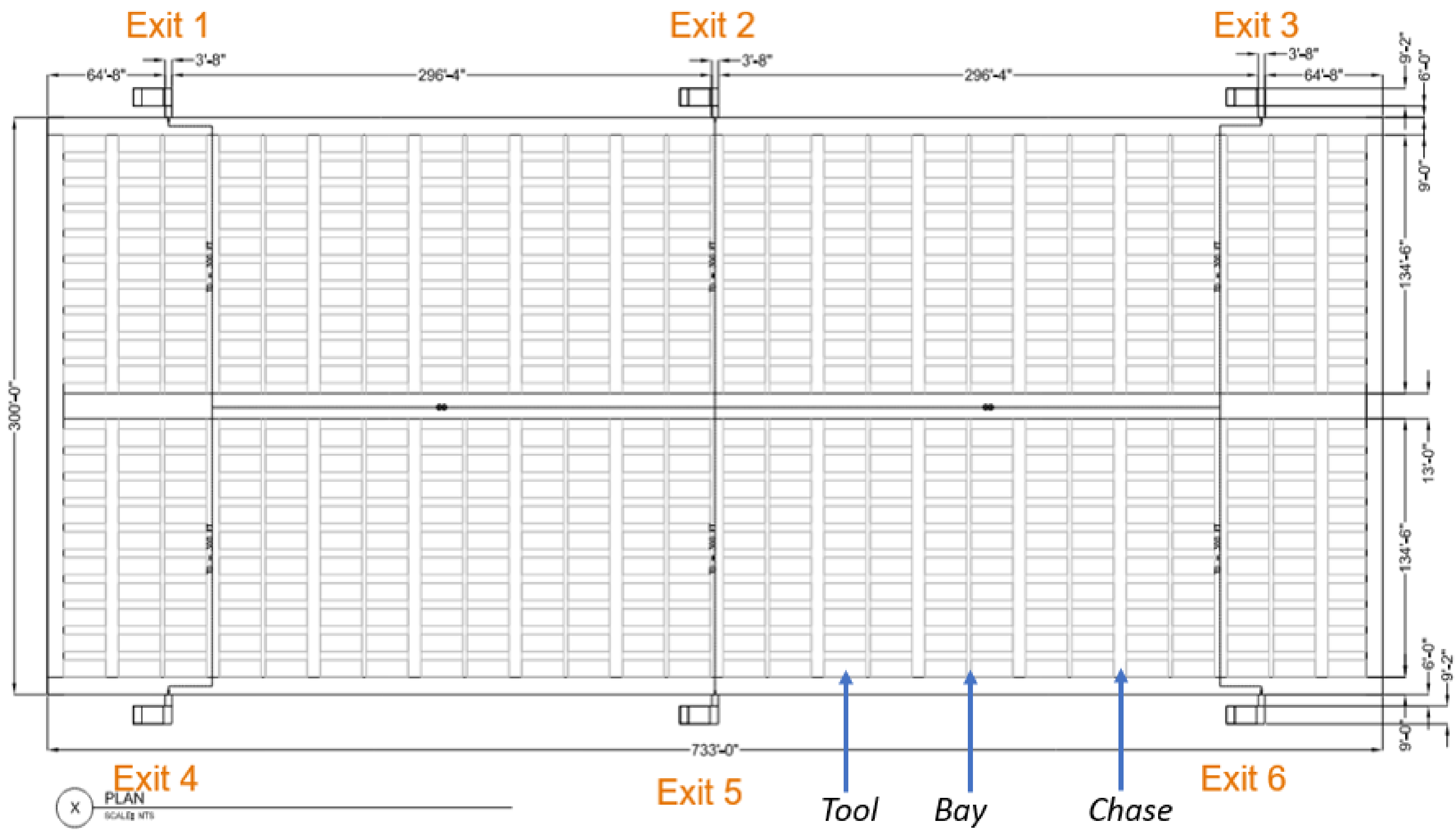

Figure 2-1. Layout of generic fab

2.3. EGRESS STUDY PARAMETERS

Important parameters and assumptions were selected based on information provided by the SIA Fire and Building Standards Committee, data published in the fire protection engineering literature, and engineering judgment. These parameters are summarized in Table 2-1.

Table 2-1. Summary of Assumptions Utilized in Egress Study

Parameter Description	*Assumption*	*Remarks*
1. Geometry		
a. Fab type	Flow-Through	Two-story air zone
b. Fab size – plan view	300-ft width 220,000 SF	See Figure 2-1
c. Fab height – section	16 ft	Minimum distance between RMF and Filter Ceiling
d. Tool sizes (LxWxH)	23 x 9 x 10 ft	See Figure 3-1; also evaluated 16 x 10 x 8 ft tools and 23 x 9 x 8 ft tools
e. Tool spacing	Perimeter aisles: 9 ft wide Center aisle: 13 ft wide Between tool spacing: 3 ft	See Figure 3-1
2. Occupants		
a. Occupant load factor	200 gross	2018 IBC Table 1004.5[1]
b. Occupants	1,100	Based on 2018 IBC 1004.5
c. Travel speed	3.9 ft/s for 96.4% of occupants; 2.46 ft/s for 3.6% of occupants	Normal walking speed [SFPE, 2019]. 3.4% of occupants working in the facility may have mobility limitations requiring the use of a cane or crutch.
3. Means of Egress		
a. Exit width door	37 in. clear width	IBC 2018 Section 1005.3[1]
b. Exit width stairs	55 in. wide	IBC 2018 Section 1005.3[1]
c. Total exit capacity	1,110 door capacity modeled 1,100 stair capacity modeled	Stair quantity: 6 (3 on each side)
d. Egress convergence	Yes	2018 IBC Section 1005.6[1]; assume occupants at 3 levels evacuate at the same time
4. Materials		
a. Ceiling and Walls	Type X gypsum	Material density: 800 kg/m^3 Specific heat: 1.1 kJ/(kg·K) Thermal conductivity: 0.17 W/(m·K) Emissivity: 0.9
b. Raised Metal Floor (RMF)	Aluminum	Modeled as aluminum screen with 20% free area Material density: 284 kg/m^3 Specific heat: 1.0 kJ/(kg·K) Thermal conductivity: 1.32 W/(m·K) Emissivity: 0.9
c. Fab floor	Concrete waffle slab	Outside of model domain

Parameter Description	*Assumption*	*Remarks*
5. Ventilation		
a. Filter coverage	Minimum 25% coverage	33% and 50% FFU coverage also modeled
b. Filter air flow rate	19 CFM/SF	Rounded to 20 for purpose of this study
c. Exhaust	Not modeled	See Section 5.2
d. Smoke control	Not modeled	not required by 2018 IBC/IFC
e. MAH	Not modeled	See Section 5.2
6. Design Fire		
a. Fuel source	1 lb/SF non-FM 4910 plastic at tool; 40 MW peak	Average energy content from representative worst-case tool data provided by taken as 20 MJ/kg
b. Growth Rate	Ultra-fast	Based on parameters for t-squared fires [Evans, 1995]
c. Fire location	Center SW corner West wall	Center: no exits blocked SW corner: 1 exit blocked West wall: 1 exit blocked beginning at 380 sec
7. Alarms		
a. Smoke detection	EWFD system installed	
b. Water flow	Building fully sprinklered	Water flow alarm does not trigger building evacuation automatically
c. Manual pull stations	Installed	Operated by occupants
d. Emergency response	Trained ERT onsite	Study does not credit ERT response, assumes that investigation occurs during incipient phase of fire prior to design fire curve.
8. Fire Timeline		
a. EWFD alarm	14% obscuration/m	Based on Geiman & Gottuk, 2003
b. Water flow alarm	Sprinklers are quick response (RTI of 50 $(m \cdot s)^{1/2}$), 5.6 K-factor, standard temperature 171 °F (77 °C), 8.5 ft x 15 ft spacing	Ordinary Hazard Group 2. Sprinklers included for fire notification purposes. Suppression/control of fire not credited.
c. Delay for occupant movement	30 seconds after announcement to evacuate	
9. Tenability Criteria		
a. Visibility	At least 33 ft (10 m) to illuminated object while en route to exit; At least 10 ft (3.3 m) to illuminated object while in exit queue	Research has shown people are willing to move through smoke if visibility is more than 33 feet (10 m) [Yamada & Akizuki, 2016].
b. Thermal exposure	76 °C	Based on 20-minute exposure before incapacitation [Purser & McAllister, 2016].
c. Toxic gas concentration	600 ppm CO	Concentration levels of approximately 600 ppm can affect cardiac function for some individuals [Purser & McAllister, 2016]. CO concentration of 600 ppm (0.06%), measured 1.83 m (6 ft) above the floor, used for this analysis.

[1] 2018 Edition was used since it was available and in use when the modeling was performed. Values are unchanged in the 2021 Edition.

2.4. PERFORMANCE OBJECTIVES AND CRITERIA

Performance objectives were selected to ensure that occupants would not encounter untenable conditions during the period of egress. Visibility, thermal exposure, and smoke toxicity encompass the commonly used tenability parameters for egress studies. Table 2-2 summarizes the threshold criteria that were used for these parameters with further discussion provided in the sections below.

Table 2-2. Summary of Performance Criteria for Egress Study

Parameter	*Performance Criteria*
Visibility distance	At least 33 ft (10 m) to illuminated object while en route to exit; At least 10 ft (3.3 m) to illuminated object while waiting in exit queue
Temperature	Less than 76 °C (169 °F) measured at 6 ft (1.8 m) above floor
Toxic Gas (measured as Carbon Monoxide concentration)	Less than 600 ppm measured at 6 ft (1.8 m) above floor

2.4.1. Visibility

In order to safely egress from a building, occupants must be able to navigate to one of the building exits; however, the presence of smoke will reduce the visibility and make navigation difficult. Research has shown that people are generally willing to move through smoke if the visibility is more than 33 ft (10 m) [Yamada & Akizuki, 2016]. Given the large travel distances to exits, a visibility distance of 33 ft (10 m) to illuminated objects was used while occupants are traveling to an exit. The use of an illuminated object as compared to a non-illuminated object was appropriate since the egress path in semiconductor fabrication facilities is predictable due to the linear tool layout. With the presences of long unobstructed egress aisles, the expectation is that backlit exit signs will be visible throughout much, if not all, of the egress path. Due to the hazardous nature of semiconductor processing, occupants are well trained for emergencies and extremely familiar with the building layout and location of exits.

Once occupants are approaching the exit, or in queue at the exit stair, it is acceptable for the visibility to be less than 33 ft provided that the visibility distance is at least equal to the remaining distance to the exit, with a minimum requirement of 10 ft (3 m) to a backlit exit sign. This assumption is based on research that has shown that most people will continue traveling to a queue as the visibility is dropping as long as they can see it rather than changing their route to a different exit [Bryan, 1977].

2.4.2. Temperature

There are three temperature effects to consider with fire: skin burns, hyperthermia (increase in core body temperature), and respiratory tract damage. Research has shown there is a narrow margin between pain due to thermal exposure and burns due to thermal exposure. A radiant heat flux of 1.7 kW/m^2 has been suggested by Mudan and Croce to ensure that no pain is experienced, regardless of the exposure duration [Mudan & Croce, 1984]. For occupants that are passing under a hot smoke layer while exiting the building, a 1.7 kW/m^2 radiant heat flux corresponds to a smoke temperature of approximately 172 °C.

When occupants directly traverse through warm air and smoke, the main heat transfer method is convection. For exposures of up to 2 hours to convective heat from air containing less than 10 % by volume of water vapor, the time to incapacitation in minutes, $t_{\mathrm{I_{conv}}}$, at a temperature T (°C) is calculated from the following equation [Purser & McAllister, 2016]:

$$t_{\mathrm{I_{conv}}} = 5 \times 10^{7} T^{-3.4}$$

Using this equation, the temperature that an occupant can be exposed for up to 20 minutes is calculated to be 169 °F (76 °C). For the purpose of this analysis, exposure times for occupants directly traversing through warm air and smoke caused by stratification are not anticipated to exceed 20 minutes. Therefore, a thermal criterion for distances within 1.8 meters (6 feet) of the finished floor of 169 °F (76 °C) was used since it was more conservative than the value associated with thermal burns.

2.4.3. Toxicity

Carbon monoxide (CO) is commonly considered the most dangerous asphyxiant released during fires. Other toxic gases could be released in the event of a fire (such as hydrogen chloride or hydrogen cyanide); however, these gases were not evaluated specifically since FDS model results showed CO concentrations measured 6 ft above the floor. Presence of toxic gases are commensurate such that more dangerous concentrations of other toxic gases would not be expected in the absence of high CO concentrations. Therefore, CO concentrations provided an appropriate representation of toxic gases for this analysis.

Incapacitation from CO inhalation can occur in approximately 5 minutes for concentrations ranging from 6,000-8,000 ppm and in approximately 30 minutes for concentrations ranging from 1,400-1,700 ppm. However, a concentration of approximately 600 ppm can affect the cardiac function for some individuals, particularly those with underlying health conditions [Purser & McAllister, 2016]. A CO threshold of 600 ppm (0.06%), measured 6 ft (1.83 m) above the floor was conservatively used for this analysis.

3.0 Design Fire

3.1. DESIGN FIRE SCENARIO SELECTION

In order to determine the worst-case design fire scenario for this analysis, the credible threats were evaluated in terms of their severity and the length of time required for fire development. Potential fire scenarios that could develop in the generic fab include:

1. Stocker fires,
2. Flammable liquid fires,
3. Flammable gas fires, and
4. Tools fires.

Confidential large-scale testing conducted by Hughes Associates showed that fires involving Front Opening Unified Pods (FOUP) storage stockers can be very large and are dependent on the FOUP construction material [Hughes Associates, 2011]. However, a development period of at least 5-10 minutes is needed for the fire to spread up the rows of FOUPs, to adjacent rows, and to the opposing wall of FOUPs. While a steady-state stocker fire may be more severe than for other fire scenarios, the severity during the time period where occupants would be egressing the facility is expected to be less compared to a tool fire.

Fires involving flammable liquids and gases will not pose a large threat for egress by themselves, due to the small amount of liquid stored in the fab and the low gas flow rates through process piping. In addition, the soot producing potential of these materials is low in comparison to the plastic materials used in FOUP and tool construction. However, these fires could serve as an ignition source for plastic contained in a process tool. A large amount of energy is required to ignite the types of plastics used in tool construction whereas a smaller amount is needed for ignition of flammable liquids or gases.

Per input from SIA members, most new tools in semiconductor facilities are constructed of non-combustible materials or plastics that meet the requirements of FM 4910. FM 4910 compliant materials present a low risk for fire development due to their inability to propagate flame and a low ability to generate smoke [Factory Mutual, 2009]. Selected tools, such as wet process tools, may contain larger portions of non-FM 4910 materials due to performance requirements. Typically, these tools are outfitted with onboard suppression systems. Factory Mutual has driven stringent management practices for combustible plastics in tools with a metric of 1 lb per square foot.

Based on this information, it was determined that ignition of a flammable liquid spill with subsequent ignition of the non-FM 4910 plastic in a tool would result a bounding design fire scenario.

3.2. DEVELOPMENT OF TOOL FIRE SCENARIO

The tool fire scenario was developed based on a generic tool size, the spacing between tools, and a maximum allowable fuel load limit of 1 lb/SF of non-FM 4910 plastic. This information was used to model the fire development for a worst-case tool, and the ability for fire to spread to adjacent tools either in the same row or across the bay or chase.

It was assumed that the tool fire growth rate would follow an ultra-fast growth curve (α= 0.1876 kW/sec^2) [Evans, 1995]. Based on the fuel load limit of 1 lb/SF and the generic tool size and spacing shown in Figure 3-1, fire growth and decay was calculated until available fuel was consumed. Most tools that have a notable quantity of non-FM 4910 plastics contain a mixture of plastics with many having a much lower energy content (e.g. heat of combustion) than polypropylene. Industry data provided by the SIA members for a selection of wet tools were used to calculate an average heat of combustion of 20 MJ/kg.

Based on this average heat of combustion, it was determined that the peak heat release rate would be 20 MW, allowing for 75% of the plastic to be consumed during the growth phase and 25% during the decay phase. Radiation calculations were performed and it was determined that fire spread to adjacent tools could occur in 350 sec (5.83 min), but the amount of fuel present was not sufficient to create the exposure needed to spread across the bay or chase. Figure 3-2 shows the resulting design fire curve where the peaks and valleys correspond to the growth and decay periods. With the spread dynamics, at most 2 tools will be burning at a time at their maximum heat release rate. To provide a conservative bound, the heat release rate curve was simplified by assuming that the heat release rate will remain at 40 MW once it is reached at 462 sec (7.7 min). A more detailed explanation of the calculations associated with this fire scenario are provided in Appendix A.

Several studies provide data that are useful for validation of these calculations. Large scale testing was performed by Factory Mutual in 1995 for a wet bench constructed of 100% polypropylene (e.g. effectively solid sheets of polypropylene) [Wu et al., 1995]. This bench was 71 inches long by 40 inches wide by 66 inches high and weighed 616 lbs. In terms of polypropylene per unit area, the fuel load density was 31 lbs/SF. In the test performed, a maximum heat release rate of 10 MW was measured. The tool evaluated is dramatically different from any tool positioned in cleanrooms currently since polypropylene has largely been replaced with either FM 4910 materials, plastics with lower energy contents, or non-combustible materials.

More recently, Jensen Hughes conducted a confidential tool specific study for a semiconductor processing tool. As part of this study, modeling was performed using conservative assumptions to determine that a maximum heat release rate of 20 MW could potentially be supported with the quantity and location of plastic contained in the tool [Jensen Hughes, 2020]. The majority of the plastic contained in the tool in terms of energy content is polypropylene, with a total mass of 340 kg. However, multiple failures would need to occur to support this heat release rate since the polypropylene is concentrated in distinct enclosed modules within the tool. Involvement of the multiple modules needed to support a 20 MW fire would require structural failure of the enclosures housing the modules, a possible but highly unlikely event, and failure of the onboard suppression system. This tool represents an extreme in terms of the tools that are typically positioned in semiconductor fabrication facilities. Examination of this information provides additional rationale that a maximum heat release rate of 20 MW per tool is an appropriately conservative bound for this type of fire.

Factory Mutual loss data further support that this design fire scenario is extreme and statistically improbable. FM 7-7 *Semiconductor Fabrication Facilities* Data Sheet (2019 Edition) states that the majority of fire losses reported during the period of 2003-2013 occurred outside of the cleanroom area (Section 3.7.1.3) [Factory Mutual, 2019]. Section 3.7.1.3 expands upon this point further by stating that the use of FM 4910 plastics in tool construction and the implementation of third-party review (SEMI S2, SEMI 314, and FM 7701) of process tools and associated support equipment has resulted in a significant reduction in fire losses in the semiconductor industry. This information further supports the position that the design fire scenario will provide a conservative bound for egress calculations.

Three locations for this fire were explored: center, southwest corner and west wall (see Figure 4-1). Fire development associated with these locations affected the number of exits that would be blocked during an evacuation and the smoke spread dynamics. More specific details about these locations are provided in Section 4.3.

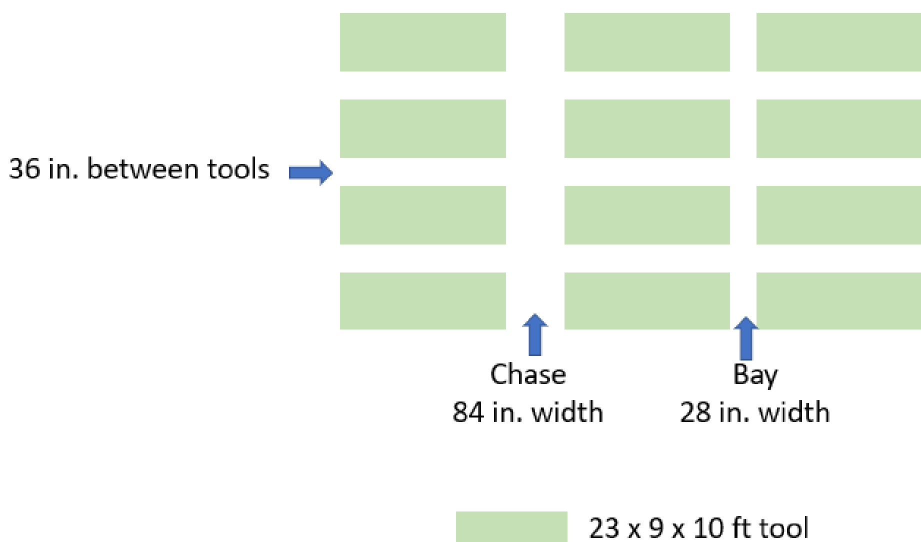

Figure 3-1. Generic tool layout used for tool fire development

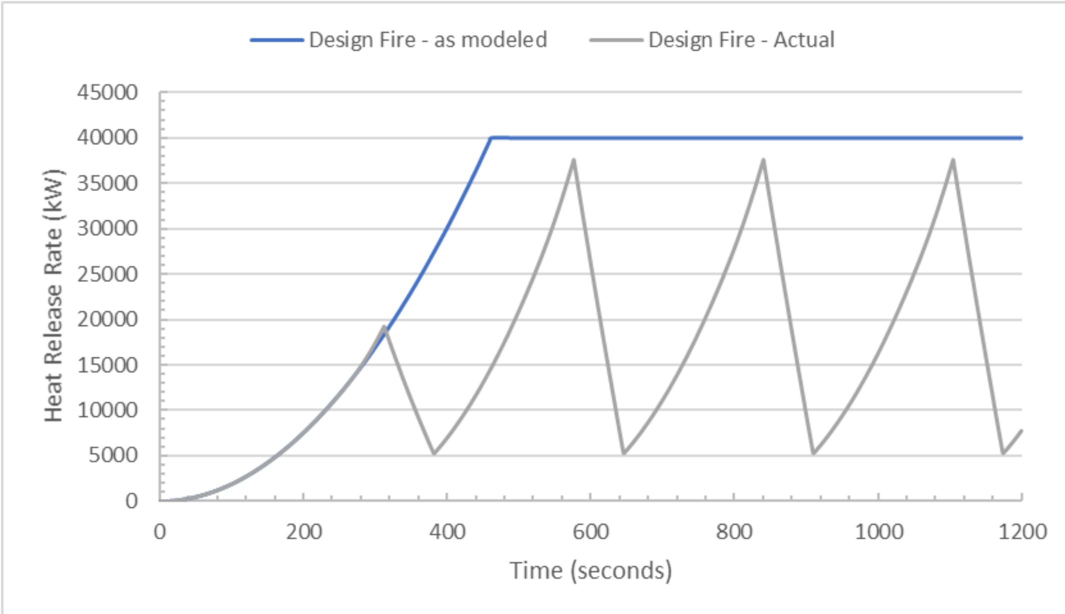

Figure 3-2. Heat release rate curve for design tool fire scenario

4.0 Egress Modeling

The required safe egress times were determined by defining various components of the egress event. The following equation was used:

$$RSET = t_{\text{det}} + t_{\text{warn}} + 1.5(t_{\text{pre}} + t_{\text{trav}})$$

where t_{det}, is the detection time, t_{warn} is the warning time, t_{pre} is the premovement time, and t_{trav} is the travel time. For the purpose of this study, the travel time (t_{trav}) was defined as the time at which the last occupant cleared the door entering the exit stair enclosure (e.g. vestibule). Smoke spread into the stair enclosures was not modeled; it was assumed that these enclosures will remain tenable during the time of egress. A safety factor of 1.5 was added to the premovement and travel times following the requirements for smoke control systems as specified in IBC 909.4.6 [IBC, 2018].

4.1. DETECTION AND WARNING TIMES

In order to define the detection time, it was assumed that at least two means of fire detection would occur prior to the announcement to evacuate the building. Many scenarios may occur; however, careful analysis was conducted to ensure that the notification times were conservative. For the purpose of this analysis, it was assumed that at least a single EWFD (such as VESDA) alarm and verification of sprinkler activation would provide a reasonable bound for notification of an incipient fire in the facility. The times at which these alarms would be expected were predicted from the FDS model runs (see Section 5). Activation of an EWFD alarm was based on optical density measurements 1 ft below the floor between the Fab and Subfab levels. The alarm threshold was set as 0.14%/m based on research performed by Geiman and Gottuk [Geiman & Gottuk, 2003]. Table 4-1 shows the amount of time required for the first smoke alarm and sprinkler activation as determined by FDS. For all fire locations, the amount of time required for sprinkler activation is longer than for smoke detection. The time to sprinkler activation is nearly the same for the 3 fire locations with 120 sec (2.0 min) for the center and west wall locations and 115 sec (1.9 min) for the southwest fire location. As a conservative bound, t_{det}, was taken as 125 seconds.

The warning time was based on criteria outlined in NFPA 72. NPFA 72 §17.13.2 permits a response time up to 90 seconds for the initiation of alarm-producing sprinkler waterflow devices and the §10.11.1 permits a 10 second signal delay [NFPA 72, 2019]. A detection and warning time of 225 sec (3.75 min) was conservatively used based on the amount of time required for smoke detection, sprinkler activation, and NFPA 72 signal time allowances (90+10 seconds). At 225 sec (3.75 min), the fire size would be approximately 9.5 MW which is comparable to a fire involving a furnished room [NIST, 2020]. Realistically, a fire of this magnitude would prompt the decision to evacuate either by action of the Emergency Response Team (ERT) or personnel working near the fire (by manual fire alarm activation).

Table 4-1. Summary of detection, warning and premovement times

Fire Location	*Smoke Detection Time (sec (min))*	*Sprinkler Activation Time (sec (min))*	$t_{det} + t_{warn}$ *(sec (min))*	$t_{det} + t_{warn} + 1.5 \times t_{pre}$ *(sec (min))*[1]
Center	70 (1.17)	120 (2.0)	225 (3.75)[2]	270 (4.5)
Southwest corner	65 (1.08)	115 (1.92)	225 (3.75)[2]	270 (4.5)
West wall	65 (1.08)	120 (2.0)	225 (3.75)[2]	270 (4.5)

[1] Premovement time of 1.5 x (30 sec) used

[2] Sprinkler activation time of 125 seconds used

4.2. PREMOVEMENT TIME

Occupant characteristics affect the premovement time, t_{pre}, and will depend upon occupant familiarity with the building and the quality of emergency direction and information [Gwynne & Boyce, 2016]. Personnel in H5 occupancies are assumed to be awake and familiar with the building, the alarm signals, and evacuation procedures. As a result, the premovement time was taken as 30 sec (0.5 min). This time period allows for occupants to evaluate the situation and determine which exit route to take. Selection of this premovement time is based on interviews and data recorded from actual fires and evacuation exercises [Proulx, 2008].

Table 4-1 shows that with the addition of a 30 second pre-movement time and a 50% safety factor, the total delay used for the determination of RSET was 270 sec (4.5 min). The delay to start evacuation as defined in this study is independent of the actions performed by the ERT. Protocols should be in place for the ERT with respect to emergency response procedures after an initial alarm is received. It is expected that they would successfully investigate and extinguish most fires during the incipient phase, prior to the beginning of the ultra-fast growth phase. As a result, the delay of 270 sec (4.5 min) after the initiation of ultra-fast fire growth following an incipient phase provides a conservative bound for the egress timeline.

4.3. PATHFINDER MODEL

In comparison to empirical calculations, the use of a computer egress simulation offers the added benefit of calculating the egress time for complex exiting configurations. This is particularly important in spaces such as large industrial facilities that have several levels and multiple exit paths where traditional hand calculation techniques can be less accurate. In order to determine the RSET values for the generic fab, the dynamic, three-dimensional egress model Pathfinder (Version 2020.04.0902) was utilized [Thunderhead Engineering, 2020].

According to the Pathfinder Technical Reference, Pathfinder is an “agent-based egress simulator that uses steering behaviors to model occupant motion.” The Pathfinder simulator can use two different methods to model occupant motion: the steering model and the SFPE method. The steering method was used for this project as it better predicts the occupant behavior for complex environments (see Section 4.6 for further discussion).

The Pathfinder model was used to calculate the movement portion of the occupant egress time and considers the occupant characteristics, occupant loading, and the interactions of occupants with each other and the structure as they egress. Time delays associated with fire detection, warning and premovement delays were added to the movement times calculated by Pathfinder. A safety factor of 1.5 was applied to the evacuation time to determine the RSET

4.4. EGRESS MODEL CONSTRUCTION

A single model was constructed to include the Fab, Subfab, and Utility levels to allow for a determination of the effects of queueing at the exits on all levels simultaneously. Six exit stairwells were located around the perimeter of the building, serving all floors. The utility floor was located at ground level such that the entrances to the exit stairs discharged directly to the outside and no vertical travel was necessary. An overview of the Fab level exit locations is shown in Figure 4-1.

Based on required door and stair dimensions per IBC 2018 section 1005.3, doors leading into the exit stairs were modeled to provide a clear width of 37 in. (0.94 m) between the door frames. Exit stairs were 55 in. (1.4 m) wide with 55 in. (1.4 m) wide landings.

The egress aisles on the perimeters of the fab (e.g. north, south, east and west sides) were modeled as 9 ft (2.74 m) wide. A center aisle measuring 13 ft wide (3.96 m) divided the north and south halves of the fab. Subfab and Utility levels were modeled as open floors completely free of any obstructions or tools.

The tool rows separated the navigation meshes into the bay on one side of the row and the chase on the other side. All bays had a clear width of 28 in. (0.7 m) and were modeled as unobstructed multi-directional exit access aisles. The widths of the chases were 7 ft (2.13 m). One-way doors were provided at the end of the chases, allowing occupants to egress from chases, but not allowing occupants outside of the chase to enter them.

These models incorporated the assumptions listed in Table 2-1 relative to the number of occupants and occupant travel speed. Occupants were dispersed evenly over the fab floor area with the exception of in the bays as it was assumed that personnel would not normally be working in them. Further details about the construction of these models is provided in Appendix B.

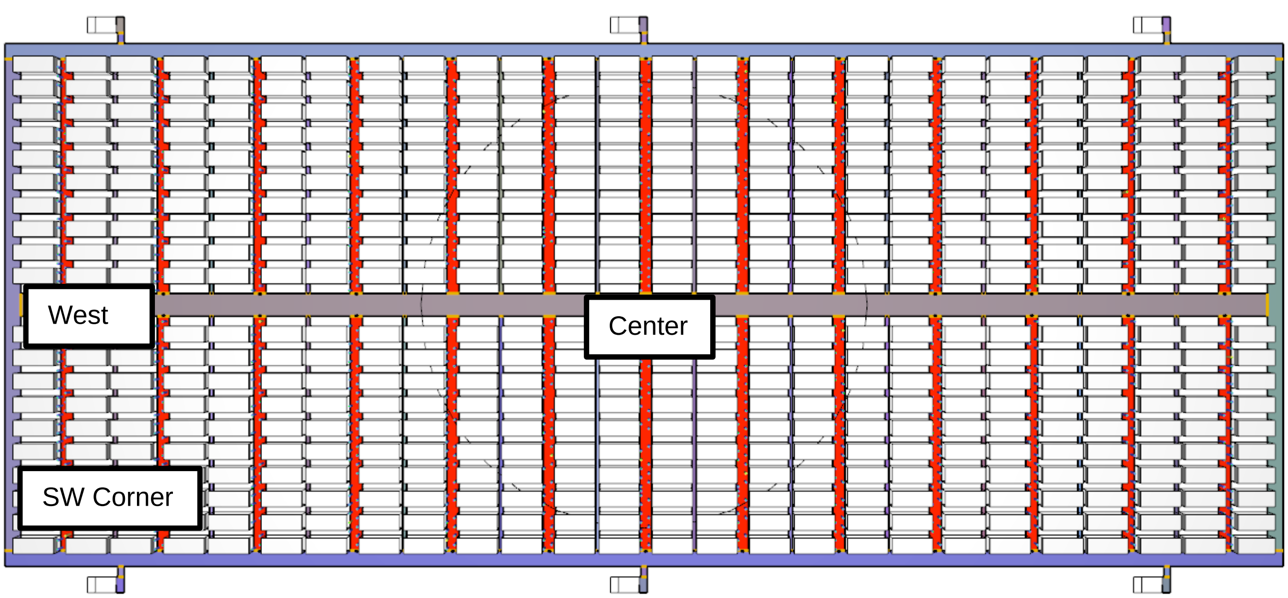

Figure 4-1. Overview of generic fab as modeled in Pathfinder

4.5. EGRESS MODEL SCENARIOS

Three fire locations were modeled as labeled in Figure 4-1. The central tool fire was located slightly south of the fab center aisle to simulate a fire in the center of the fab as closely as possible. All of the exits were available for use with this fire location. The southwest corner fire was chosen to determine if corner effects would have an impact on smoke layer development. With this fire location, one of the six exits (Exit 4) was blocked for use by the occupants due to the untenable conditions near the fire. The west wall location was positioned just south of the center aisle on the west side of the fab. Initially, all exits were available for this scenario. However, the tenability conditions at Exit 4 are exceeded at 380 seconds at which point the exit is blocked in the model.

Table 4-2 describes the four scenarios that were evaluated in Pathfinder. In scenarios 1-3, the baseline tools were modeled (23 ft long), yielding 13 chases and bays on each side of the center aisle. In scenario 4, the tools were reduced to 16 ft long, resulting in 17 chases and bays. Scenario 4 was included to evaluate the relationship between the number of egress aisles and the travel times. The center fire location was modeled in this scenario, and the resulting trends were assumed to be representative of the three fire locations.

In addition to the blocked exits in scenarios 2 and 3, movement in the area of the fire was restricted for each scenario. This involved partitioning that prevented occupants from traveling through regions where untenable conditions would occur. These locations are described in Table 4-2.

Table 4-2. Egress Model Scenarios

Scenario	*Fire Location*	*Number of Exits Available*	*Number of bays and chases on each side*	*Closed Exits and Exit Accesses*
1	Center	6	13	Four bays and five chases on both sides of the center aisle.
2	SW Corner	5	13	Two bays and two chases and west aisle on south side of center aisle and Exit 4.
3	West Wall	5[1]	13	Two bays, two chases and west aisle on both sides of center aisle. All exits available initially; Exit 4 closed at 380 seconds due to loss of visibility.
4	Center	6	17	Six bays and six chases on both sides of the center aisle.

[1] Exit 4 closed at 380 seconds due to loss of tenability

4.6. EGRESS MODEL RESULTS

Values for the required safe egress times are provided in Table 4-3 for each scenario. The model was executed multiple times to ensure that the results did not vary more than 10 seconds between runs. Evacuation times (without factor of safety) ranged between 6.5 and 9.6 minutes. As expected, the shortest times corresponded to cases where all six exits are available. The closure of a single exit (Exit 4) increases the travel time since Exit 4 users are reassigned to other available exits, increasing the queuing at those exits. Comparison of the results for Scenarios 1 and 4 confirm that the addition of egress aisles (resulting from smaller tools) will decrease the travel time. In this case, the travel time is 21 seconds less when additional egress aisles are available. RSET values range between 10.4 and 15.1 minutes. The largest value was measured for the case where all of the exits are open until one of the exits becomes untenable and the occupants must leave the queue and travel to a different exit. Figure 4-2 shows a timeline for different stages of the evacuation with respect to the fire development for all four scenarios.

Table 4-3. Summary of Required Safe Egress Time Results

Scenario	*Fire Location*	*Available Exits*	$t_{det} + t_{warn}$ (sec (min))	t_{pre} (sec (min))	t_{trav} (sec (min))	*RSET* (sec (min))
1	Center	6	225 (2.08)	30 (0.5)	256 (4.27)	655 (10.92)
2	SW Corner	5	225 (2.08)	30 (0.5)	385 (6.42)	847 (14.12)
3	West Wall	5[1]	225 (2.08)	30 (0.5)	423 (7.05)	904 (15.07)
4	Center	6	225 (2.08)	30 (0.5)	235 (3.92)	623 (10.38)

[1] Exit 4 closed at 380 seconds due to loss of tenability

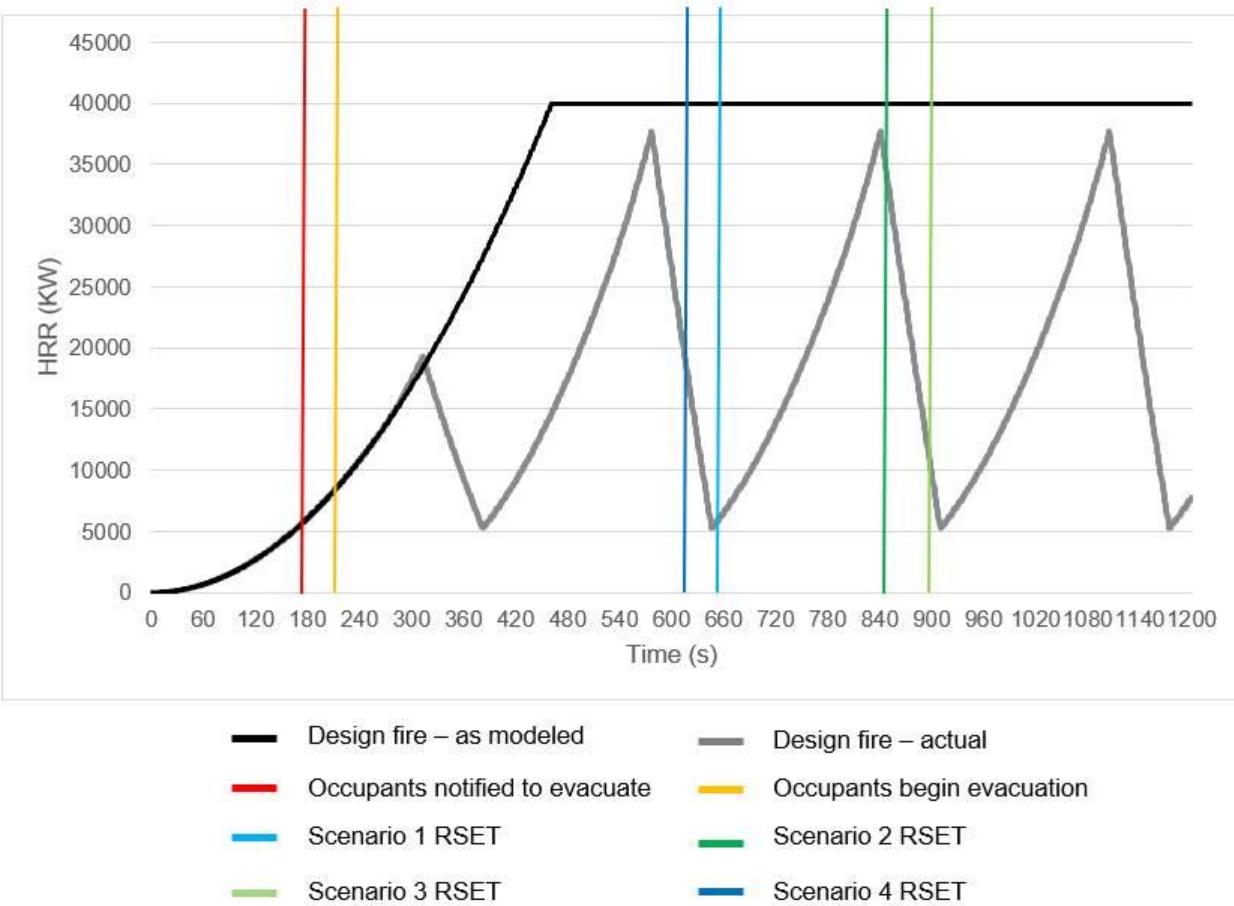

Figure 4-2. Timeline for egress scenarios

Runs were performed with the SFPE behavior model for comparison. Analysis of the results from these runs show that they were reasonably close to the results of the steering behavior mode analysis and less conservative, except for scenario 2 which yielded unreasonably conservative results. Since the SFPE behavior does not explicitly model behavior that detracts from movement, results from the SFPE behavior analysis were not used. The SFPE behavior includes preventing collision with other occupants and edges of the navigation meshes (e.g. walls, guard rails, or obstructions) while passing or waiting. The results are dependent on assigned maximum density in the stairs, and once the density is reached, the model does not allow occupants to enter stairs until the density is reduced. A maximum density of 0.33 person/SF was used for each scenario. Table 4-3 shows the results from the SFPE model compared to the Pathfinder steering model.

Table 4-3. Comparison Between Steering and SFPE Behavior Model Results

Scenario	Travel time (s)		Evacuation time (s)		RSET (s)	
	Steering behavior	SFPE behavior	Steering behavior	SFPE behavior	Steering behavior	SFPE behavior
1	256.4	228.2	511.4	483.2	654.6	612.3
2	422.6	575.2	677.6	830.2	903.9	1132.8
3	384.7	381.2	639.7	636.2	847.1	841.8
4	250	229.4	505	484.4	645	614.2

5.0 Fire Modeling

5.1. FDS MODEL DESCRIPTION

The effects from the tool fire scenario in the fab were analyzed using the Fire Dynamics Simulator (FDS) Version 6.7.4 computational fluid dynamics computer model developed by the National Institute of Standards and Technology (NIST) [McGrattan et al., 2020]. For each fire location, a row of tools was positioned to simulate fire spread from a center tool to the adjacent tools. Figure 5-1 shows a plan view of the center fire location where the tools involved in the fire are shown in red, the sprinkler grid is shown in blue, and the surrounding tools (not involved in the fire) are shown in light blue. The grid of sprinklers was positioned over the tools with spacing of 8.5 ft by 15 ft. Sprinklers were activated for the purpose of capturing the mixing effects that occur when the water droplets vaporize and suppression effects were not incorporated.

The model domain extended from the ceiling system to 3.3 ft beneath the RMF. It was assumed that the Filter Ceiling will remain intact for the duration of the fire. If localized failure of the Filter Ceiling were to occur, hot gases would fill the interstitial space and increase the amount of time needed for smoke to fill the Fab level. The RMF was modeled as a porous screen with 20% free area and the volume below the RMF was modeled as open space with the lower boundary open to atmospheric pressure.

Scoping runs were performed to determine if simplifications could be made to the model without affecting the results. For example, one scoping run consisted of a model in which the volume of the subfloor and the air intakes in the subfloor were included. The results of this model indicated that the area below the RMF could effectively be ignored without a significant impact on the smoke and temperature results in the fab volume.

Scoping runs were also performed to determine the optimal cell size for the model. Based on the results of this analysis, 0.66 ft cells were used in an approximately 275 ft by 283 ft region around the design fire and 1.31 ft cells were used in the rest of the domain. Materials and surfaces for solid boundaries were specified in the model according to Table 2-1. The exterior surfaces of the computational domain were specified as open boundaries (ambient conditions outside the domain).

Optical density detectors were positioned at the raised metal floor level (above and below) to simulate EWFD detection. Research conducted by Geiman and Gottuk has shown that optical densities of 0.14 OD/m corresponded well with the alarm state for standard smoke detectors [Geiman and Gottuk, 2003]. In reality, EWFD systems would likely provide earlier warning of a fire than standard smoke detectors; therefore, this is a conservative assumption.

The fuel properties were chosen to be representative of non-FM 4910 plastic and are summarized in Table 5-1.

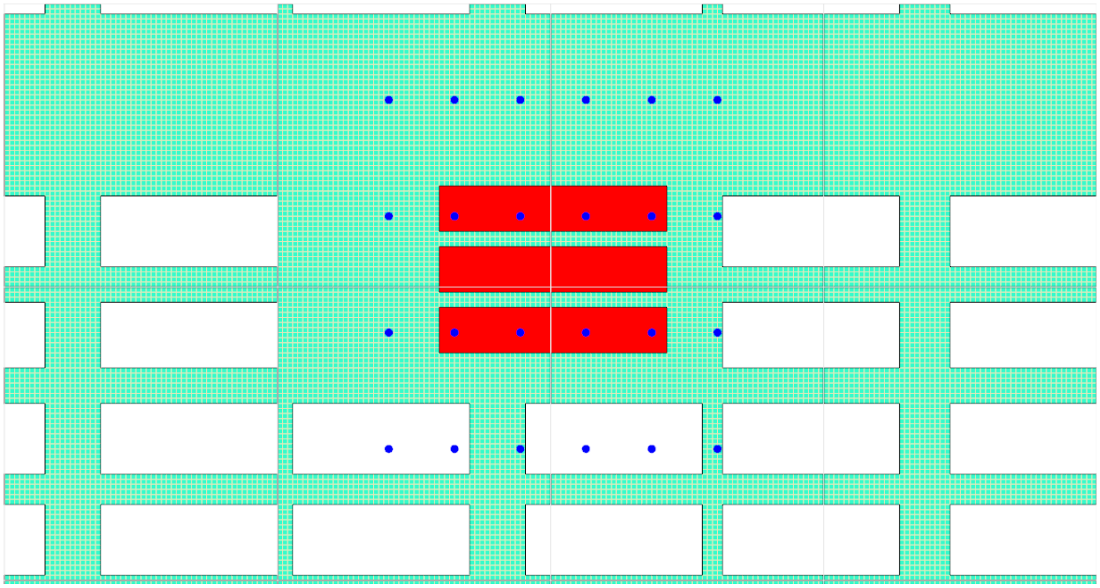

Figure 5-1. Tool and sprinkler layout of center fire location

Table 5-1. Fuel Properties Used in FDS Models

Parameter	*Value*
Chemical Composition	C = 1.0 H = 0.88 O = 0.13
Soot Yield	0.112
CO Yield	0.054
Heat Release per Unit Mass of Oxygen (MJ/kg)	13.1

5.2. BUILDING VENTILATION

The fab ventilation system was modeled as a generic fan filter unit (FFU) system where FFUs, located in the Filter Ceiling system, supply clean air to the fab. Air is either removed from the fab by exhaust fans (such as general, scrubbed, and solvent exhaust) or by being forced through the waffle slab into the Subfab. At the Subfab level, air is drawn into return air shafts and flows up to the interstitial area for the FFUs. Makeup air fans are used to replace the air removed by the exhaust systems and to ensure that the necessary pressure differential is maintained in the fab. Figure 5-2 shows this system conceptually.

For FDS modeling purposes, the aspects of the fab ventilation system that are important for studying smoke movement within the cleanroom space were evaluated. Quantifying smoke generated by the fire and capturing smoke that is stirred up and removed from the fab volume as a result of the building ventilation systems were identified as the critical aspects affecting the results. As a result, the control volume (model domain) was defined as the fab where the fire generates smoke, and a portion of the smoke generated is being removed by the ventilation systems. From this modeling perspective, smoke particulate was removed from the fab domain either by being forced down through the waffle slab or extracted by mechanical exhaust. By design, a portion of smoke particulate will be removed by exhaust and most will be drawn into the subfab and recirculated. The particulate that is recirculated will be filtered and removed by the ULPA filters in the FFUs such that it is appropriate to conclude it is also removed from the domain. Soot loading on the ULPA filters was not evaluated; rather, it was assumed that there would be no reduction in filter/fan performance during the timeframe of the evacuation.

In the FDS models, the ventilation provided by the FFUs was included, but not the ventilation from the makeup and exhaust air systems. If individual tool exhaust were modeled, detailed information on those systems would be needed. Initial scoping models were constructed to support the conclusion that much of this detail is at sub-grid scale, meaning it would be difficult to model appropriately in an FDS model of this size without introducing error. This approach provided the same air change rate in the fab but simplified the smoke removal aspect by assuming it was removed from the domain in the subfab rather than via a combination of exhaust and HEPA filtration. Since the intent of the study was not to evaluate subfab conditions, conditions in the subfab were not quantified in the models. (One model was constructed to address this concern; details are provided in Appendix C). As such, the conclusion was that this approach provides a representative, yet conservative, assessment of the smoke removal efficiency of the building ventilation systems. Removing smoke particulate higher in the space (e.g., at tool exhaust inlets) would be expected to provide more efficient smoke removal and better results. Ultimately, any results obtained with this configuration would likely be improved based on how exhaust is actually extracted from the facility.

Although the ventilation approach was simplified for this specific purpose, it highlighted what would be expected as a realistic outcome of a fire in a fab. That is, the smoke conditions will not be influenced in a significant way by the balance of exhaust and makeup air. Rather, the air change rate through the fab driven by the FFUs is a major driver for smoke movement. This is a positive aspect to the FFU design as the study findings are representative, and applicable, for the various stages of qualification and startup where makeup air and exhaust are being ramped up.

Fan filter units were spaced evenly in the model to provide a minimum of 25% coverage over the fab. Figure 5-3 provides a plan view of the FFU layout as modeled in FDS. While FFU coverage was simplified for modeling purposes and may not completely match the actual fab arrangement; the results of the analysis will not be impacted significantly by small changes in the specific FFU layout. An important assumption for this analysis is that the fab operational procedures specify that ventilation systems be shut down manually and no provision for automatic shutdown is provided. For this reason, the scenario where the ventilation is shut down was not evaluated.

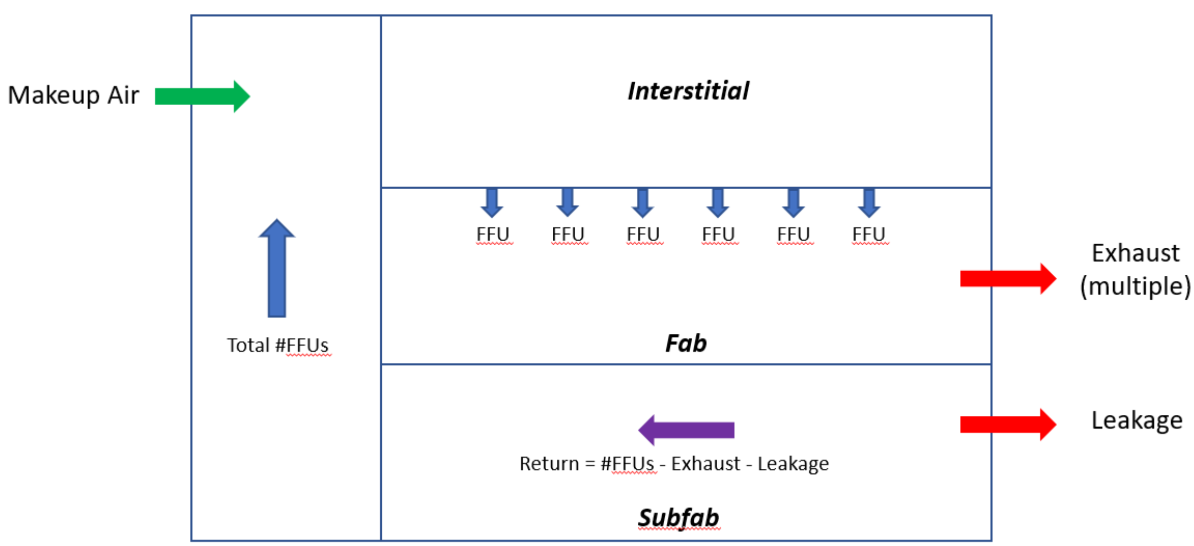

Figure 5-2. Schematic of FFU ventilation design

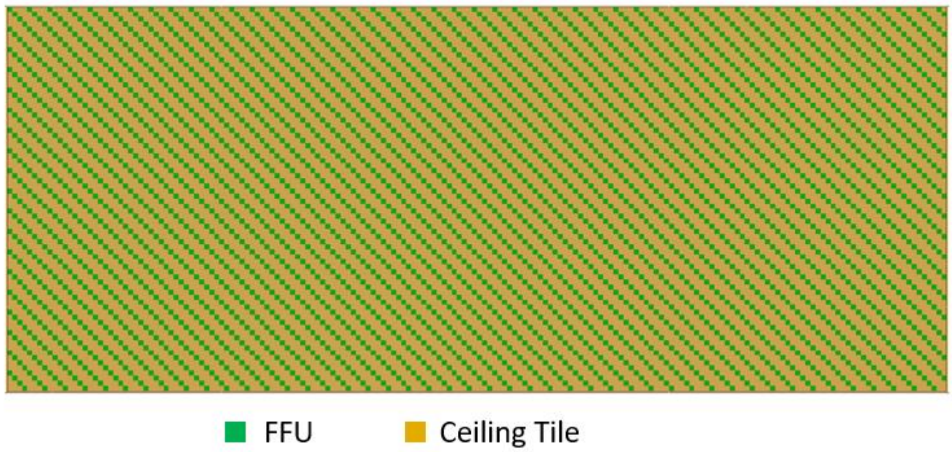

Figure 5-3. Diagram of FFU layout as modeled in FDS for 25% coverage

5.3. RESULTS

The results from the FDS fire modeling are overlaid with the Pathfinder results in the following figures. For each scenario, the visibility, temperature and CO concentration are shown as measured at a height of 6 ft above the RMF. In the visibility figures, the colors correspond to different visibility distances to an illuminated object. Black is used to highlight a visibility of 33 ft (10 m). Areas shown in the green / blue scale are indicative of visibilities greater than 33 ft (10 m) and in the yellow / orange / red, less than 33 ft (10 m) visibility. Results for temperature and CO concentration are shown with a similar color gradient with the exception that red corresponds to areas where the tenability criterion is exceeded.

In all cases, the visibility distances are the limiting performance criterion. In other words, visibility levels are diminished to the tenability threshold more quickly than temperature and CO concentrations. Appendix D includes additional visibility images for each scenario. These images show visibility in the fab as modeled in FDS overlaid with the Pathfinder results at time steps of 1, 3, 5, 7, 9, 11, 13, and 15 min.

5.3.1. Center Fire Location

The visibility conditions at the RSET of 655 seconds are shown in Figure 5-4 for the center fire location. This figure shows that the visibility in approximately 50% of the fab is greater than 30 m. Four of the six exits have visibilities that exceed 30 m. Figures 5-5 and 5-6 show the thermal conditions and CO concentrations at 655 sec. The temperature threshold of 76 °C is exceeded in a small area surrounding the fire location; however, this area does not affect the tenability at any of the exits. With the exception of a small region near the fire, there are no measurable changes in the CO concentrations.

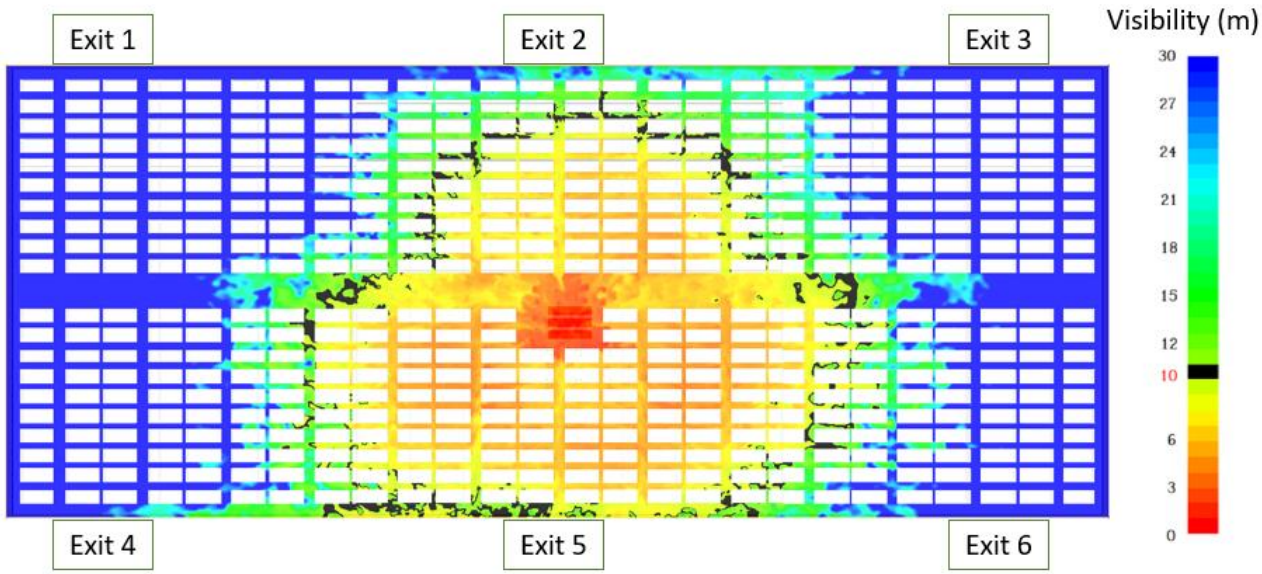

Figure 5-4. Visibility conditions 6 ft above the floor at RSET (655 sec (10.9 min)) for center fire location

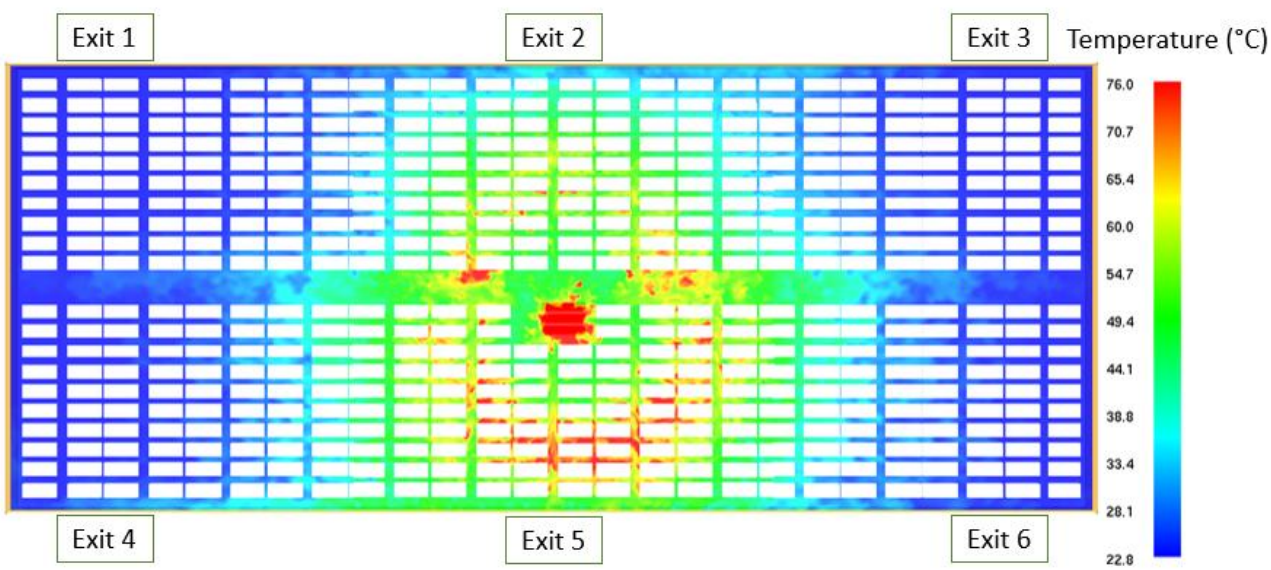

Figure 5-5. Thermal conditions 6 ft above the floor at RSET (655 sec (10.9 min)) for center fire location

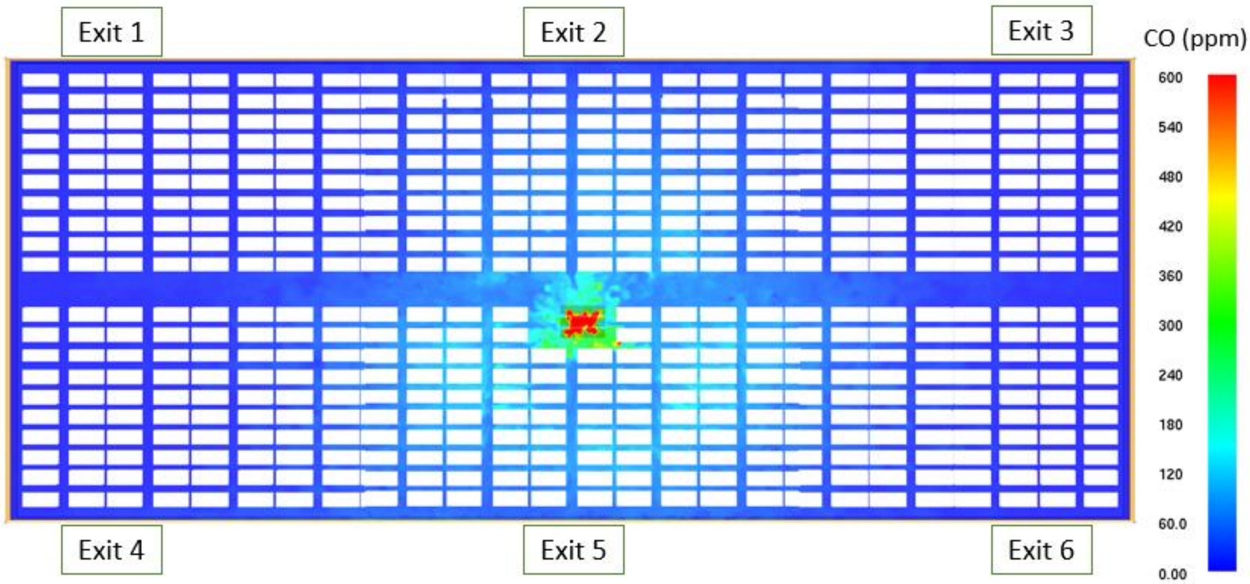

Figure 5-6. CO concentrations 6 ft above the floor at RSET (655 sec (10.9 min)) for center fire location

5.3.2. Southwest Corner Fire Location

Figure 5-7 shows the visibility conditions for the southwest corner fire location at the RSET of 847 seconds. The visibility in approximately 70% of the fab is greater than 30 m. Four of the six exits have visibilities that exceed 30 m. As expected, there is zero visibility at Exit 4, the blocked exit. The visibility at Exit 1 is less than 30 m, but still well above the performance criterion of 10 m.

Figure 5-8 demonstrates that the thermal conditions in the fab are well below the tenability criterion of 76 ºC in most of the fab. The thermal performance criterion is exceeded near the fire, extending to the fab centerline. Similarly, Figure 5-9 shows that the CO concentrations are below the tenability criterion of 600 ppm throughout the fab with the exception of a small region above the fire.

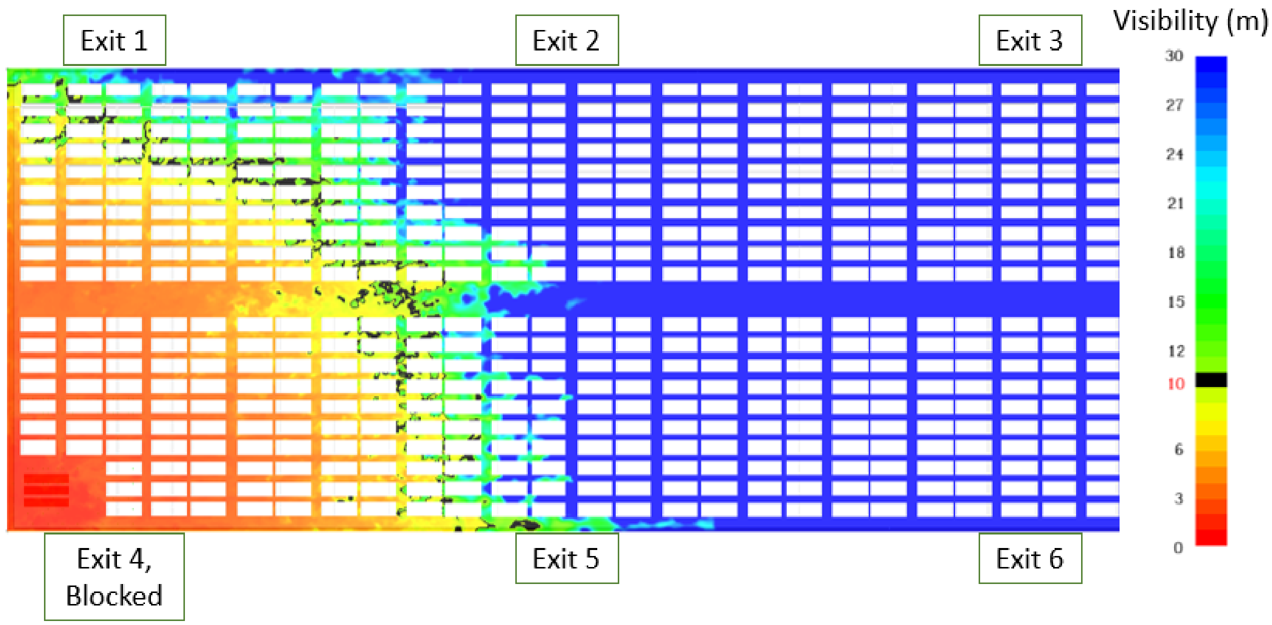

Figure 5-7. Visibility conditions 6 ft above the floor at RSET (847 sec (14.1 min)) for southwest corner fire location

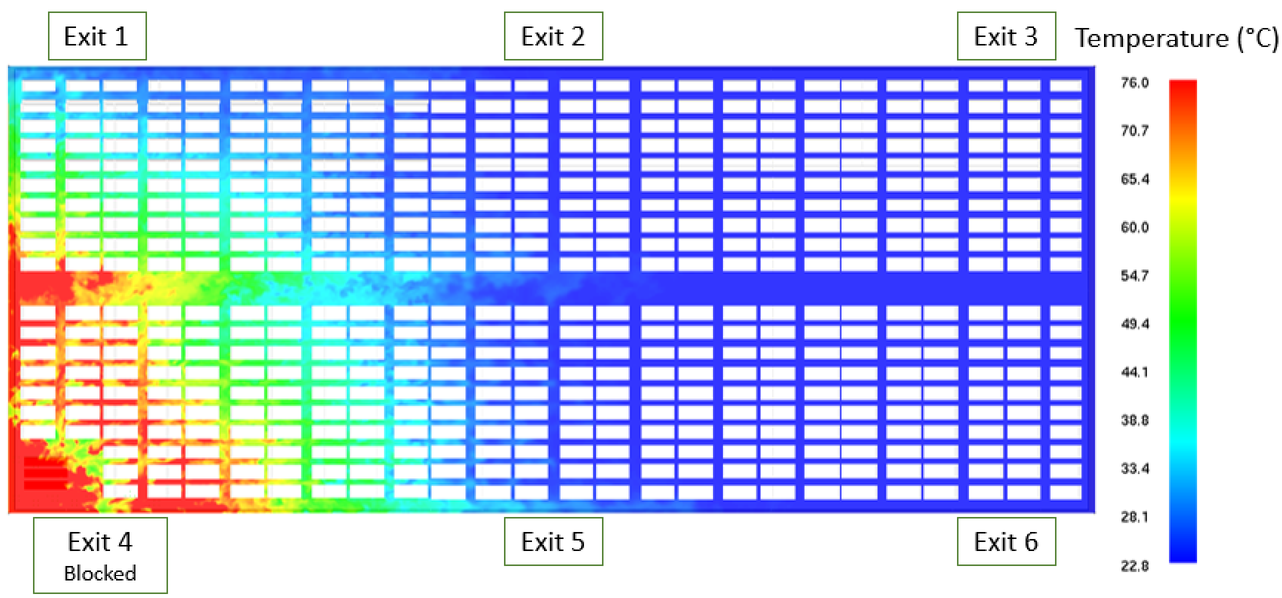

Figure 5-8. Thermal conditions 6 ft above the floor at RSET (847 sec (14.1 min)) for southwest corner fire location

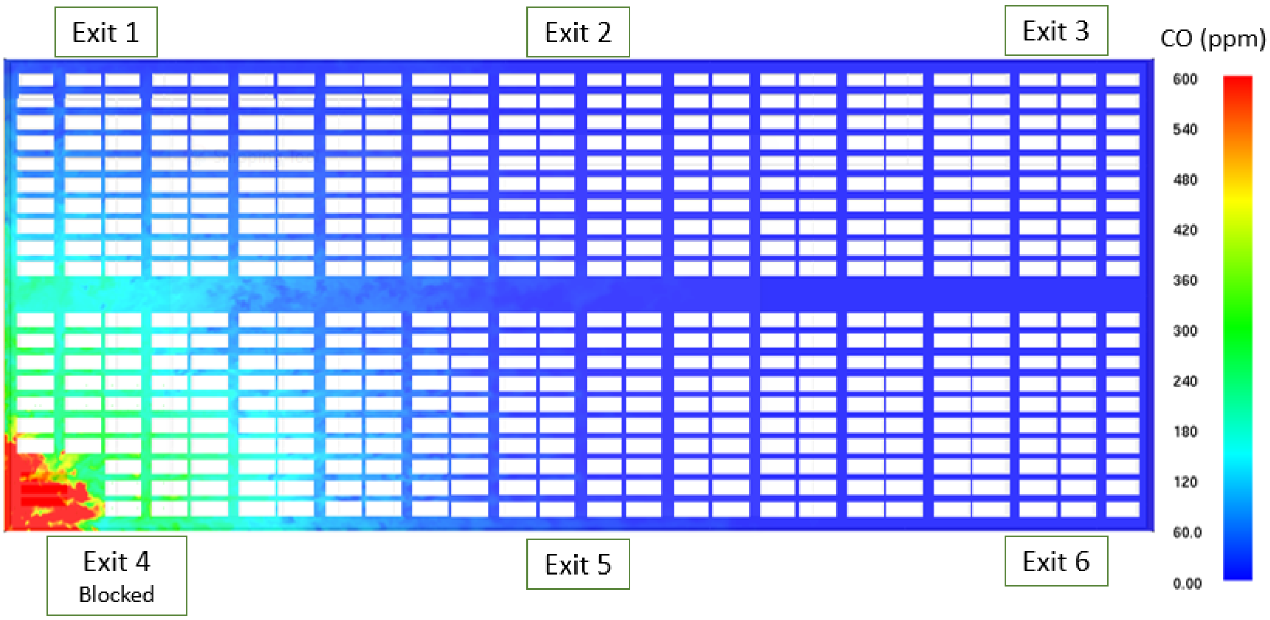

Figure 5-9. CO concentration 6 ft above the floor at RSET (847 sec (14.1 min)) for southwest corner fire location

5.3.3. West Fire Location

The visibility conditions at the RSET of 904 seconds are shown in Figure 5-10 for the west wall fire location. These results are similar to those obtained for the southwest corner location where the visibility in the western portion of the fab is less than 10 m, including at two of the exits (Exit 1 and Exit 4). However, the visibility at the remaining four exits is greater than 30 m.

Figures 5-11 and 5-12 show the thermal conditions and CO concentrations, respectively. The temperature threshold of 76 °C is exceeded in a small area surrounding the fire location, affecting the tenability at Exit 4. With the exception of a small region near the fire, there are no measurable changes in the CO concentrations.

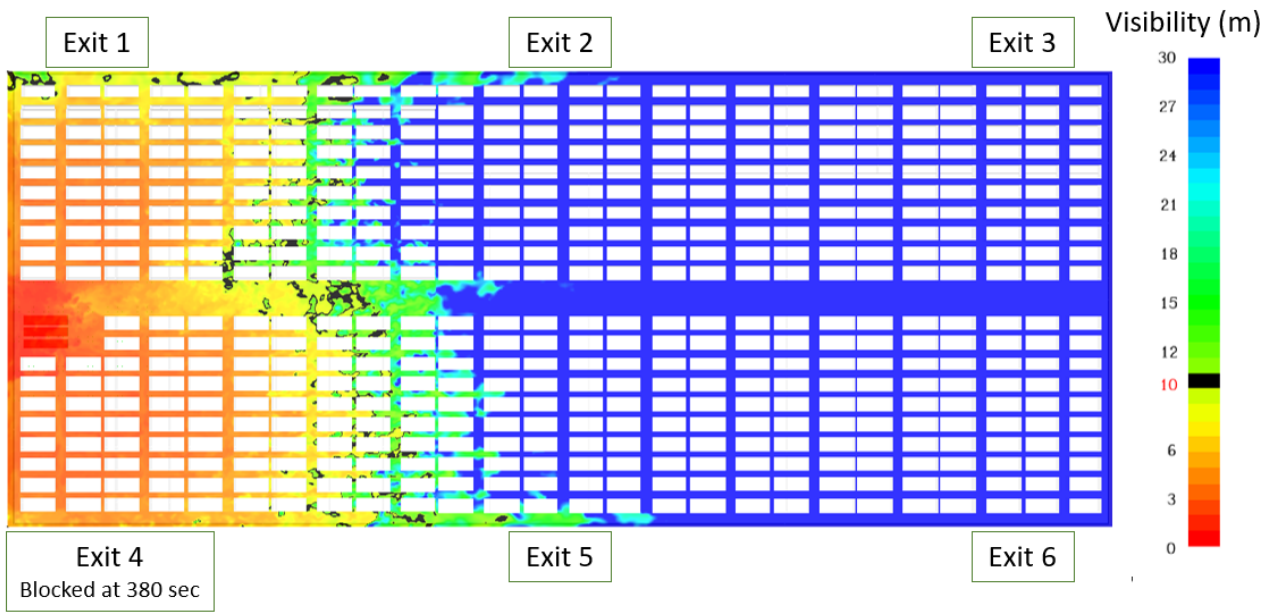

Figure 5-11. Visibility conditions 6 ft above the floor at RSET (904 sec (15.07 min)) for west wall fire location

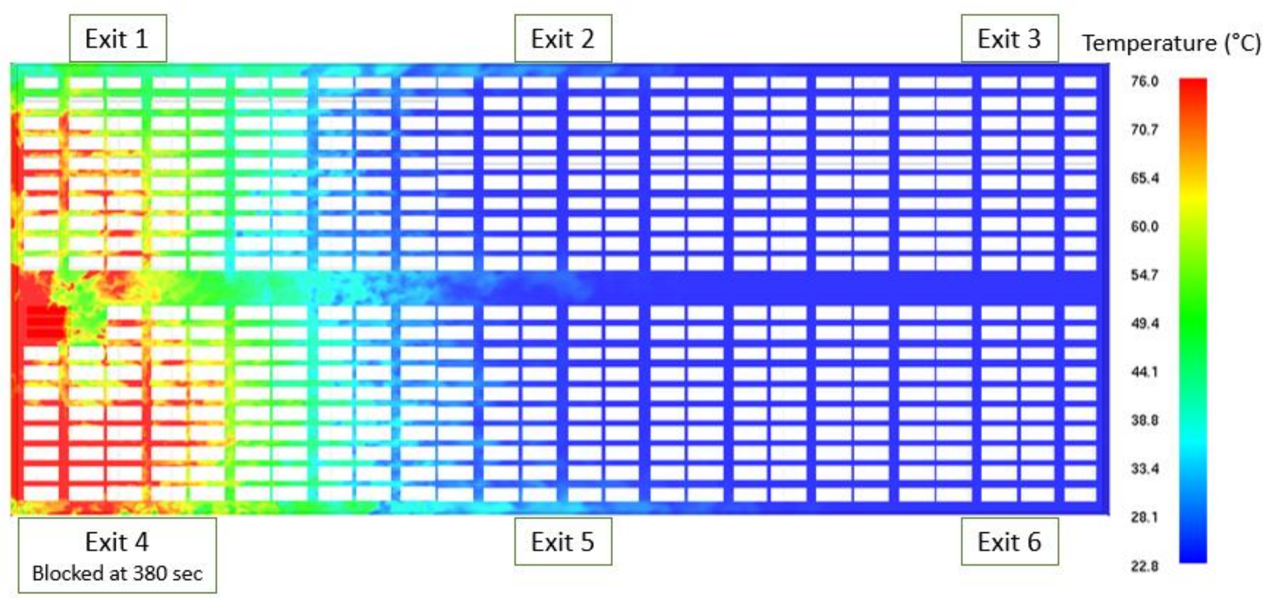

Figure 5-12. Thermal conditions 6 ft above the floor at RSET (904 sec (15.07 min)) for west wall fire location

Figure 5-13. CO concentrations 6 ft above the floor at RSET (904 sec (15.07 min)) for west wall fire location

6.0 Discussion

6.1. MARGIN OF SAFETY

Comparison of the three tenability parameters showed that visibility is the limiting parameter in the situations modeled. That is, reductions in visibility were noted prior to increased thermal and toxic gas conditions. This result is consistent with observations from other modeling and experimental studies. For this reason, the remainder of the discussion will focus on the tenability results specific to visibility.

Examination of the FDS results show that the high ventilation rates (e.g. 19 cfm/SF as compared to the IBC requirement of 1 cfm/SF) are effective at reducing the spread of smoke in the fab. Smoke, and other products of combustion, are diluted within the fab and a portion of the smoke is pushed into the subfab in the area of the fire, resulting in a weaker ceiling jet formation. (Ceiling jet is the term given to "the relatively rapid gas flow in a shallow layer beneath the ceiling which is driven by the buoyancy of the hot combustion products" [Evans, 1995].) Viewing the visibility slices in elevation shows advancement of a vertical "wall of smoke" moving radially from the fire location as shown in Figure 6-1 (taken at 500 sec). A pattern was established where smoke fills the fab from the fire outward resulting in a perimeter area that is largely clear of smoke. Examination of the FDS results for longer fire durations show that the radial smoke spread from the fire source is slow and eventually will reach a steady-state condition when the soot production rate reaches a balance with the ventilation rate.

In contrast, the typical behavior observed for a building fire is for the formation of a two-layer environment where the upper layer consists of hot (buoyant gases) containing the products of combustion and the lower layer consists of the cool, clean air that is entrained into the fire. If the ventilation rates were lower in the fab, the behavior for a traditional 2-layer environment would be for a uniform smoke layer to form at the ceiling level and spread more quickly in the radial direction until reaching the exterior walls, then bank down at these walls due to cooling effects. This situation creates an environment where smoke collects around the edges of the facility, which is where the exits are located in the generic fab.

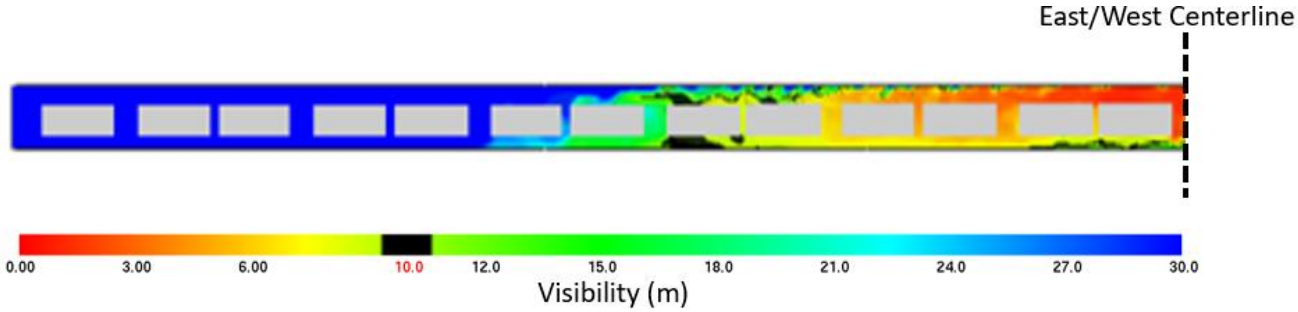

Figure 6-1. Section view of visibility at 500 sec (8.33 min) for central fire location (section taken through fire center looking north, west half of fab only)

Traditionally, egress studies will identify values for the available safe egress times (ASET) to determine a factor of safety. ASET values are selected based on the development of untenable conditions, generally due to poor visibility. With a conventional two-layer environment, this delineation is straightforward since the visibility is reasonably uniform at a given height in the space. Based on the dynamics resulting from the generic fab ventilation scheme, unsafe conditions due to loss of tenability do not occur. Reduced visibility at several locations may exist while the remainder of the fab is completely clear; therefore, safe exit options remain for personnel. For this reason, ASET values were not assessed per se.

Review of the FDS results with respect to time showed that the visibility conditions will reach a steady-state value once the soot generation rate and ventilation rates equalize, generally by 500 seconds. RSET visibility figures represent these steady-state visibility conditions where the areas of reduced visibility in the fab will not increase regardless of the fire duration. These results demonstrate that there is a large, and arguably indefinite, margin of safety associated with egress in the generic fab design.

6.2. SENSITIVITY ANALYSIS

Since assumptions were made to generalize this analysis, a sensitivity study was performed to determine if the results for the baseline models discussed in Section 5.3 would change if particular design parameters were adjusted. The parameters that were examined are summarized in Table 6-2.

Table 6-2. Parameters Evaluated for Sensitivity Study

Parameter	*Values Examined*	*Result*
Fire Location	Center, SW Corner, West Wall (varied as part of baseline evaluation)	Percentage of fab with reduced visibility is smaller for SW Corner and West Wall locations
FFU coverage	25% (baseline), 33%, 50%	Visibility conditions improve with increasing FFU coverage
Air Change Rate	19 cfm/SF (baseline), 23.5 cfm/SF	Visibility conditions improve with increased air change rate
FFU Dimensions	4 x 4 ft (baseline), 2 x 4 ft	No notable change in visibility conditions
Tool Height	10 ft (baseline), 8 ft	No notable change in visibility conditions
Tool Size	23x9x10 ft (baseline), 16x10x8 ft, 23x9x8 ft	No notable change in visibility conditions
Sprinklers (mixing effects)	Sprinklers (baseline), no sprinklers	No notable change in visibility conditions
Tools	Tools (baseline), no tools	Larger area of reduced visibility when tools are removed

6.2.1.1. Effect of FFU coverage

The percentage of FFUs in the Filter Ceiling was varied between 25, 33 and 50% for a fire located in the center of the fab. In each case, the cfm rating for the FFUs was adjusted to maintain 19 cfm/SF in the fab. The results of these models are shown in Figure 6-2 where an identical oval is shown on each image for easier comparison of the region where the visibility is less than 10 m. A similar area of smoke spread results for coverages of 25% and 33%, with a slightly smaller area noted for a coverage of 33%. Results for the 50% coverage show a dramatic reduction in smoke spread where the visibility criterion is exceeded in less than 20% of the fab. Based on examination of the smoke flow patterns higher in the fab, this trend can be attributed to the FFU layout rather than the change in FFU face velocity. As a result, it can be concluded that FFU percentages that are higher than 25% will result in more favorable visibility conditions in the fab.

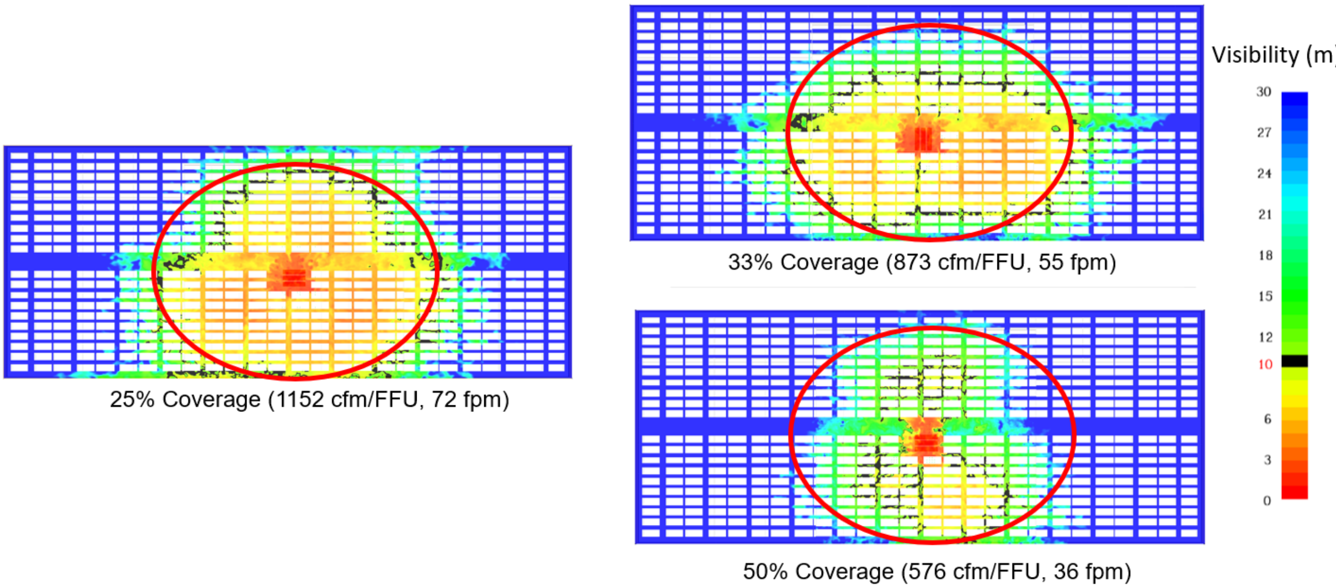

Figure 6-2. Comparison of visibility conditions at 655 sec for center fire location for varying FFU coverages (6 ft above the floor)

6.2.1.2. Effect of Air Change Rate

The effect of the air change rate (i.e., cfm/SF) was evaluated for the baseline case of 19 cfm/SF and a higher rating of 23.5 cfm/SF. For these models, the cfm rating for the FFUs was changed to maintain the 25% FFU coverage over the fab. A comparison of these two configurations is provided in Figure 6-3 for the center fire location. The results show that the area with reduced visibility is slightly smaller when the air change rate is increased.

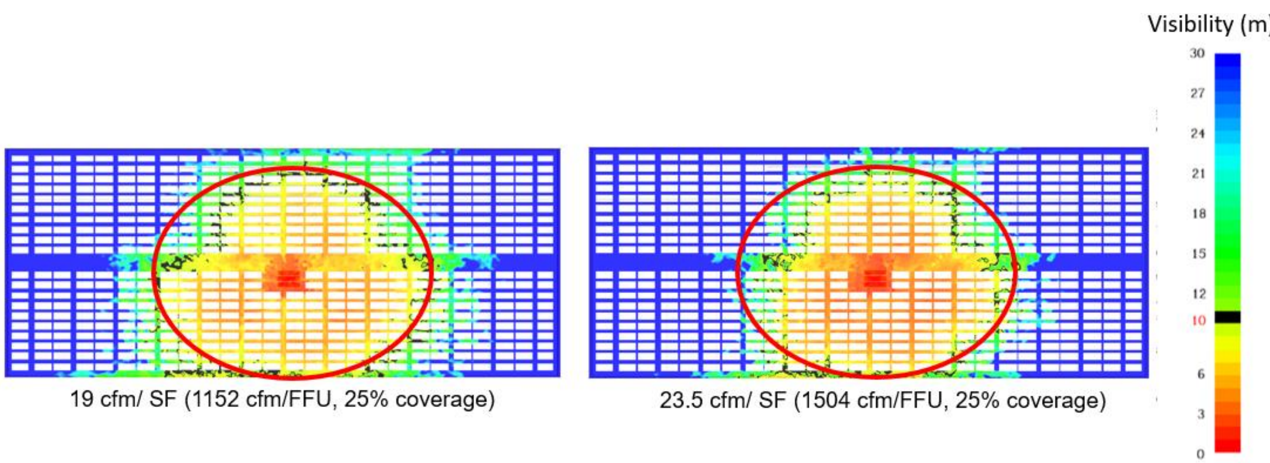

Figure 6-3. Comparison of visibility conditions at 655 sec for center fire location for varying air change rates (6 ft above the floor)

6.2.1.3. Effect of FFU Dimensions

Baseline FFU dimensions of 4 x 4 ft were used in the majority of the FDS models. Since the FFU dimensions will affect the FFU layout in the Filter Ceiling, the impact of FFUs measuring 2 x 4 ft was examined. A comparison of the results for the center fire location with these two FFU sizes are shown in Figure 6-4. These figures demonstrate that the FFU dimensions and different FFU Filter Ceiling pattern does not have a significant impact on the results of this study since the extent of smoke spread is very similar.

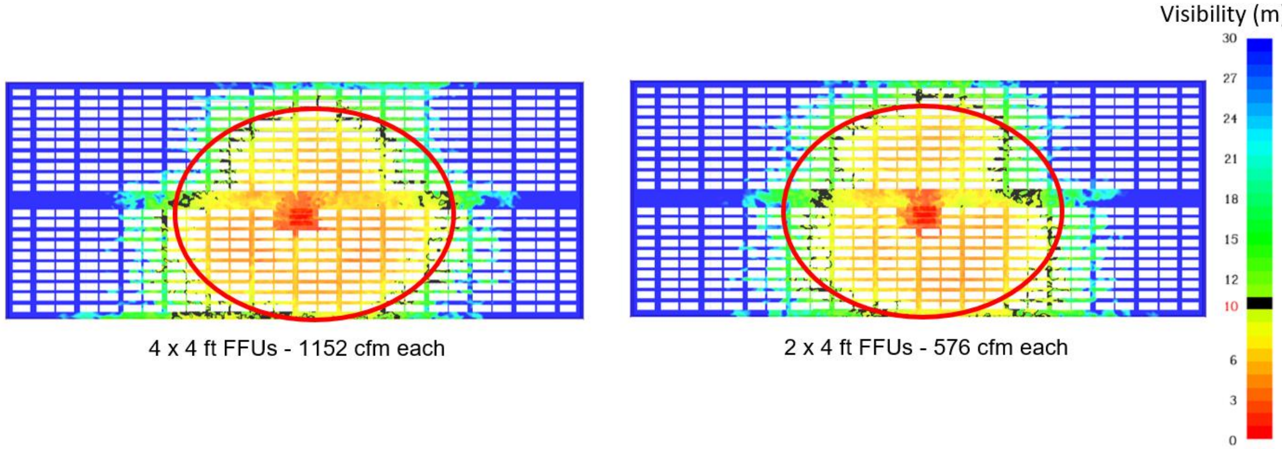

Figure 6-4. Comparison of visibility conditions at 655 sec for center fire location for varying FFU dimensions (6 ft above the floor)

6.2.1.4. Effect of Tool Size

The size of the tools was varied to determine if either the tool footprint or the tool height would have an effect on the smoke spread in the fab. Tool footprints of 23 x 9 ft and 16 x 10 ft and tool heights of 8 ft and 10 ft were examined. Results from these models are provided in Figure 6-5, which were run for the center fire scenario. The smoke spread in each model is nearly identical supporting that the footprint and height of the tool does not have a significant impact on the results of this study.

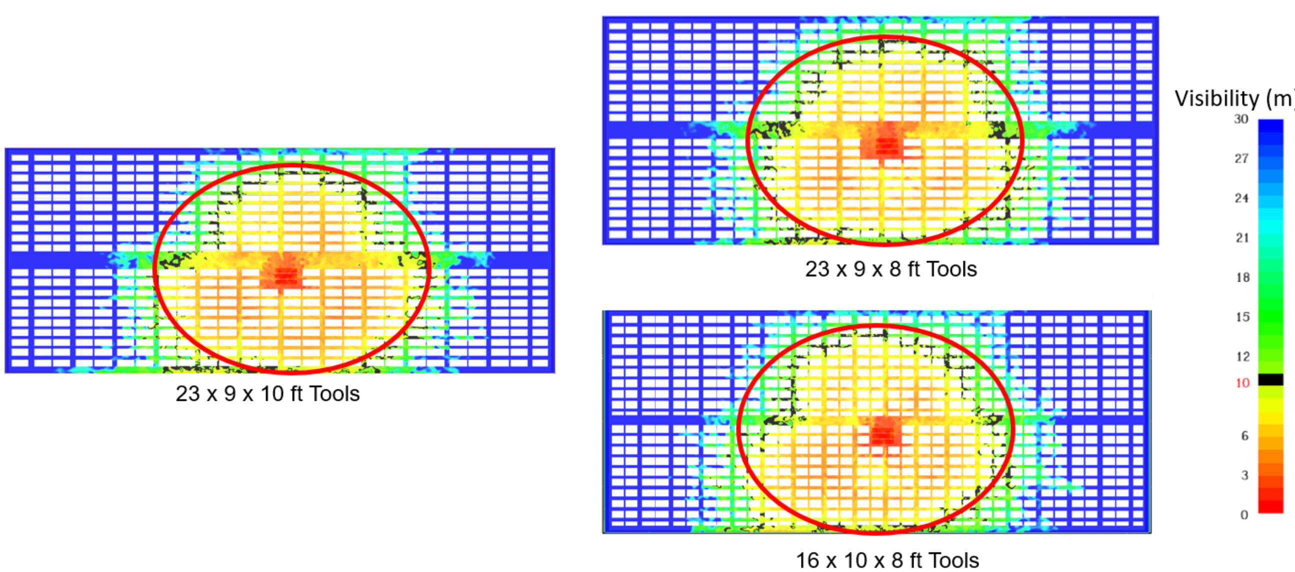

Figure 6-5. Comparison of visibility conditions at 655 sec for center fire location for varying tool sizes (6 ft above the floor)

6.2.1.5. Effect of Sprinklers

While suppression effects were not credited in the models, mixing effects resulting from the vaporization of the water from the sprinklers in the region of the fire were included in the baseline models. For comparison, several models were executed without sprinkler activation to compare the impact of these mixing effects. Figure 6-6 shows a comparison of a center fire scenario with and without the water added from the sprinklers. When sprinklers are omitted, the area with visibility less than 10 m is slightly larger than when sprinklers are included. However, these differences are not significant, and it can be concluded that the effect of mixing introduced by the sprinklers is negligible.

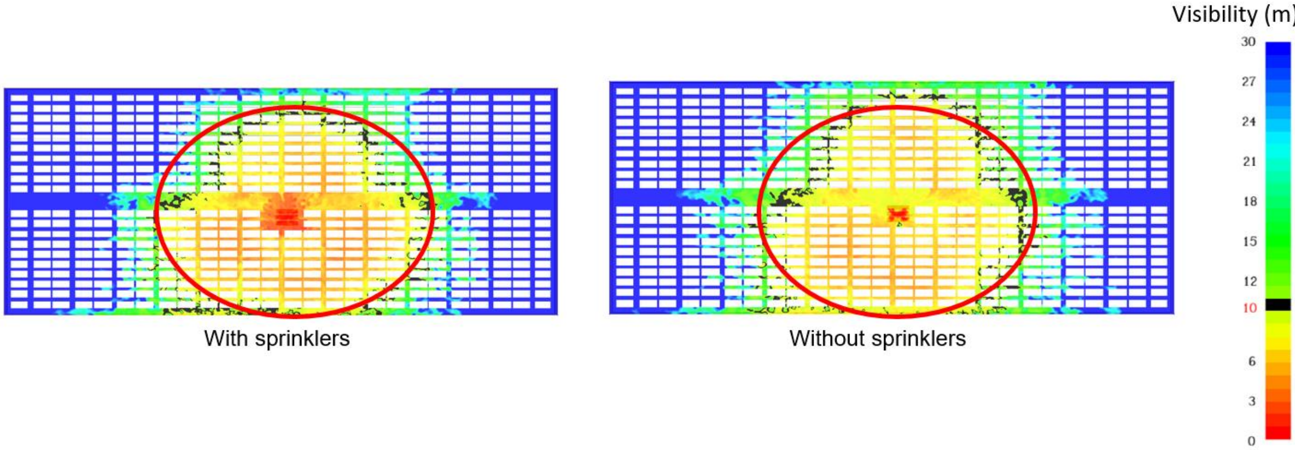

Figure 6-6. Comparison of visibility conditions at 655 sec for center fire location with and without sprinklers (6 ft above the floor)

6.2.1.6. Effect of Tool Presence

Since there may be situations where semiconductor fabrication facilities may not be completely fit out with tools, the FDS model was executed with and without tools. These models represent the two possible extremes and provide insight on assumptions related to tool dimensions. A comparison of the visibility conditions for the center fire scenario with and without tools is provided in Figure 6-7. Two ovals are imposed on each image to provide bounds for the region where the visibility exceeds 10 m and the region where the visibility is less than 30 m. The pattern of smoke spread around the fire differs between the two scenarios; however, the region where the visibility is less than 10 m is very similar. More notably, the area with between 10 and 30 m visibility is larger when the tools are removed, suggesting that the tools channel a portion of the smoke, containing it in a smaller area. In either case, the majority of the exits remain tenable in either situation further supporting that the results are not dependent on the presence or size of the tools.

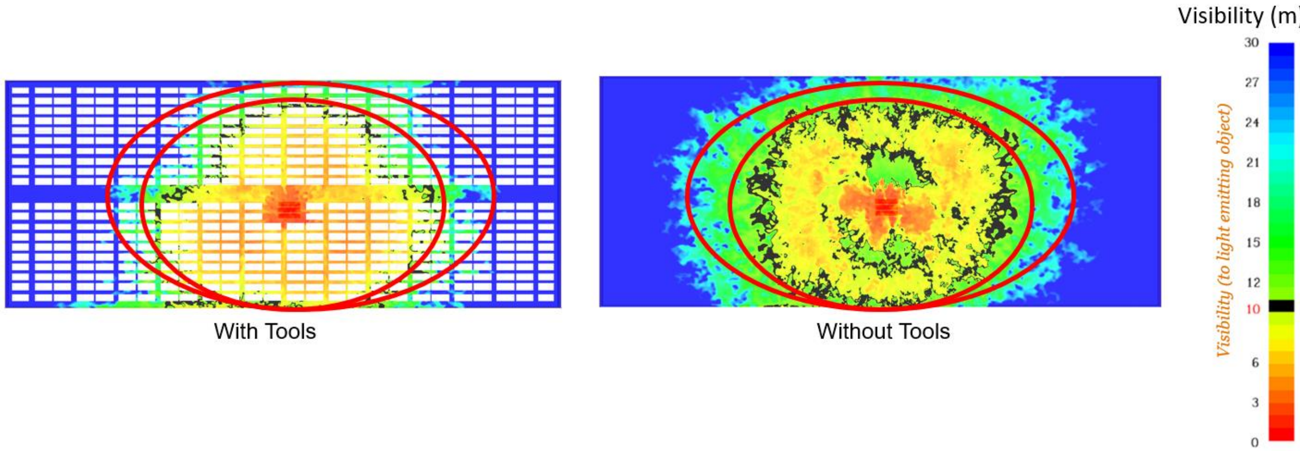

Figure 6-7. Comparison of visibility conditions at 655 sec for center fire location with and without tools (6 ft above the floor)

6.3. CONSERVATIVE MODELING ASPECTS

Multiple conservatisms have been incorporated into this study. Modeling results showed that this fab design will result in safe egress conditions even with these conservatisms. More notable conservative aspects include:

1. **Occupant Loading:** In order to bound RSET values, maximum occupant loading of 1,100 occupants per level based on building code allowances were utilized. This value is likely larger than would be expected, especially on the Utility and Subfab levels. Lower occupant loads would have a direct impact on RSET values since queue times of up to 3 minutes were noted.

2. **Egress Travel Path:** The Pathfinder model was simplified to allow limited travel in the chases and no travel between tools. In reality, occupants will use the space between tools to reduce the travel distance if they perceive any information indicating that evacuation should occur quickly. Since the occupants will be extremely familiar with the facility and well-trained for evacuation procedures resulting from regular evacuation drills, it is expected that the egress paths will be more direct than those noted in the Pathfinder model. More direct egress paths will result in shorter egress travel times.

7.0 Conclusions

Modeling was performed to compare the required safe egress time with predicted tenability conditions for a generic semiconductor fabrication facility to determine if safe conditions will exist in the event of a fire. Important findings and conclusions from this study include:

1. **Performance Criteria:** Performance criteria were defined for tenability parameters consisting of visibility, temperature and toxic gas (e.g. carbon monoxide) concentrations. The visibility threshold was defined as a distance of 33 ft (10 m) to an illuminated object. Visibility conditions were limiting as compared to temperature and CO concentrations.
2. **Design Fire Scenario:** A worst-case design fire scenario based on a flammable liquid spill that ignites and spreads to a process tool was developed. This fire scenario incorporated the fuel loading for process tools and the spread characteristics that would be expected based on a tool layout that is representative of factories. Three fire locations (center, southwest corner and west wall) were evaluated to examine the effect of physical location on the smoke layer development. These fire locations affected the number of exits available for use during the evacuation simulation; therefore, the sensitivity of the results to the number of exits available for use was evaluated.

3. **Ventilation Scheme:** It was determined that the ventilation rate has a large impact on the smoke movement in the fab. Viewing the visibility slices in elevation showed advancement of a vertical "wall of smoke" moving radially from the fire location. A pattern was established where smoke fills the fab from the fire moving outward resulting in a perimeter area that is largely clear of smoke during the evacuation time.
4. **Egress Model Results:** Required safe egress times were calculated using the Pathfinder people movement model and included a factor of safety consistent with NFPA standards and IBC. Values ranged between 10.9 and 15 minutes depending on the fire location. Modeling included the loss of an exit which may occur when the fire is located near an exit.
5. **Fire Model Results**: Comparison of the RSET values with the tenability results calculated by FDS showed that all occupants will exit the facility before untenable conditions occur. The visibility while occupants are traveling to an exit will be above 33 ft (10 m). Visibility levels may be reduced below 33 ft while occupants are in the exit queue; however, visibility will remain above 10 ft (3.3 m) and the ability to see exit signage will be maintained.
6. **Margin of Safety:** Review of the FDS results with respect to time showed that the radial spread of smoke will eventually reach a steady-state condition once when the soot production rate reaches a balance with the ventilation rate. The results demonstrate that there is a large, and potentially indefinite, margin of safety associated with egress in the generic fab design.
7. **Tenability Conditions in the Subfab:** A model was constructed to determine if the amount of smoke entering the Subfab through the waffle slab would be sufficient to cause untenable conditions for occupants exiting from the Subfab level (details in Appendix C). Results showed that the visibility distances will be sufficient for safe egress from the Subfab level and that the conditions on the Fab level are limiting.
8. **Minimum design parameters –** The study established minimum design values for the fab width, footprint, ventilation rate and distances between the RMF and Filter Ceiling. For situations where these minimum values are exceeded, comparable or possibly smaller areas of smoke spread would be expected than shown in this report.
9. **Ventilation Control Sequence:** Semiconductor fabrication facilities should maintain the practice of allowing all fans serving the fab to remain operational in the event of a fire in the fab. These fans should only be shut down by manual initiation of ERT members or firefighters after it has been verified that all occupants have safely exited the building. These requirements should be part of the Standard Operating Procedures (SOP). **Shutting down ventilation will lead to the loss of visibility in the fab.**

Summary

Based on the results from this study, Jensen Hughes finds that the egress distance associated with the proposed generic fab design will meet the intent of the IBC provided that the following design specifications are met:

+ Minimum fab width of 300 ft;
+ Minimum fab area of 220,000 SF;
+ Flow-through fab (ballroom design);
+ Minimum distance between raised metal floor (RMF) and the Filter Ceiling of 16 ft;
+ Minimum (supply) ventilation rate of 20 cfm/SF (with a minimum 25% fan filter unit (FFU) coverage over the fab); and
+ Ventilation must remain running at full capacity during egress.

Therefore, the fab geometry and increased travel distance of 300 ft is acceptable and will not impact the safety of occupants in the event that emergency evacuation during a fire is necessary.

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Appendix A. *Design Fire Calculations*

This appendix provides an explanation of the calculations that were used to develop the tool design fire scenario.

A.1. SINGLE TOOL FIRE

A.1.1 Growth Phase

The growth phase of the fire is described using a t-squared fire growth model. The heat release rate (HRR) of the t-squared design fire is calculated based on the equation below [NFPA, 2018]:

$$Q = 1055(\frac{t}{t_g})^2$$

where:
Q = heat release rate of design fire (kW/sec)
t = time after effective ignition (sec)
t_g = growth time (sec)
for ultra-fast growing fire, t_g = 75 seconds.

A.1.2 Peak HRR and Decay Phase

For a single tool fire, the decay phase of the fire begins when approximately 70–80% of the design fire load has been consumed. In the decay phase it can be assumed that the heat release rate exhibits a linear decrease with time [Hadjisophocleous & Mehaffey, 2016]. The design fire is assumed to grow until the decay phase starts after 75% of total design fire load is consumed. This corresponds to an energy release of 1,908 MJ. With an ultra-fast growth rate for a t-squared fire, the total energy release of 1,908 MJ is attained at 313 seconds, with a peak HRR of 18.4 MW. The energy release during the decay phase consists of 25% of the total energy release content. This energy content during the decay phase is calculated to be 636 MJ.

Assuming a linear decrease of HRR with time, the duration of the decay phase is calculated based on the area of a triangle. The energy released during the decay phase is considered the area of the triangle, with duration as the base and peak HRR as the height.

$$Duration = \frac{2 * Energy\ Relase}{Peak\ HRR}$$

Based on this equation, the decay phase for a single tool fire contributes an additional 87 seconds of burning, with a total fire duration of 480 seconds.

The HRR during decay is calculated based on the straight-line equation, where slope is calculated by dividing Peak HRR (change in Y-axis) by decay phase duration (change in X-axis). Peak HRR is the Y-intercept and the negative sign for the slope represents the decrease in HRR.

$$HRR\ at\ t\ seconds = -\left(\frac{Peak\ HRR}{Decay\ phase\ duration}\right)t + Peak\ HRR$$

An unsteady design fire with a growth phase and a decay phase, as depicted in Figure A-1 is considered for a single tool. The decay phase is justified based on fuel configuration.

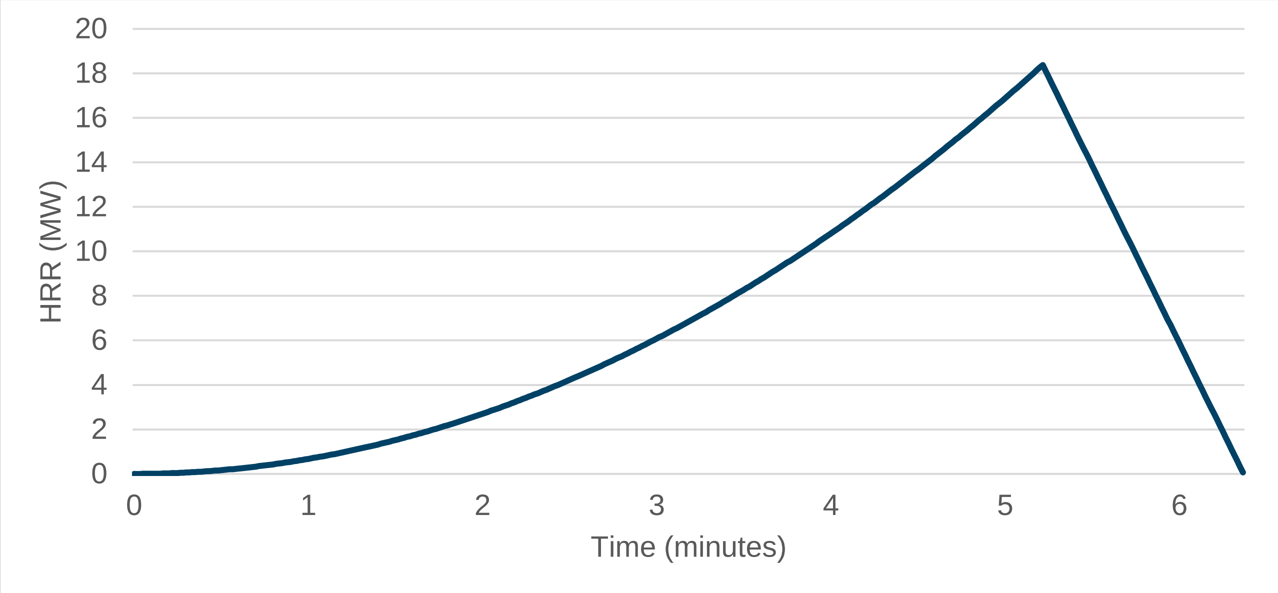

Figure A-1. Design fire of single tool

A.2. FIRE SPREAD TO OTHER TOOLS

A.2.1 Calculating Flame Height

Delichatsios (as reported by Budnick, Evans, and Nelson) developed a simple correlation of flame height for elongated fire based on experimental data [U.S. Nuclear Regulatory Commission, 2004]. In the following correlation, the flame height is based on the rate of heat release rate (HRR) per unit length of the fire:

$$H_f = 0.034\dot{Q}_l^{\,2/3}$$

Where:
H_f = flame height (m)
0.034 = entrainment coefficient
$\dot{Q}_l$= HRR per unit length of the fire (kW/m)

The above correlation is used to determine the length of the flame against the tool wall and to estimate radiative heat transfer to the adjacent tool.

A.2.2 Calculating heat flux

For targets very near the fire, methods that account for configuration (shape) factors are required. View factor for parallel, rectangular radiator is calculated based on following equation [SFPE, 2019].

$$F = \frac{2}{\pi}[\frac{X}{\sqrt{1+X^2}}\tan^{-1}\frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\frac{X}{\sqrt{1+Y^2}}]$$

where

$$X = \frac{a}{2c} = \frac{Length\ of\ tool}{2*separation\ distance}$$

$$Y = \frac{b}{2c} = \frac{flame\ height}{2*separation\ distance}$$

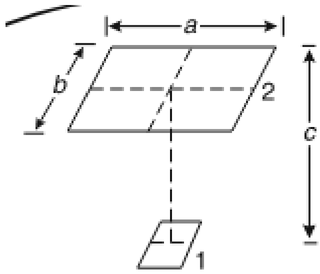

Figure A-2. View factor for parallel rectangular radiator

If the emissive power from a surface is known, then it is possible to calculate the intensity of radiation falling at a point at a known distance from the surface by incorporating the view factor, F.

$$\dot{q}" = FE$$

where,
$\dot{q}"$ = heat flux
F = view factor
E = emissive power

Shokri and Beyler correlated experimental data of flame radiation to external targets in terms of an average emissive power of the flame [U.S. Nuclear Regulatory Commission, 2004]. Effective power of the fire in terms of effective diameter is given by:

$$E = 58(10^{-0.00823D})$$

Where:
E = emissive power (kW/m^2)
D = diameter of tool fire (m)

For a non-circular fire, the effective diameter is defined as the diameter of a circular fire with an area equal to the actual pool area given by the following equation.

$$D = \sqrt{\frac{4A_f}{\pi}}$$

Where:
A_f = surface area of the tool fire (m^2)
D = diameter of tool fire (m)

A.2.3 Calculating ignition time

The ignition principle suggests that, for thermally thick materials, the inverse of the square root of ignition time is expected to be a linear function of the external heat flux away from the critical heat flux (CHF) value [U.S. Nuclear Regulatory Commission, 2004]. Based on that premise, the following equation is used to calculate the ignition time for the adjacent tool.

$$t_{ig} = \frac{\pi}{4}\left(\frac{\mathrm{TRP}}{\dot{q}"-\mathrm{CHF}}\right)^2$$

Where:
t_{ig} = ignition time (sec)
$\dot{q}"$ = heat flux (kW/m^2)
CHF = critical heat flux for ignition (kW/m^2)
TRP = thermal response parameter (kW·sec$^{1/2}$/m^2)

The above equation applies to the transient period (before steady-state). Plastic tool enclosures are assumed to behave as thermally thick materials and satisfy this equation. The CHF and TRP values are derived from the ignition data measured in the Flammability Apparatus, a commercial instrument designed by the Factory Mutual Research Corporation (FMRC) for measuring bench-scale HRR based on oxygen consumption calorimetry. The CHF and TRP values for polycarbonate are used in this analysis and are listed in Table A-1.

Table A-1. Critical Heat Flux and Thermal Response Parameters of Polycarbonate (U.S. Nuclear Regulatory Commission, 2004)

Material	*Critical Heat Flux (CHF) (kW/m²)*	*Thermal Response Parameter (TRP) (kW-sec$^{1/2}$/m²)*
Polycarbonate	15	331

Due to the transient nature of the fire, the time to ignition for adjacent tools changes. Based on the equations, the following graph was created showing the change in ignition time of an adjacent tool with the progression of the initial tool fire.

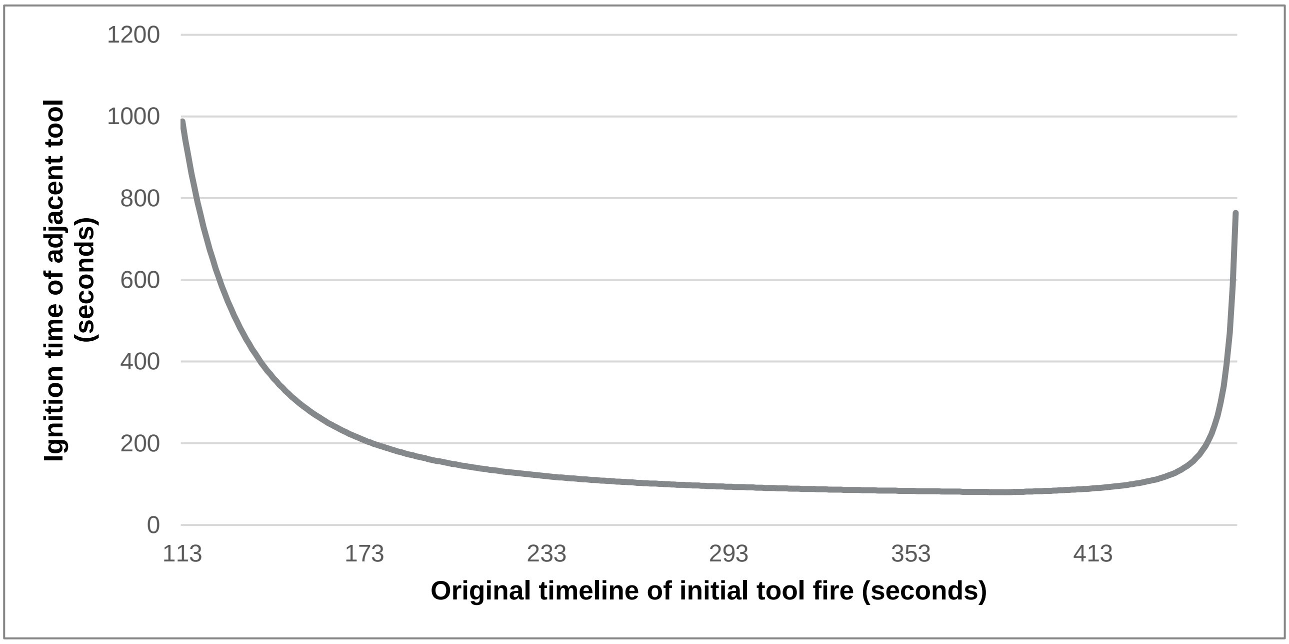

Figure A-3. Change of ignition time of adjacent tool with original time of initial tool fire

From Figure A-3, the adjacent tool ignition time reaches a steady state at approximately 210 seconds. At 210 seconds, the ignition time of an adjacent tool is calculated as 140 seconds, based on the HRR of the initial tool fire. Adding the original time and ignition time, it is predicted that the adjacent tool will be ignited at 350 seconds.

A.2.4 Fire spread across bay and chase

Similar calculations were performed to evaluate if the fire could spread across the bay or chase. Referring to Figure A-2, tool separation distances across the chase and bay are taken as 2.13 m and 1.2 m, respectively. Times to ignition of tools across the chase and bay are shown in Figure A-4 and Figure A-5. For a tool across the chase, the incident heat flux reaches its maximum at 313 seconds (at the Peak HRR), which corresponds to an ignition time of 875 seconds. However, a single tool fire duration is shorter than the time required for sustained incidental heat flux to cause ignition. Therefore, fire spread across the chase is unlikely and is not considered.

As seen in Figure A-5, the minimum ignition time required to ignite a tool across the bay is 430 seconds. Therefore, fire spread to a tool across the bay is unlikely and is not considered.

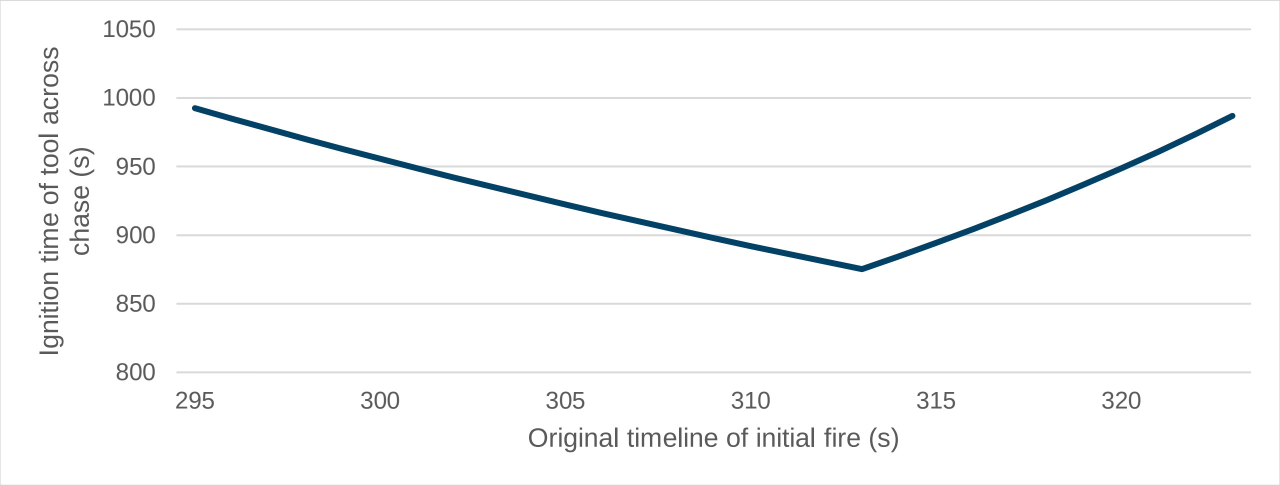

Figure A-4. Ignition time of tool across chase

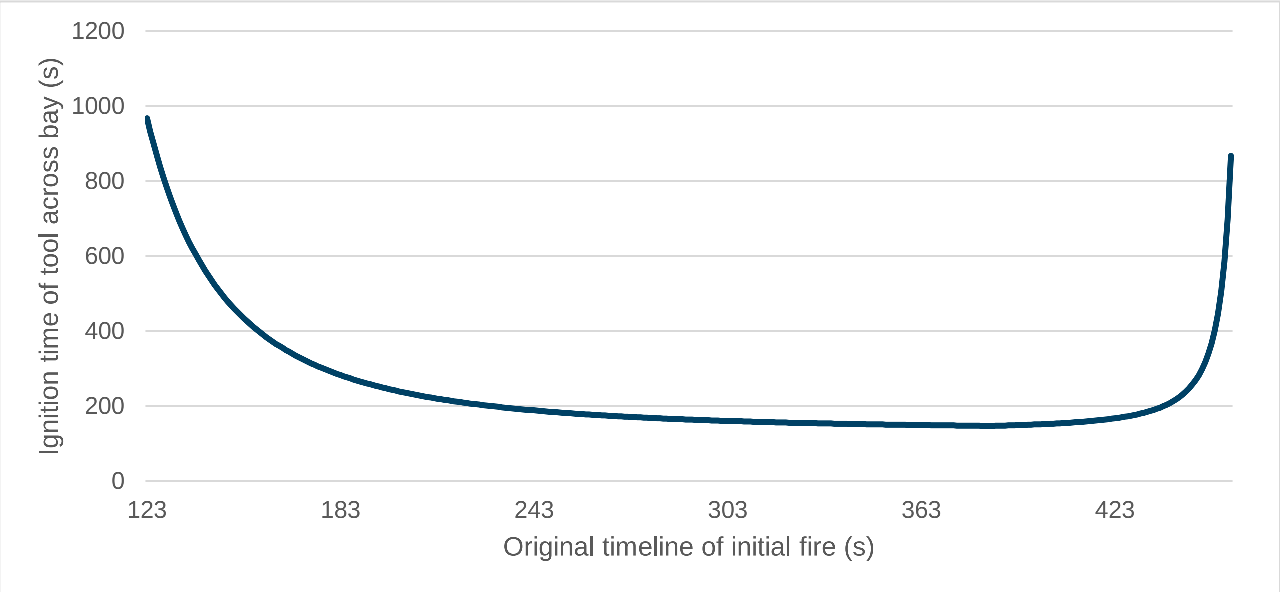

Figure A-5. Ignition time of tool across bay

As adjacent tools ignite, the HRRs are added and a cumulative HRR curve is produced. Figure A-6 shows the cumulative HRR curve, capturing the growth and decay of individual tool fires.

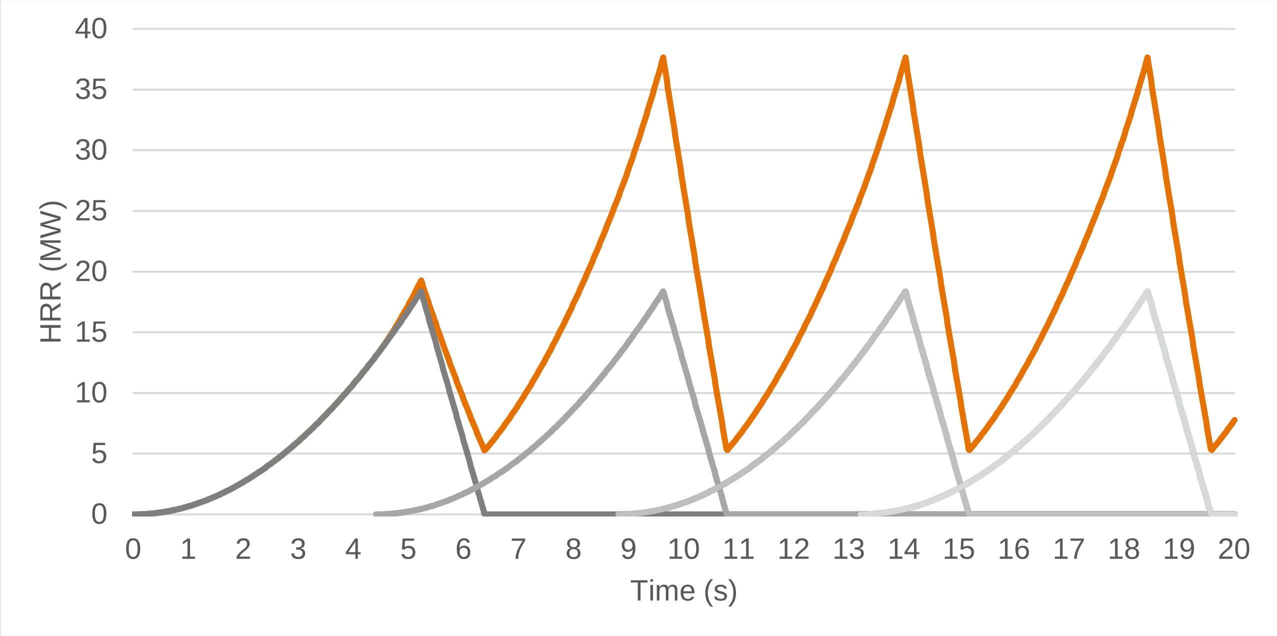

Figure A-6. Cumulative HRR of design fire (orange) and HRR of individual tool fires (gray)[1]

For the design fire, the cumulative HRR curve was simplified with a steady state at 40 MW. The growths and decays of the cumulative HRR curve is substituted by an averaged steady state phase (Figure A-7).

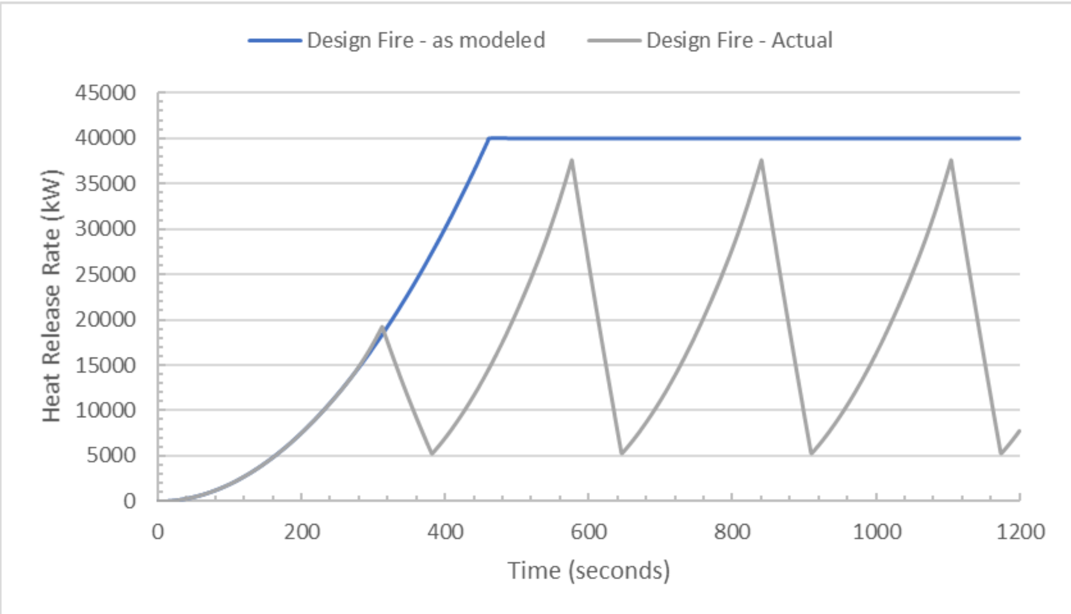

Figure A-7. Simplified design fire HRR curve (blue)

[1] The HRR curve of the initial tool fire is a single line curve, however subsequent HRR curves are all double lined, drawn one top of the other, representing two individual tools burning on both sides of the initial tool.

Appendix B. *Pathfinder Egress Model Construction*

B.1. PATHFINDER MODEL

The use of a computer egress simulation offers the benefit of calculating egress time for complex exiting configurations. This is especially important in spaces such as large facilities that have multiple levels and areas that traditional "hand calculations" cannot accurately predict. To determine the RSET for the generic H5 occupancy, a dynamic, three-dimensional egress model 'Pathfinder' is utilized.

The Pathfinder model is used to calculate the travel time and considers the occupant characteristics, occupant loading, and the interactions of occupants with each other and the structure as they exit. Time delays associated with fire detection, notification of occupants, and initial occupant decision making are included prior to the movement within the Pathfinder parameters to calculate the RSET.

In steering mode, Pathfinder uses a combination of steering mechanisms and collision handling to control how the occupant follows his / her seek curve[2]. These mechanisms allow the occupant to deviate from the path while still heading in the correct direction toward his / her goal. The steering system in Pathfinder moves occupants so they roughly follow their current seek curve and can respond to a changing environment. Inverse steering, used in Pathfinder, is the process of evaluating a set of discrete movement directions for an occupant and choosing the direction that minimizes a cost function. The cost function is evaluated by combining several types of steering behaviors to produce a cost. The types of steering behaviors used are determined by the occupant's current state, and the number of sample directions is controlled by the occupant's state and current velocity. Pathfinder defines several steering behaviors: seek, idle separate, seek separate, seek wall separate, avoid walls, avoid occupants, pass, lanes, and cornering. Most behaviors award a cost between 0 and 1 for each sample direction. The net cost for a direction is a weighted sum of these values [Thunderhead Engineering, 2020].

$$C_{ds} = .5C_{seek} + w_{ao}C_{ao} + w_{aw}C_{aw} + w_{ssep}C_{ssep} + w_{swsep}C_{swsep} + w_{lanes}C_{lanes} + w_{cnr}C_{cnr} + w_{pass}C_{pass}$$

Where:
C_{ds} = Final cost for a sample direction
C_{seek} = Cost to stay along seek curve or current path
C_{ao} = Cost of collision with other occupants
C_{aw} = Cost of collision with edge of the navigation mesh (e.g. wall, guard rail or obstruction)
C_{ssep} = Cost to separate out to maximize travel speed
C_{swsep} = Cost to maintain specified boundary layer with navigation mesh edge (e.g. wall, guard rail or obstructions)
C_{lanes} = Cost of being in a counter-flow traffic lane
C_{cnr} = Cost of cornering or cutting in front of other agents
C_{pass} = Cost to pass or wait

[2] A seek curve is generated to define the desired motion. In steering mode, this is a quadratic B-spline using the current position, the current waypoint, and a control point that is projected back along the direction from the current waypoint to the next waypoint.

The weights are defined in Table B-1:

Table B-1. Weights of Individual Steering Behavioral Costs

w_{ao}	1
w_{aw}	1
w_{ssep}	2
w_{swsep}	1
w_{lanes}	1
w_{cnr}	0.2
w_{pass}	0.5

B.2. OCCUPANT CHARACTERISTICS

The characteristics assigned to occupants play a key role in the outcome of the model simulations. Table B-2 provides a summary of the characteristics used for modeling. The walking speed was derived from SFPE's Engineering Guide to Human Behavior in Fire [SFPE, 2019]. Pathfinder applies a speed reduction factor to the walking speed of an occupant traversing stairs or ramps that is determined based upon the slope. It was considered that at least 3.4% of the occupants working in the facility will have mobility limitations, due to injury or illness. This number is selected based on employer reported incidence rates of non-fatal occupational injuries and illnesses in manufacturing industry in 2018 [Bureau of Labor Statistics, 2019].

Table B-2. Occupant Profile Characteristic used in Modeling

Percentage of Population	*Profiles*	*Speed (feet/second)*	*Shoulder Width (in)*	*Personal Distance (in)*
96.6%	Default	Maximum: 3.9	17.94	3.15
3.4%	Injured	Maximum: 2.46	17.94	3.15

A description of the various occupant parameters in Pathfinder (including those listed in Table B-3) are described below:

B.2.1 Shoulder Width

The shoulder width is the cylinder diameter that represents the size of the occupant. This value also affects how many occupants can be added to a space without overlapping. The value of 17.94 in. is based on the average of measurements of male and female persons from nine countries [Pheasant & Haslegrave, 2005].

B.2.2 Personal Distance

The personal distance specifies the desired distance one occupant will try to maintain with others nearby such as waiting in queues. The default value of 3.15 in. is used as discussed in the Pathfinder Validation and Verification Manual [Thunderhead Engineering, 2019]. The default size and Comfort Distance results in movement that matches the SFPE and experimentally measured fundamental diagrams.

B.2.3 Door State

By default, all doors are always open throughout the simulation. Door states are changed to closed for certain aisles and exits to represent egress obstructed by fire, radiation and smoke exposure.

B.2.4 Reduction Factor

The reduction factor specifies how easily an occupant may squeeze past others in tight corridors. This factor ranges between 0 and 1 and is directly multiplied by the shoulder width during calculations. A shoulder width factor of 0.7 results in an occupant being able to squeeze to 70% of its shoulder width.

B.2.5 Riser and Tread

Together, these parameters control the speed at which occupants can travel on the stairs during simulation. The default speed on stairs uses the SFPE speed modifiers [Thunderhead Engineering, 2020]. The occupant's base speed, v_b, is defined as a function of density, terrain, and a speed fraction curve based on the SFPE fundamental diagram. It does not take terrain speed modifiers or constants into account.

$$v_b = v_{max} \times v_f(D) \times v_{ft}$$

v_{ft} is a speed fraction that depends on the type of terrain being traversed by the occupant. It is defined as

$$v_{ft} = \frac{k}{1.4}$$

For stairs, k depends on the steep slope of the stairway. The SFPE guide defines k only for a limited set of known step slopes [SFPE, 2019]. In the generic H5 model stairs are modeled as having 7-inch riser and 11-inch tread.

Stair Riser (inches)	Stair Tread (inches)	k
7.5	10.0	1.00
7.0	**11.0**	**1.08**
6.5	12.0	1.16
6.5	13.0	1.23

B.2.6 Collision Response Time

The collision response is the distance ahead at which an occupant will start recording a cost for colliding with other occupants when steering. It is multiplied by an occupant's current speed to calculate the recording threshold. With the default of 1.5 s and the maximum speed of 1.19 m/s, the occupant will look ahead 1.785 m from their current position to detect potential collisions and calculate costs.

B.2.7 Behavior

By default, there is one behavior in the model called "Go to Any Exit." This behavior simply makes the occupant move from their starting position to any exit present in the model by the fastest route.

B.2.8 Path Planning (Locally Quickest)

Path planning is the process of determining a plan for moving toward a destination. Given an occupant seeking a destination, there may be multiple paths to reach the destination, each with differing lengths, number of occupants along the way, and various hazards. A naïve path planning approach to choosing a route would be to take the shortest route. This may not be the fastest or best route to the destination for an occupant, however. Locally quickest is the path planning approach used in Pathfinder to solve this problem. It plans the route hierarchically, using local information about the occupant's current room and global knowledge of the building. It is assumed that an occupant knows about all doors in their current room as well as queues at those doors. It is also assumed that the occupant knows how far it is from one of those doors to the current destination (seek goal). Locally quickest then uses this information to choose a door in the current room based on a calculated cost of that door. A path is then generated to the door, which the occupant can follow.

B.3. OCCUPANT LOAD

The occupant load within the building was determined through the occupant load factor based on the Group H-5 fabrication and manufacturing areas provided in the IBC [ICC, 2018]. Table B-3 provides the occupant load factor used for each floor. On the Fab level, occupants are distributed in tool chases. The occupant load distribution on the Fab level is shown in Figure B-1 and B-2.

Table B-3. Occupant Load Factors

Level	*Use*	*Occupant Load Factor (ft^2/person)*	*Total Number of Occupants*
Utility	Group H-5 fabrication and manufacturing areas	200 gross	1,100
Subfab	Group H-5 fabrication and manufacturing areas	200 gross	1,100
Fab	Group H-5 fabrication and manufacturing areas	200 gross	1,100

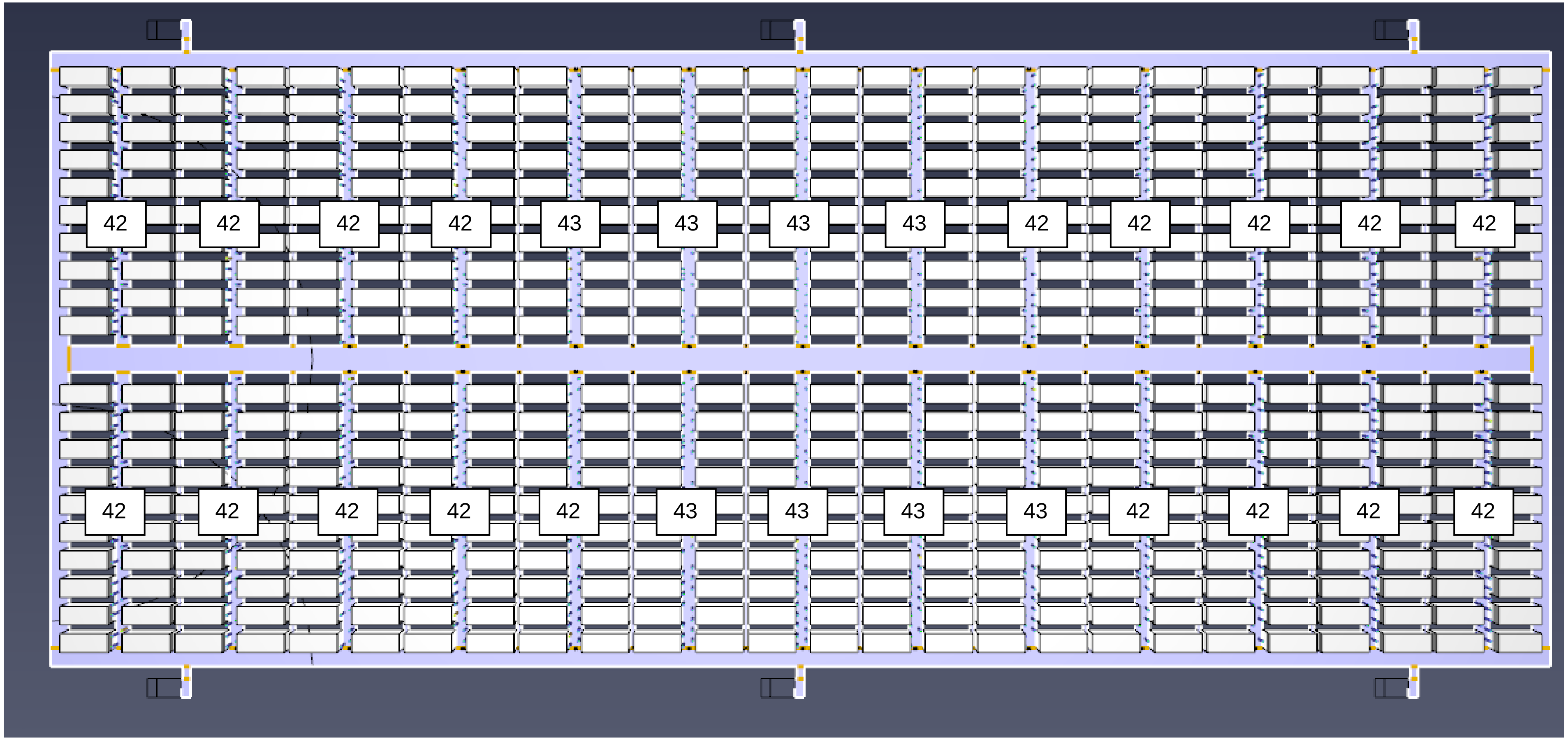

Figure B-1. Occupant distribution on Fab level for scenarios 1-3

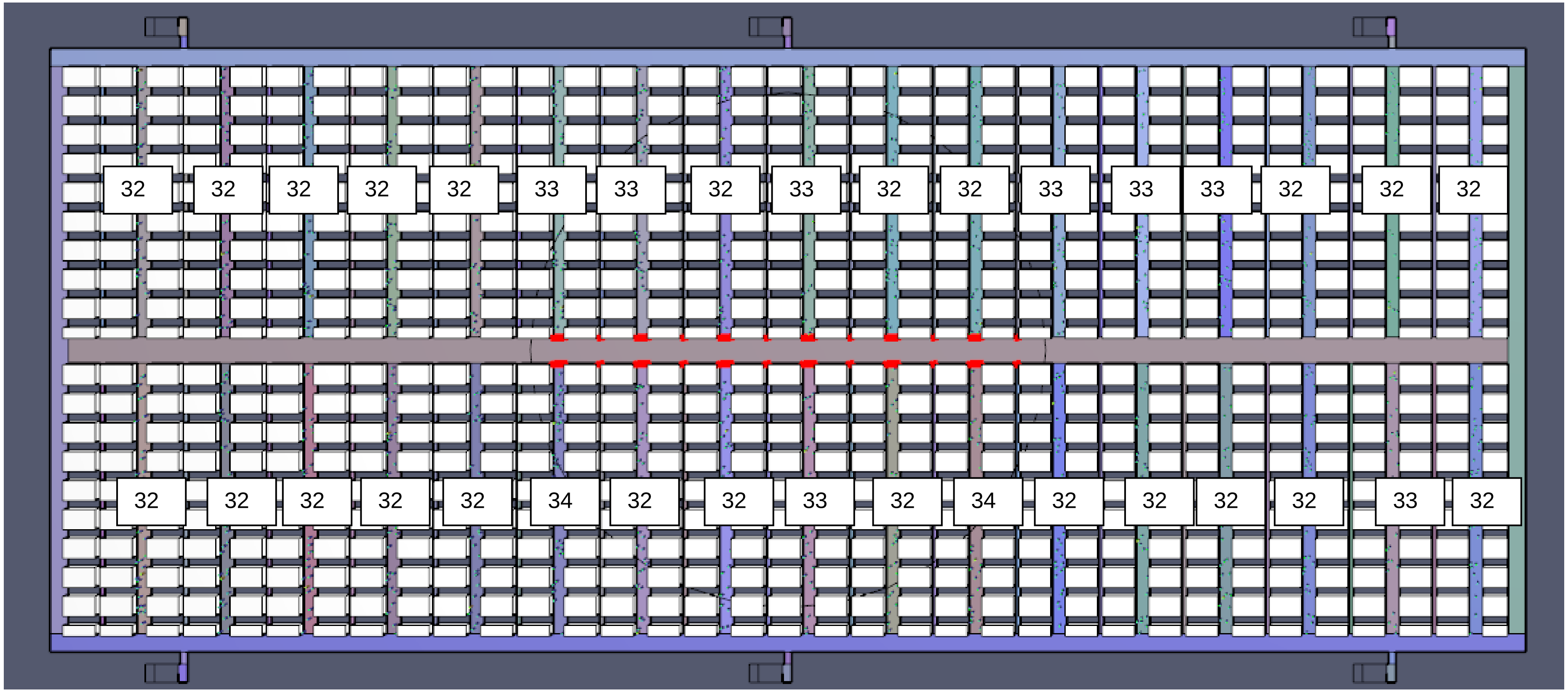

Figure B-2. Occupant distribution in the Fab level for scenario 4

B.4. EGRESS MODEL CONSTRUCTION

A single model was constructed to include the Utility, Subfab and Fab levels. All areas of the building were evacuated together, simultaneously. This allowed for a continuous comparison of occupant locations with all occupants merging within the entire building to identify choke points in the model. There are exits around the perimeter of the building on all floors. Eight exit stairs are provided to serve the floors. The Utility level is provided with six (6) entrances to the exit stairs that discharge directly to the outside, without having to travel in the vertical direction. An overview of the exit locations is shown in Figures B-2 through B-4.

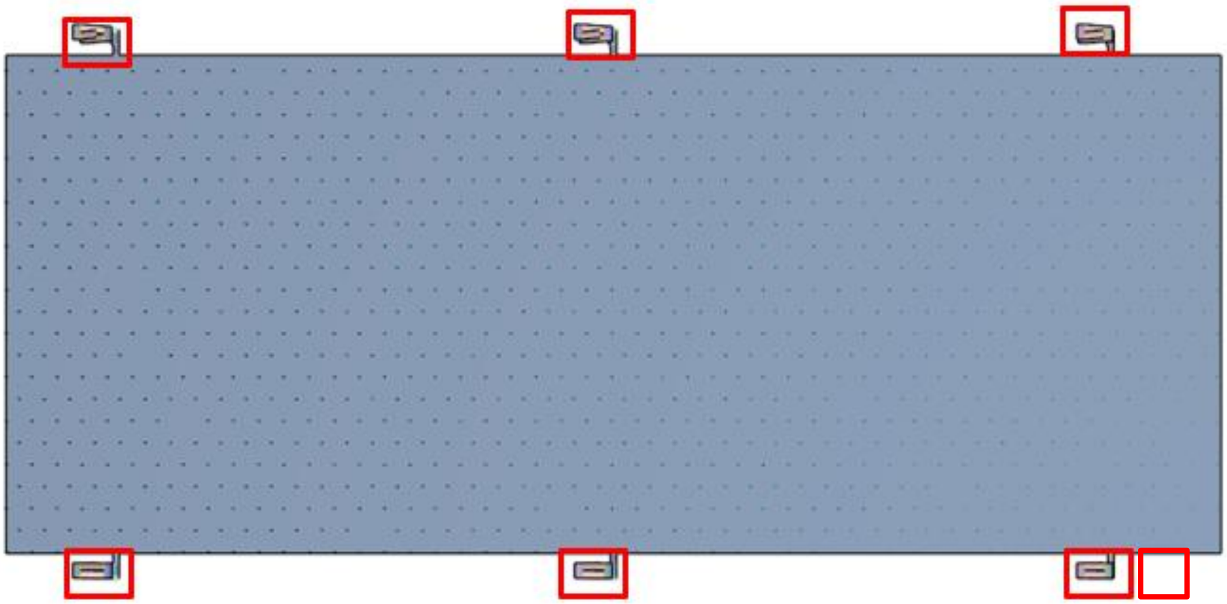

Figure B-2. Exit locations on Utility level (red squares)

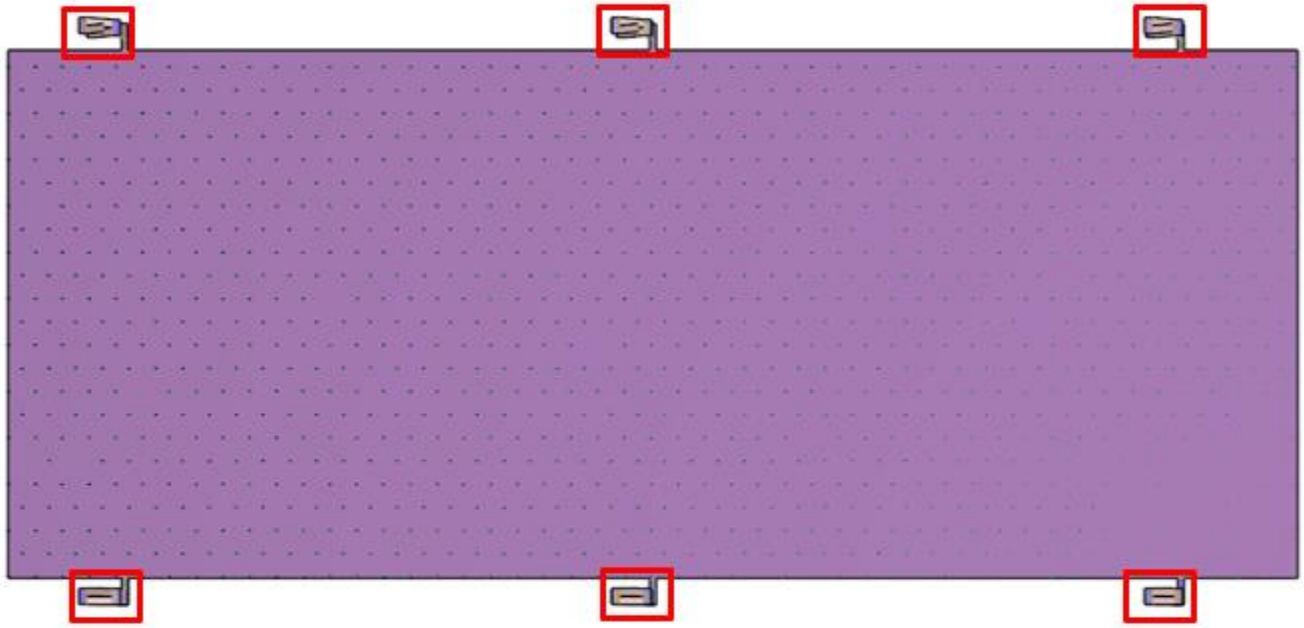

Figure B-3. Exit stair locations on Subfab level (red squares)

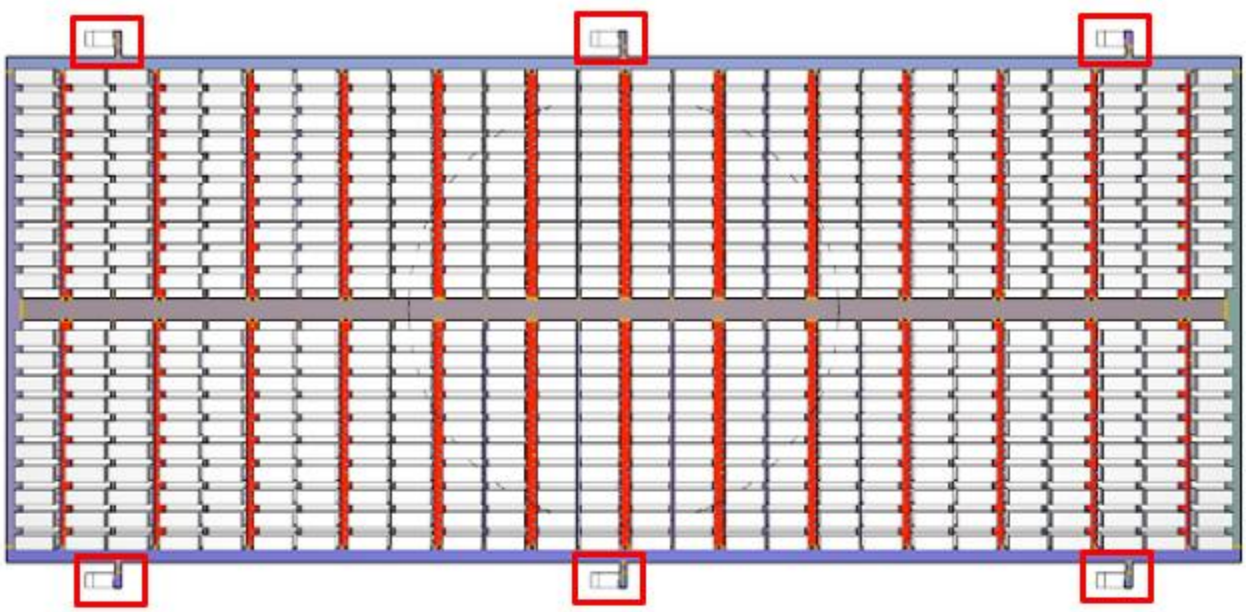

Figure B-4. Exit stair locations (red squares) on Fab level

On the Fab level, tools and stockers were excluded from the navigation meshes in the model represented as egress obstructions (Figure B-5). Two different sizes of tools are used, one is 23 ft long and the other is 16 ft long. The length of the tools contributes to the distance between the chase and adjacent bay.

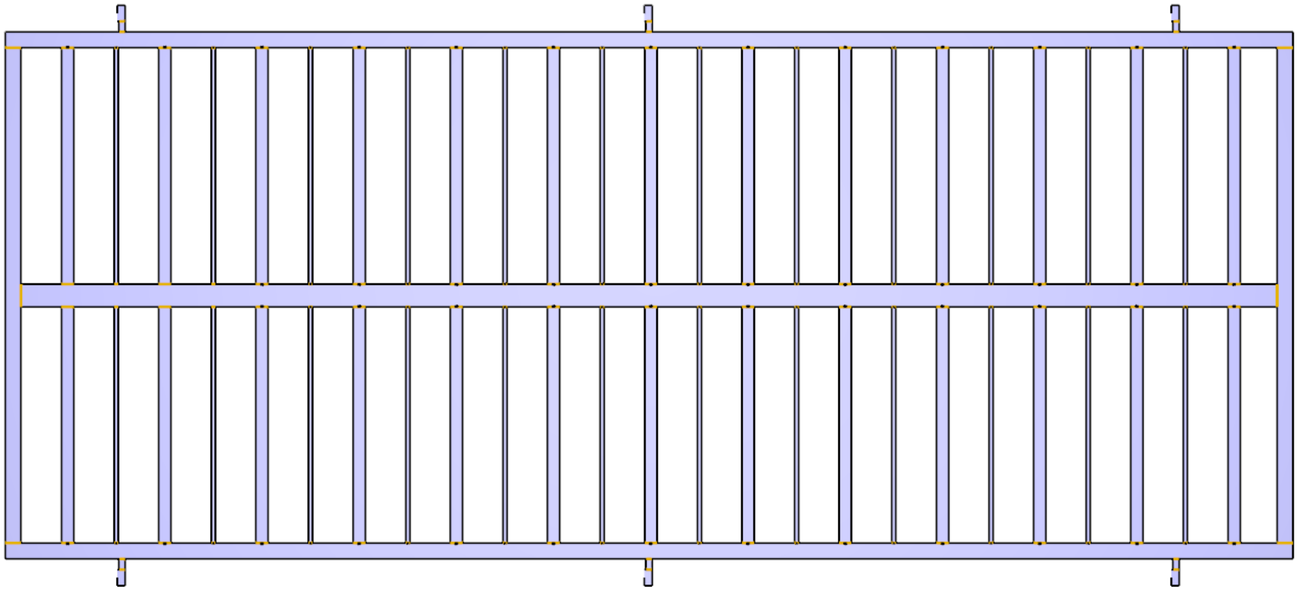

Figure B-5(i). View of the Fab level in the Pathfinder model for 23 ft long tools showing navigation meshes (grey) and egress obstructions (tools, white cut-outs within the navigation meshes)

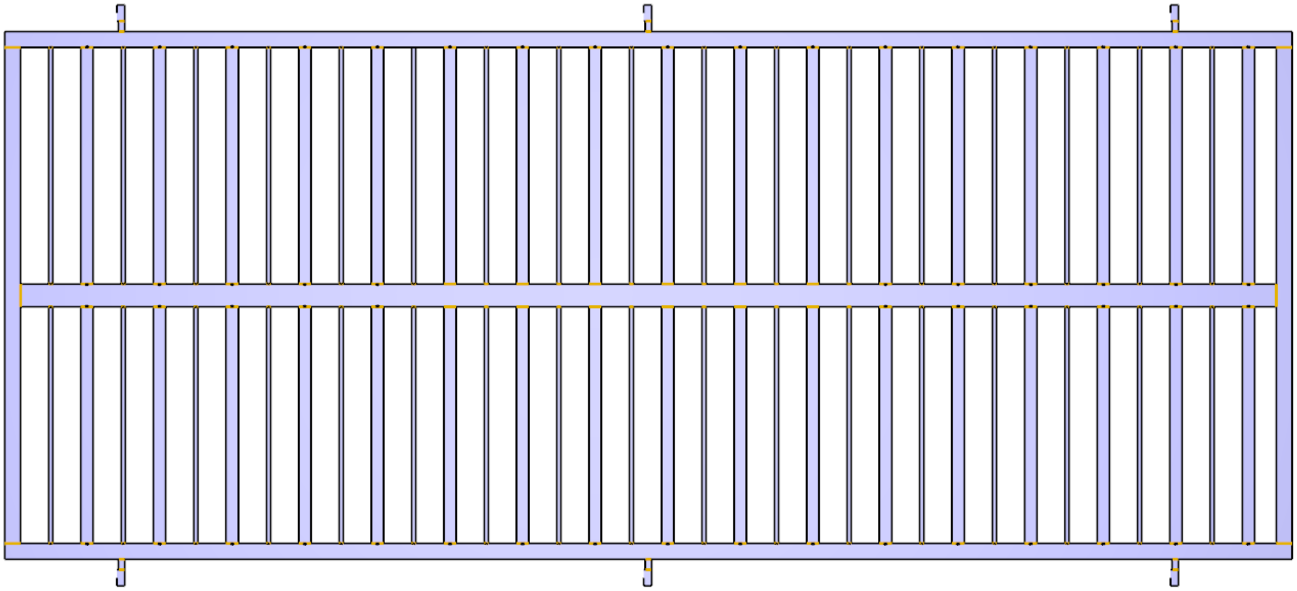

Figure B-5 (ii). View of the Fab level in the Pathfinder model for 16 ft long tools showing navigation meshes (grey) and egress obstructions (tools, white cut-outs within the navigation meshes)

The doors and stairs in pathfinder are modeled in accordance with the allowable minimum required by the IBC 2018. The doors are modeled to provide only the clear width between the door frames, which is 37 in.

The egress aisles on the periphery of the fab are 9 ft wide. A center aisle is included in the fab running east-west, which is 13 ft wide.

The tool rows separate the navigation meshes into a bay on one side of the row and a chase on the other side. All bays are 28 in. wide. The bays are modeled as unobstructed exit access aisles to be used in any direction during evacuation. The width of the chases is 7 ft. One-way doors are provided at the end of the chases, that allow occupants to egress from chases, but do not allow occupants outside the chase to egress through them. Bays and chases are shown in Figures B-6 and B-7.

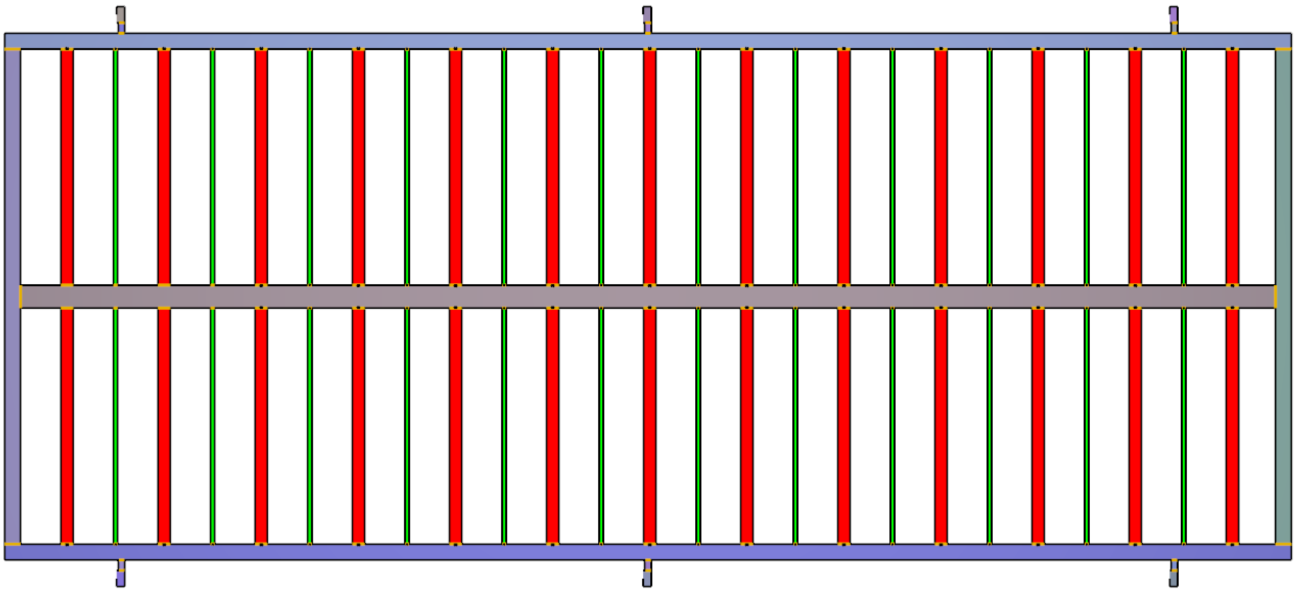

Figure B-6. Fab level egress bays (green meshes) and service chases (red meshes) in 23 ft long tool model

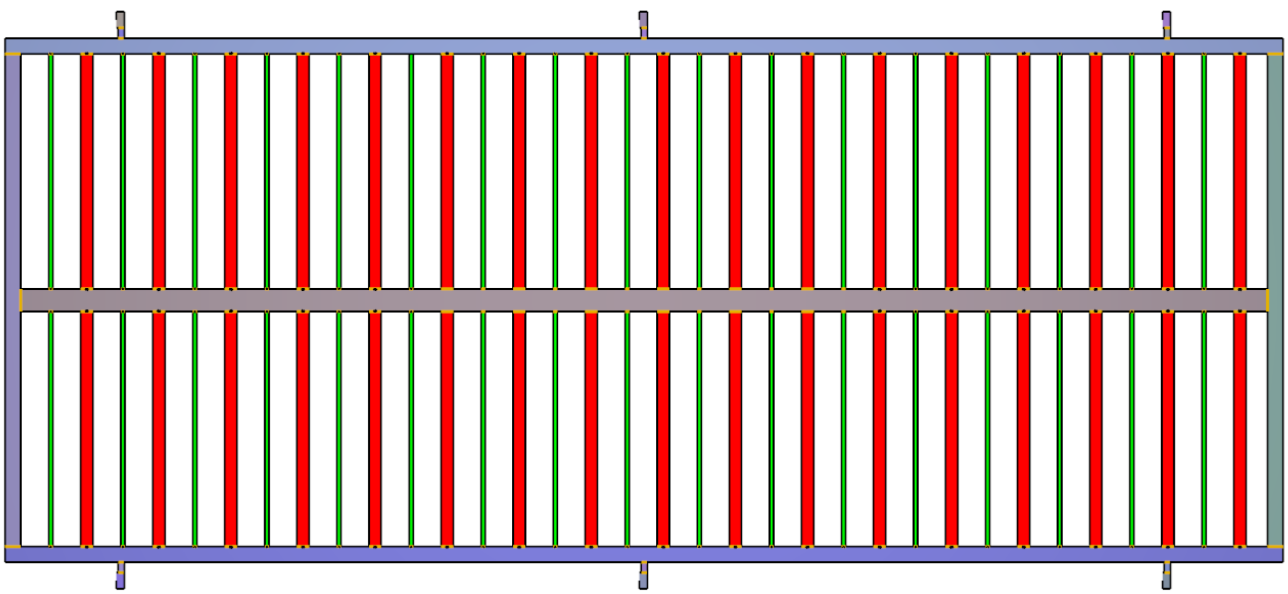

Figure B-7. Fab level egress bays (green meshes) and service chases (red meshes) in 16 ft long tool model

B.5. EGRESS MODEL SCENARIOS

Egress modeling considered of three scenarios / fire locations. The parameters for these scenarios are summarized in Table B-4 below.

Table B-4. Egress Model Scenarios

Scenario No.	*Number of exits available*	*Number of bays and chases*	*Closed bays, chases and exits*
1	6	13	Four bays and five chases on both sides of center aisle.
2	5	13	Two bays, two chases and west aisle on south side of center aisle only and Exit 4.
3	5[3]	13	Two bays, two chases and west aisle on both sides of center aisle and Exit 4.
4	6	17	Six bays and six chases on both sides of center aisle.

The location of closed exit accesses for Scenarios 1, 2, 3 and 4 is shown in Figures B-8 through B-11. Point source radiation model [Beyler, 2016] was used to determine a minimum safe distance from 40 MW fires for building occupants where the minimum safe distance is determined based upon a heat flux of 2.5 kW/m^2 or less [Purser & McAllister, 2016]. The results of the analysis found that a 40 MW fire requires a minimum safe distance of 130 ft. It is therefore considered appropriate that the model only blocked the exit access aisles, bays and chases that are within 130 ft from the fire location.

[3] All six (6) exits were available till 380 seconds.

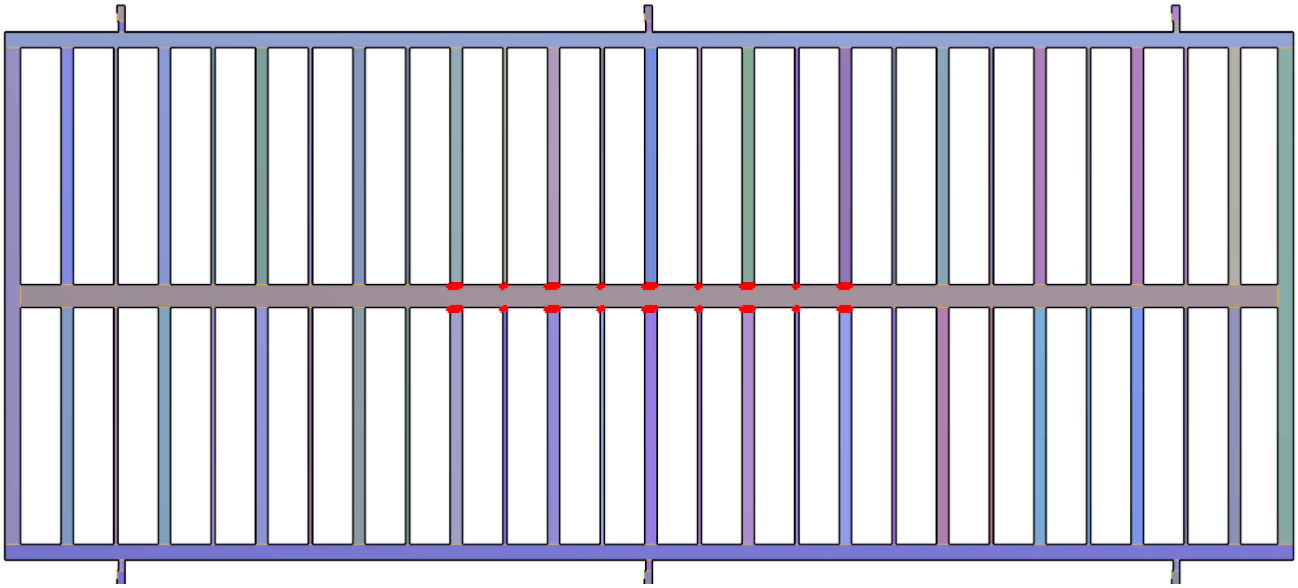

Figure B-8. Closed center aisle and chase in red for Scenario 1

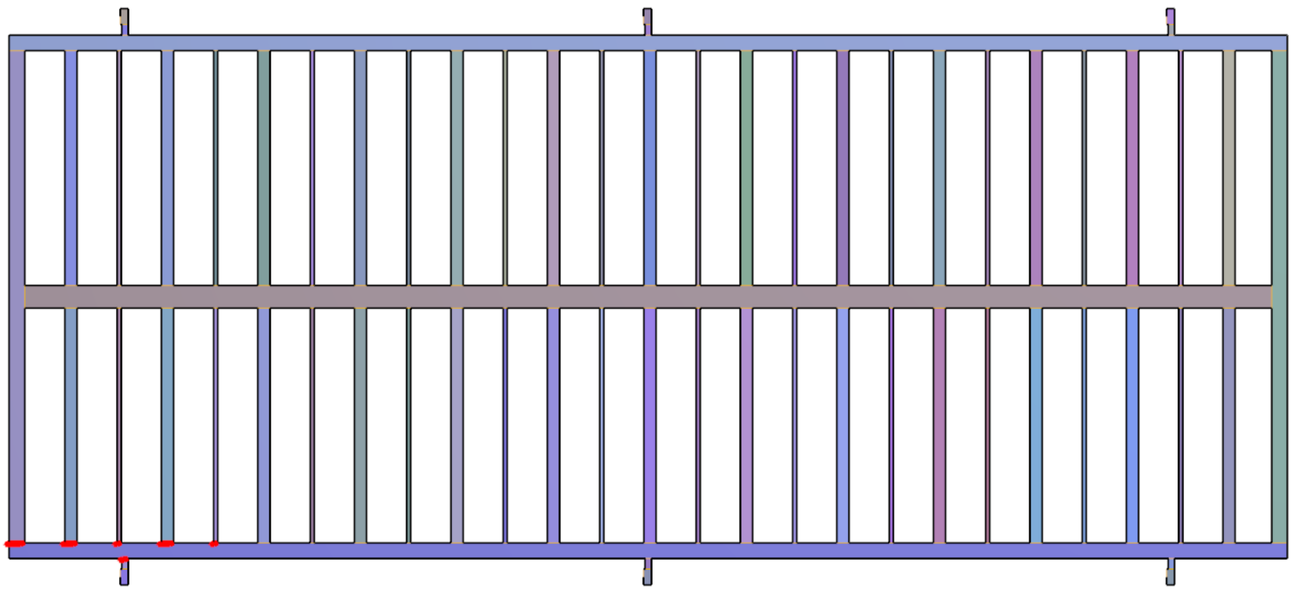

Figure B-9. Closed bays, chases and exit in red for Scenario 2

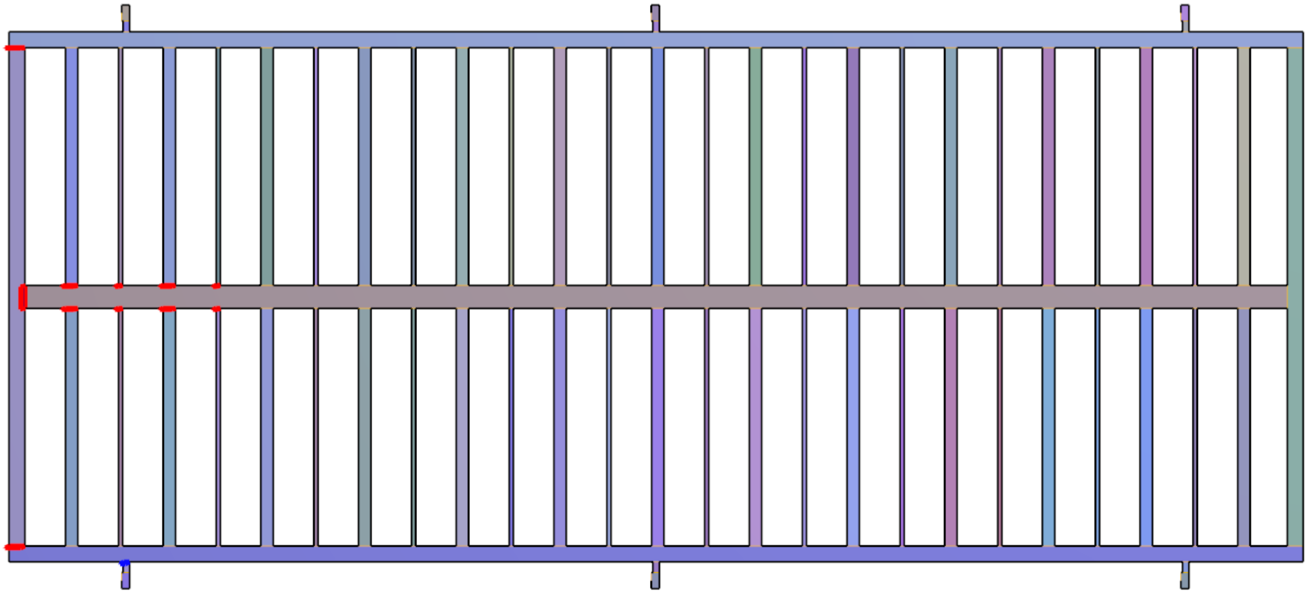

Figure B-10. Closed bays, chases and aisles in red and closed exit at 380 seconds in blue for Scenario 3

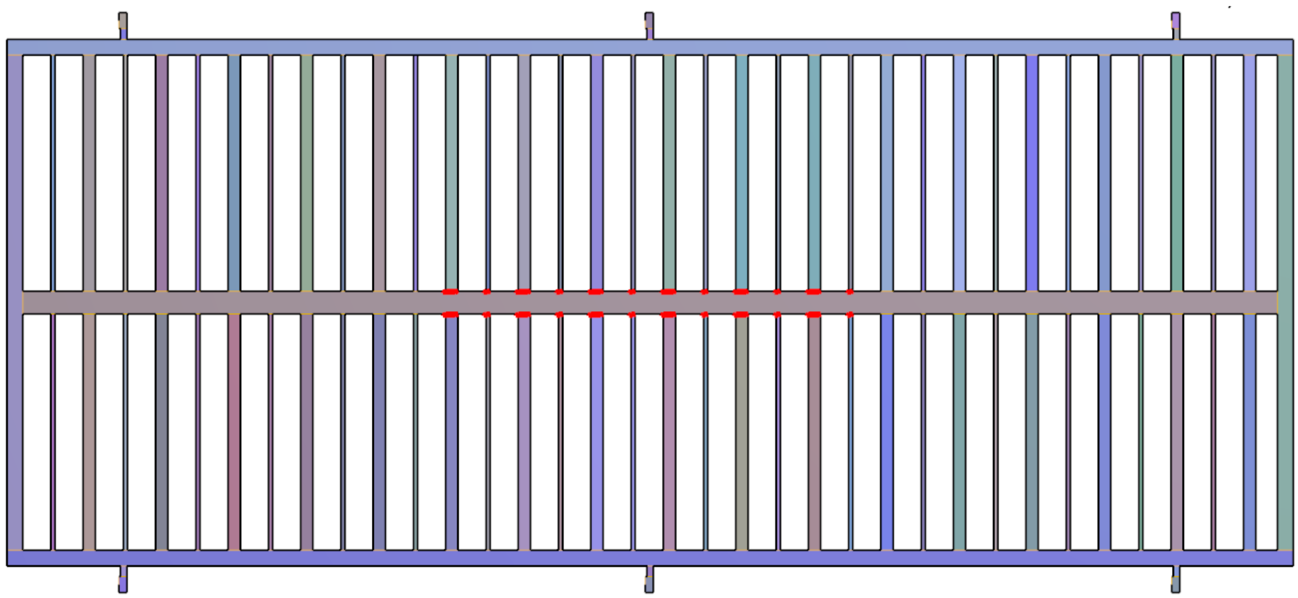

Figure C-11. Closed bays and chases in red for Scenario 4

Appendix C. *Subfab Visibility Model*

A model was constructed to evaluate the visibility conditions in the Subfab with the purpose of ensuring that tenability criteria are not exceeded during the time of occupant egress. This model included the Fab level which was modeled as explained in Section 5.1 and the Subfab level where a coarser cell size of 2.5 ft (0.76 m) was used. Materials and surfaces for solid boundaries were specified in the model according to Table 2-1. The exterior surfaces of the computational domain were specified as open boundaries (ambient conditions outside the domain).

Figure C-1 shows the visibility at 6 ft above the Subfab floor at 700 seconds for a fire in the southest corner of the Fab. With the exception of a small area in the southern portion of the fab, the visibility is greater than 10 m after the time required for occupants to egress from the Fab level. This level of smoke would not have any impact on the ability of Subfab occupants to egress from that level since evacuation times will be the same if not shorter as compared to the Fab level. The Subfab level differs from the Fab level in that the egress paths will be more direct due to the absence of tools. The location of the fire will not impact the applicability of these results; similar trends would occur for other fire locations. These results support the use of the Fab level modeling as a basis for evaluating the egress requirements for this fab design.

Figure C-1. Visibility conditions in Subfab at 6 ft above the floor at 700 seconds (fire in southeast corner of fab)

Appendix D. *Additional Egress Figures*

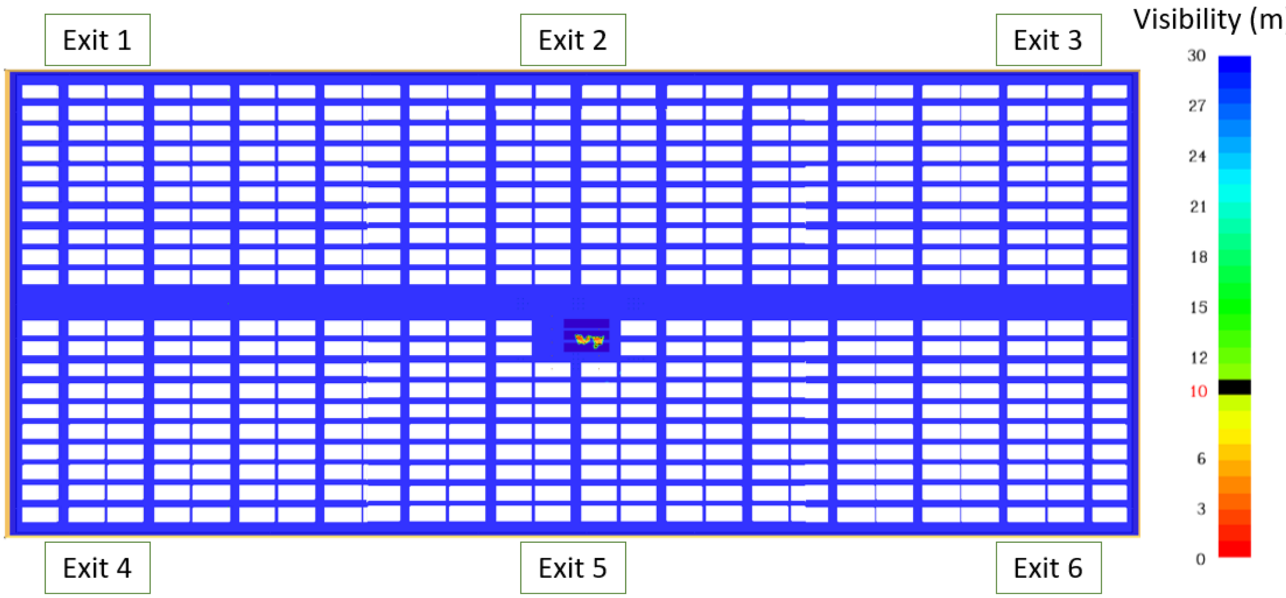

Figure D-1. Visibility conditions 6 ft above the floor at 60 sec (1 min) for center fire location

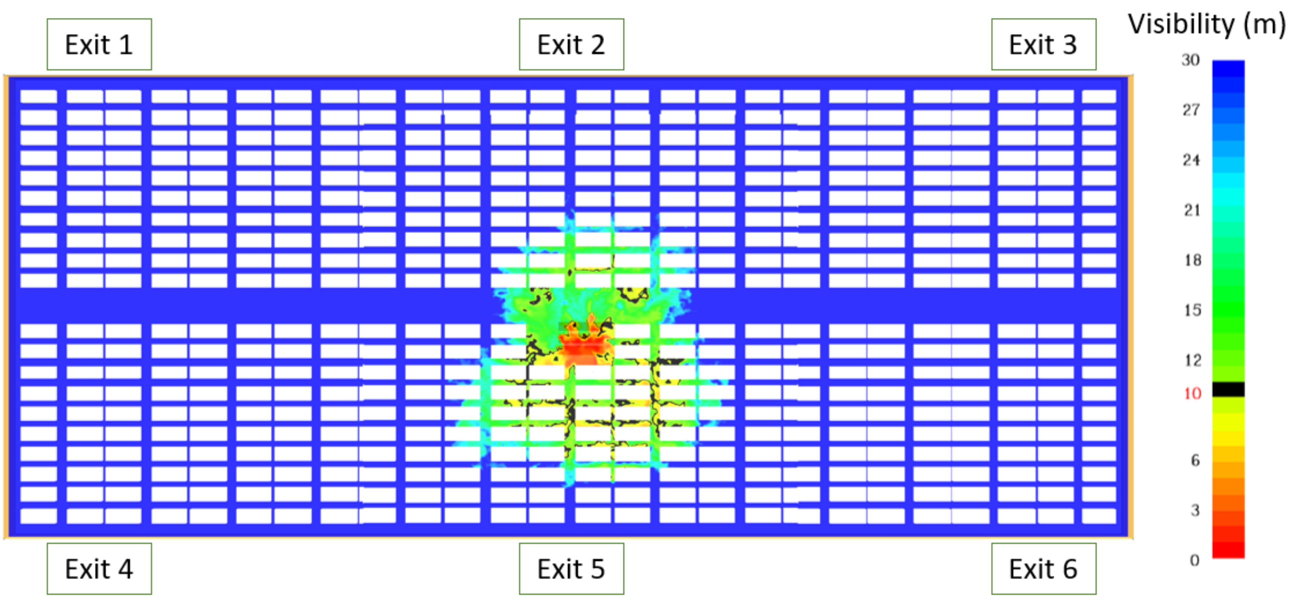

Figure D-2. Visibility conditions 6 ft above the floor at 180 sec (3 min) for center fire location

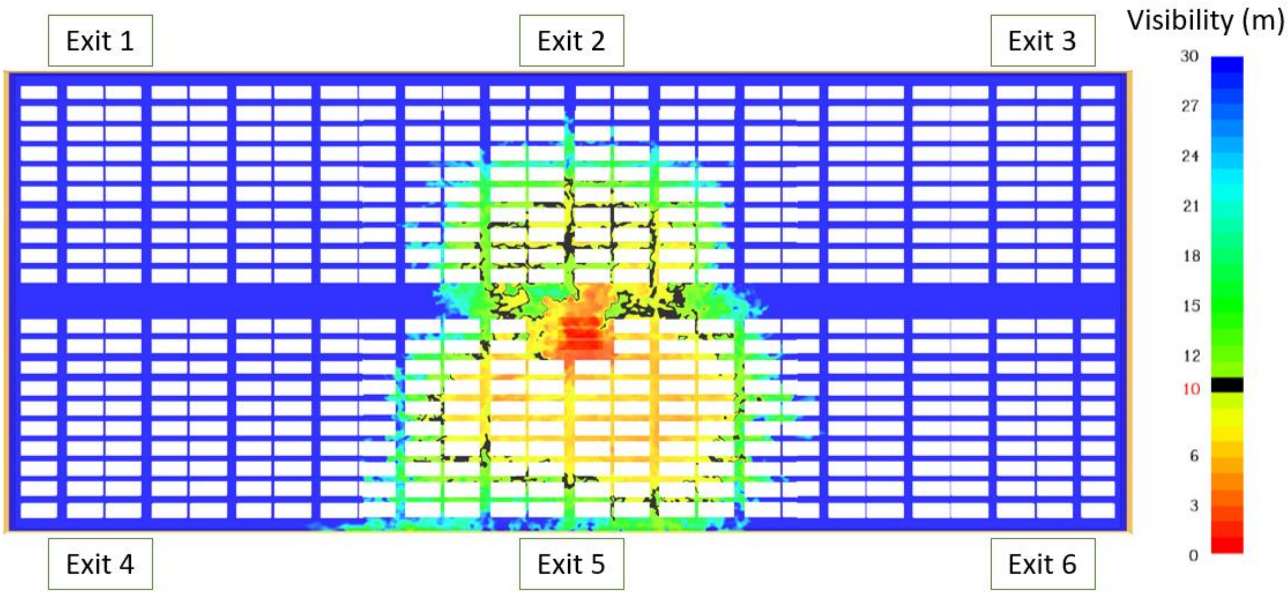

Figure D-3. Visibility conditions 6 ft above the floor at 300 sec (5 min) for center fire location

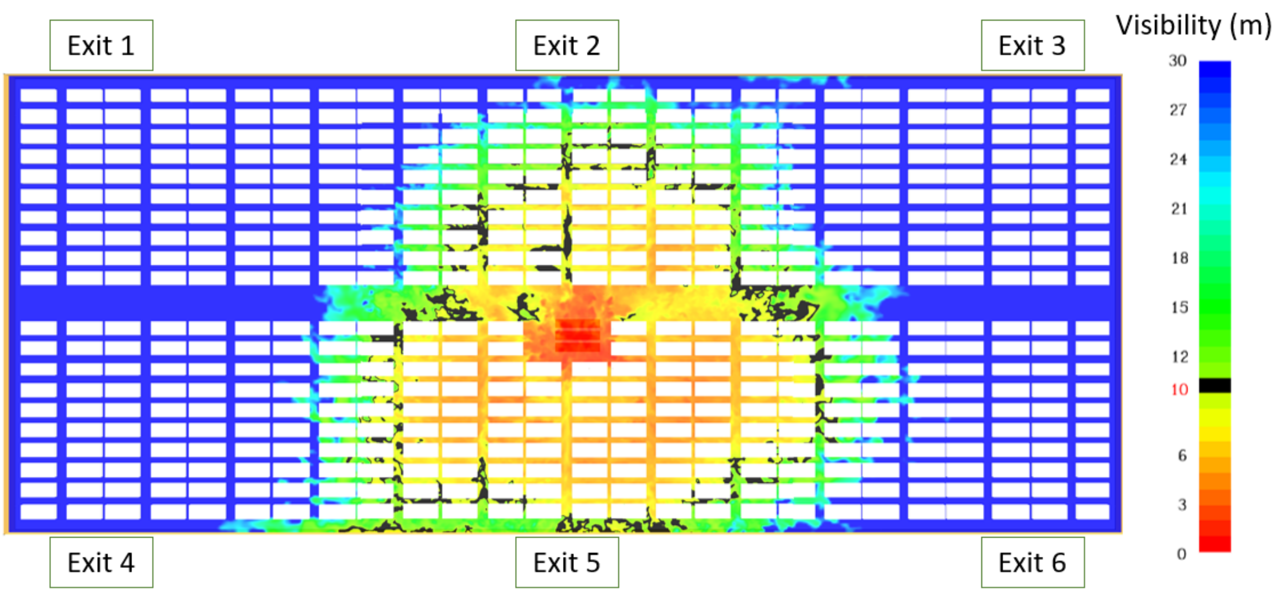

Figure D-4. Visibility conditions 6 ft above the floor at 420 sec (7 min) for center fire location

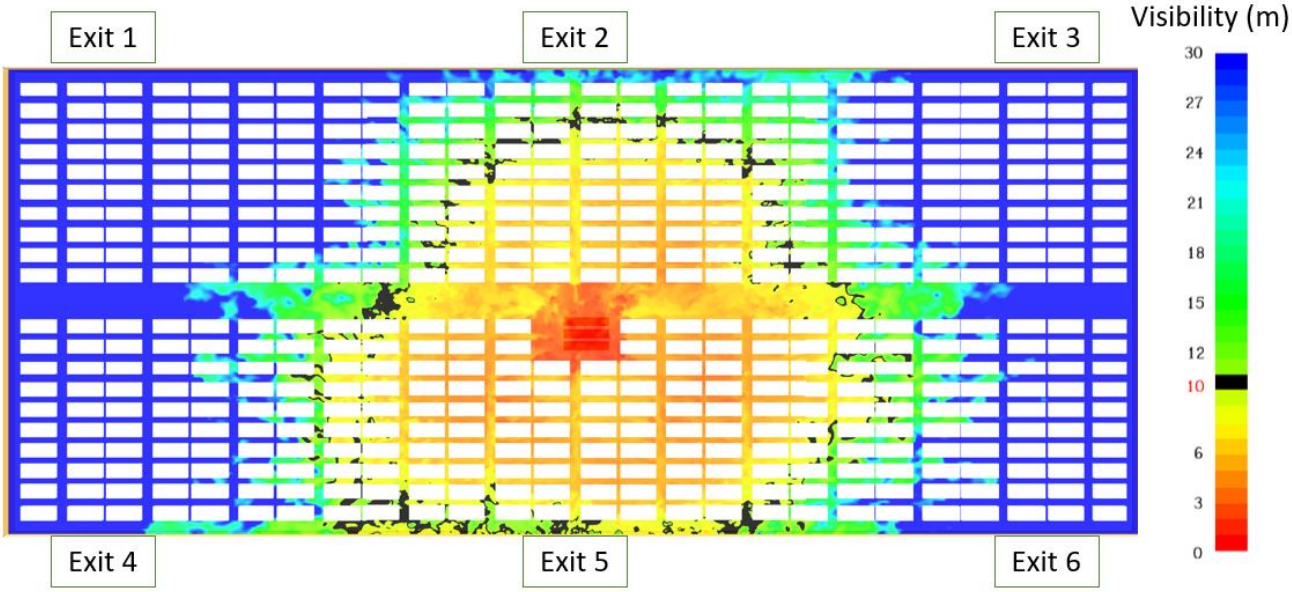

Figure D-5. Visibility conditions 6 ft above the floor at 540 sec (9 min) for center fire location

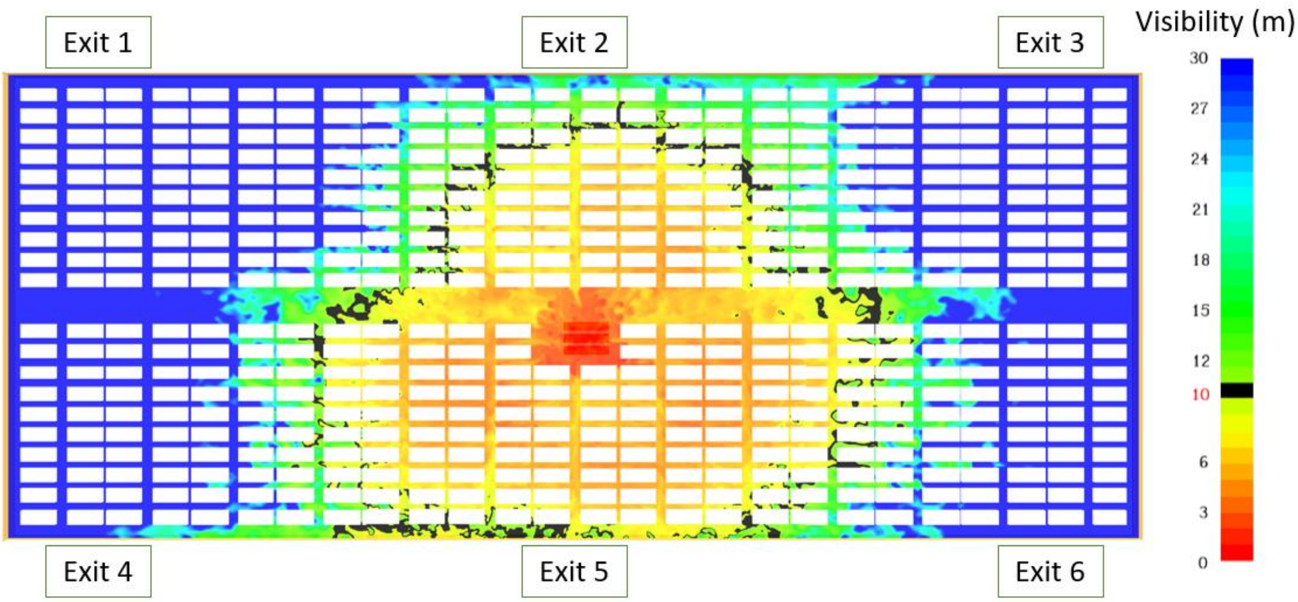

Figure D-6. Visibility conditions 6 ft above the floor at 660 sec (11 min) for center fire location

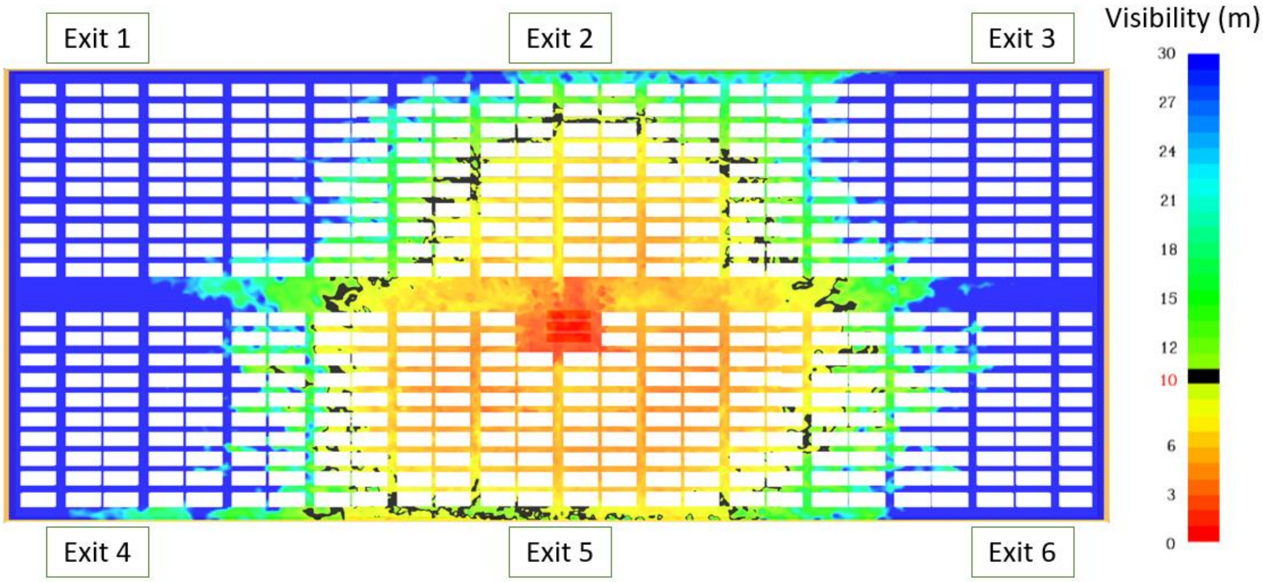

Figure D-7. Visibility conditions 6 ft above the floor at 780 sec (13 min) for center fire location

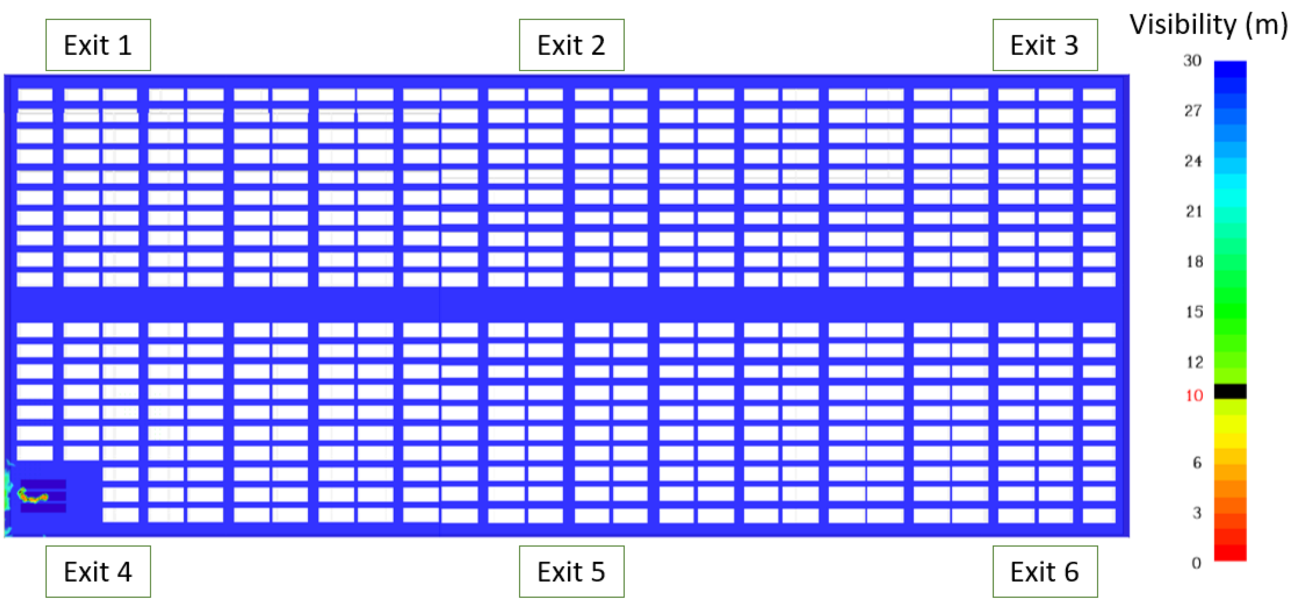

Figure D-8. Visibility conditions 6 ft above the floor at 60 sec (1 min) for southwest corner fire location

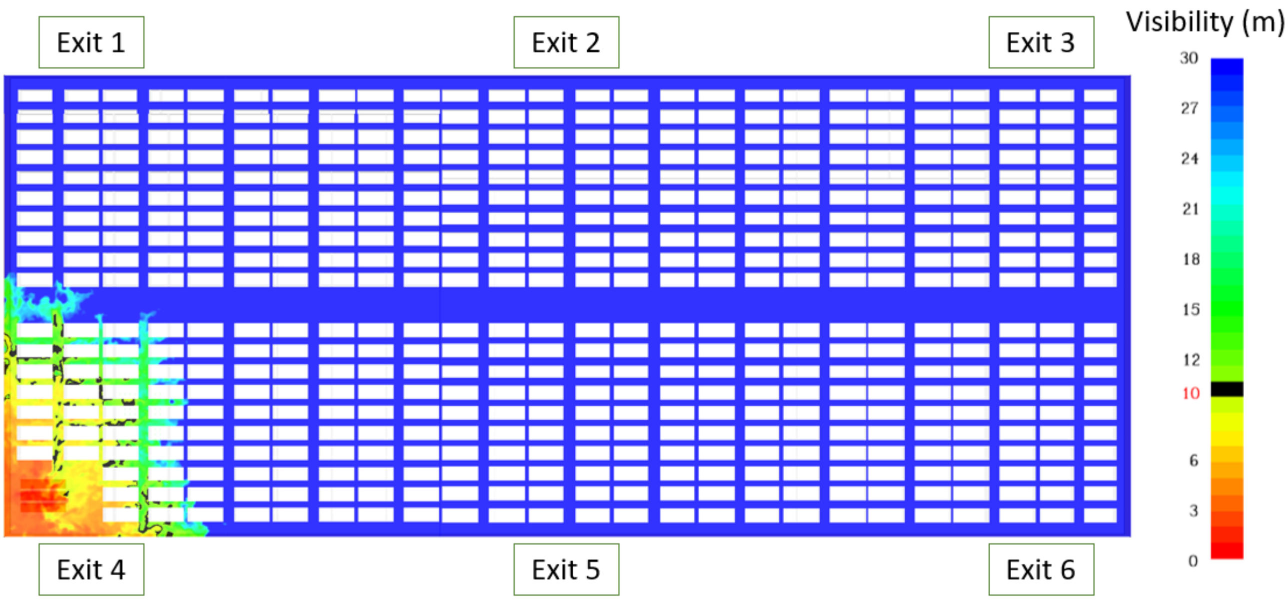

Figure D-9. Visibility conditions 6 ft above the floor at 180 sec (3 min) for southwest corner fire location

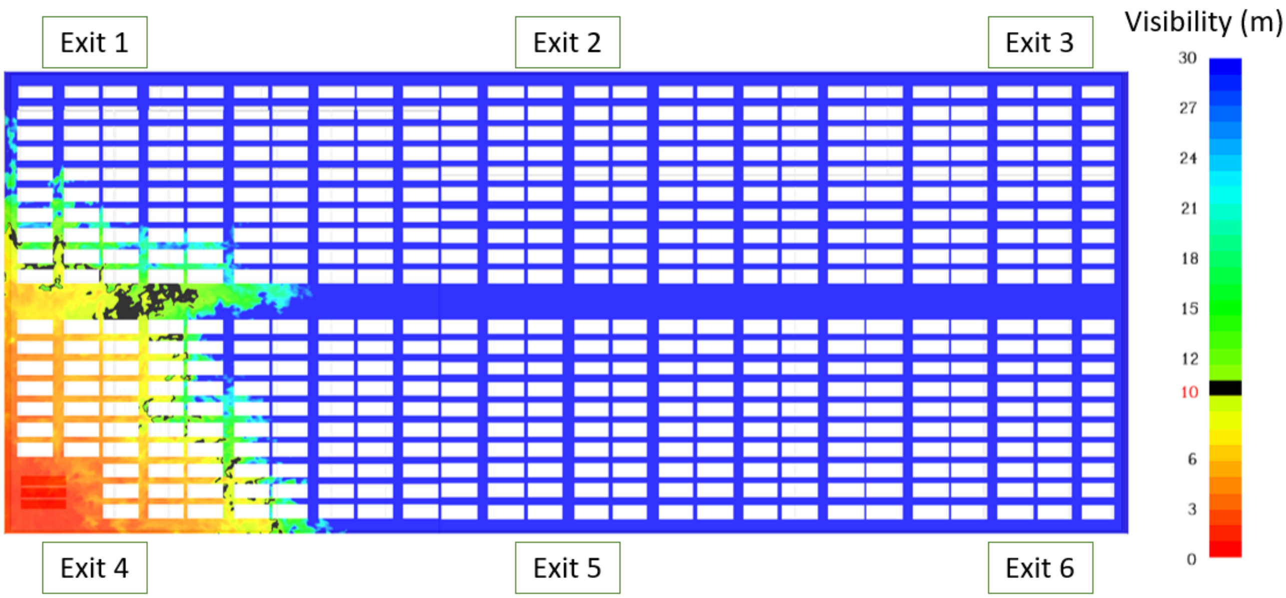

Figure D-10. Visibility conditions 6 ft above the floor at 300 sec (5 min) for southwest corner fire location

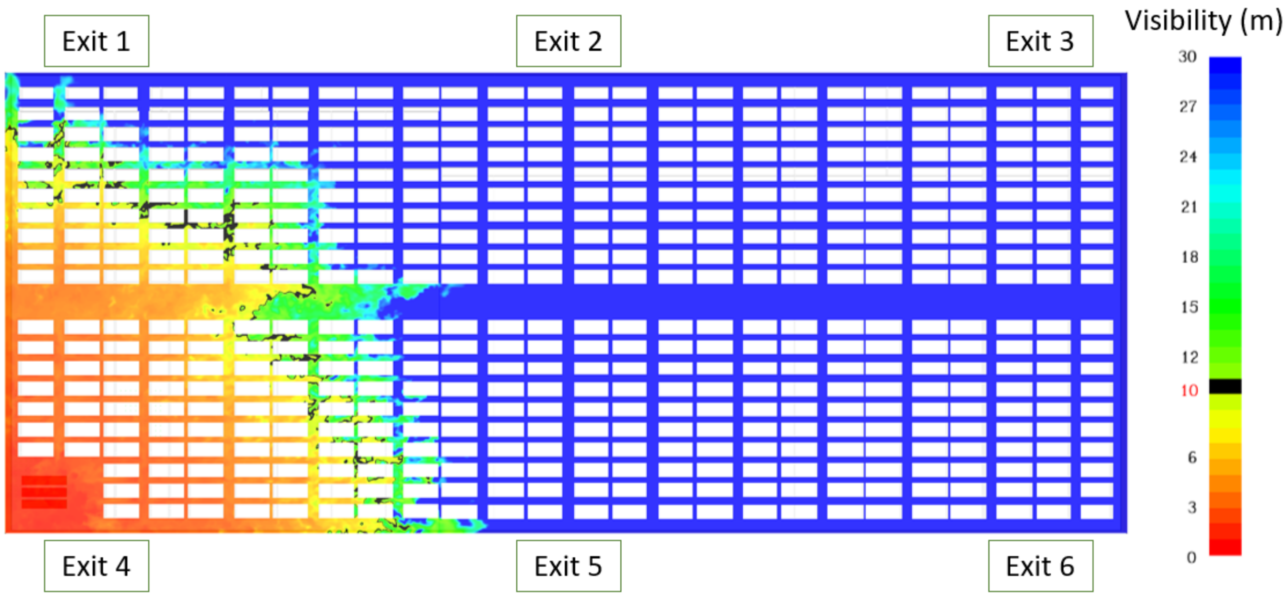

Figure D-11. Visibility conditions 6 ft above the floor at 420 sec (7 min) for southwest corner fire location

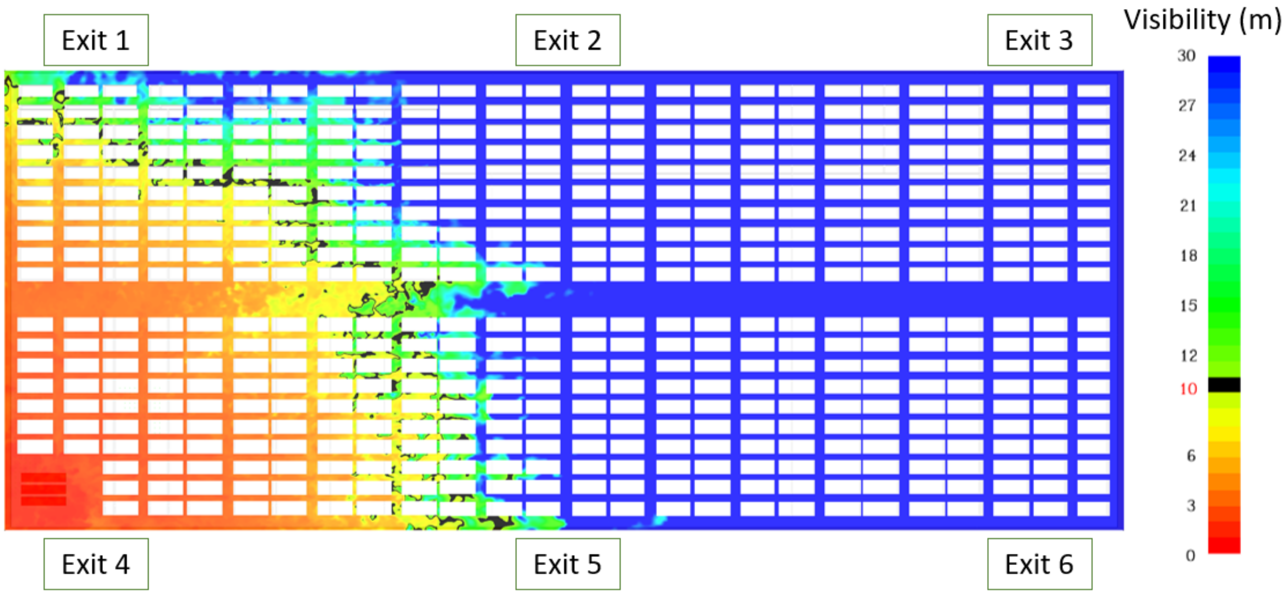

Figure D-12. Visibility conditions 6 ft above the floor at 540 sec (9 min) for southwest corner fire location

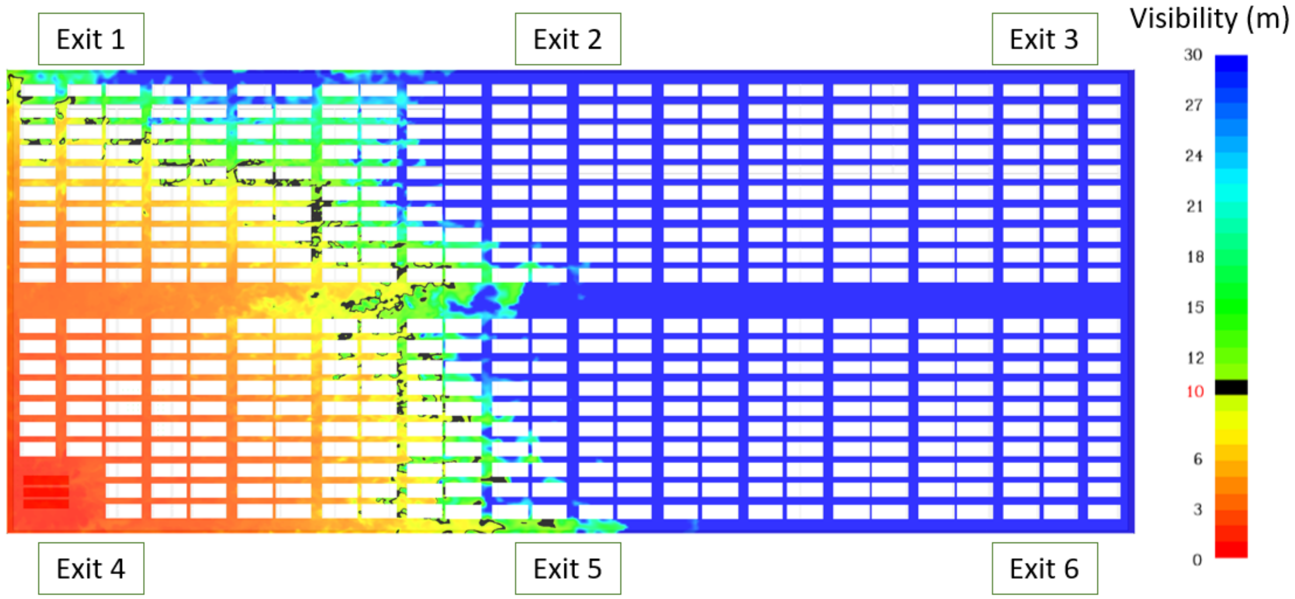

Figure D-13. Visibility conditions 6 ft above the floor at 660 sec (11 min) for southwest corner fire location

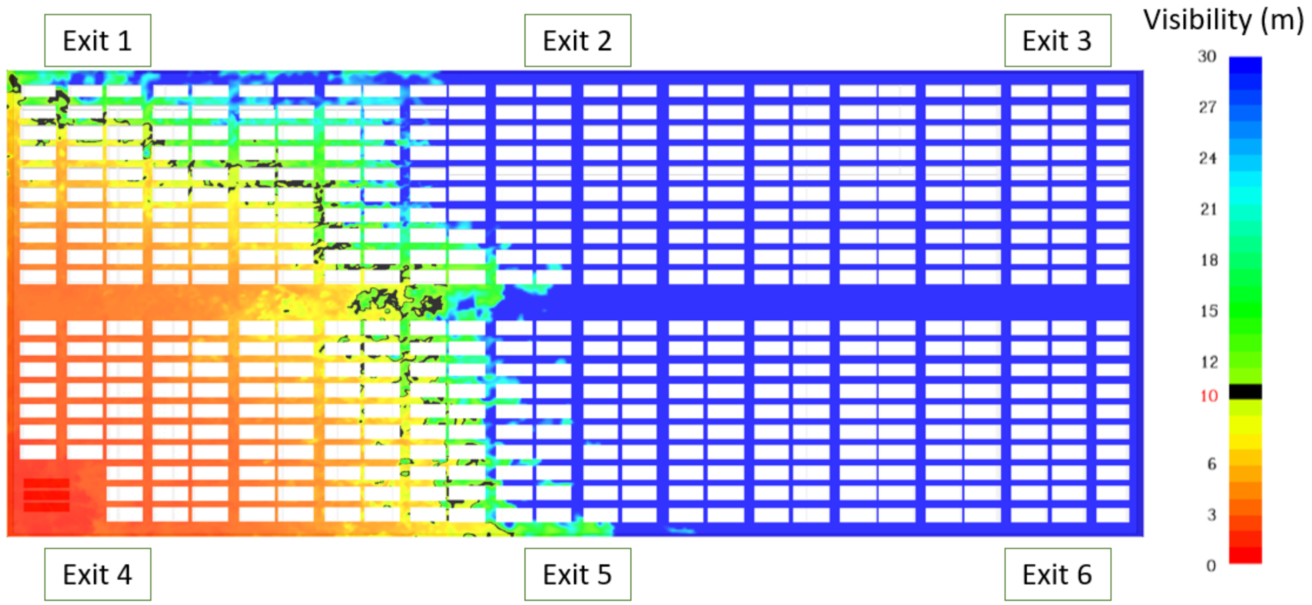

Figure D-14. Visibility conditions 6 ft above the floor at 780 sec (13 min) for southwest corner fire location

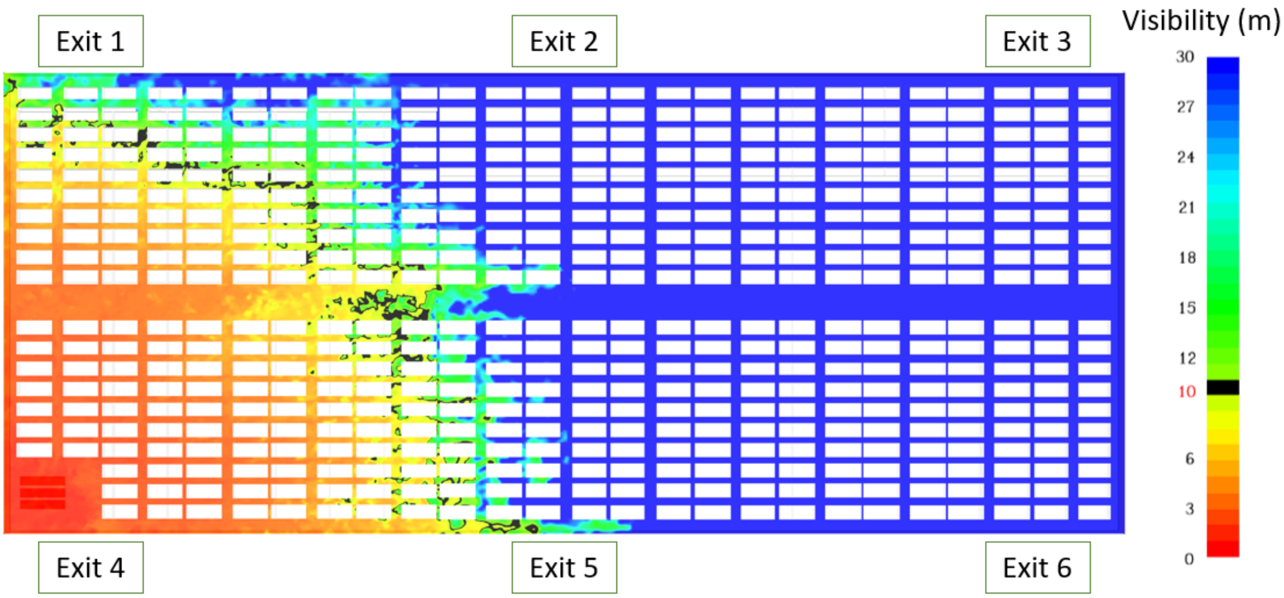

Figure D-15. Visibility conditions 6 ft above the floor at 900 sec (15 min) for southwest corner fire location

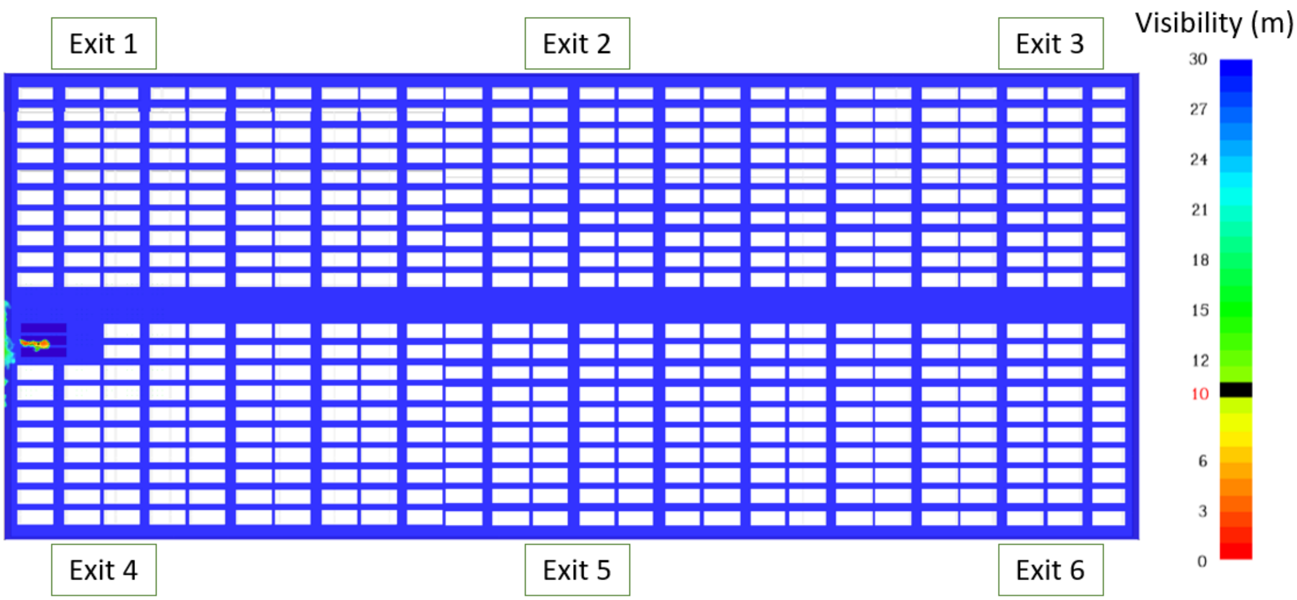

Figure D-16. Visibility conditions 6 ft above the floor at 60 sec (1 min) for west wall fire location

Figure D-17. Visibility conditions 6 ft above the floor at 180 sec (3 min) for west wall fire location

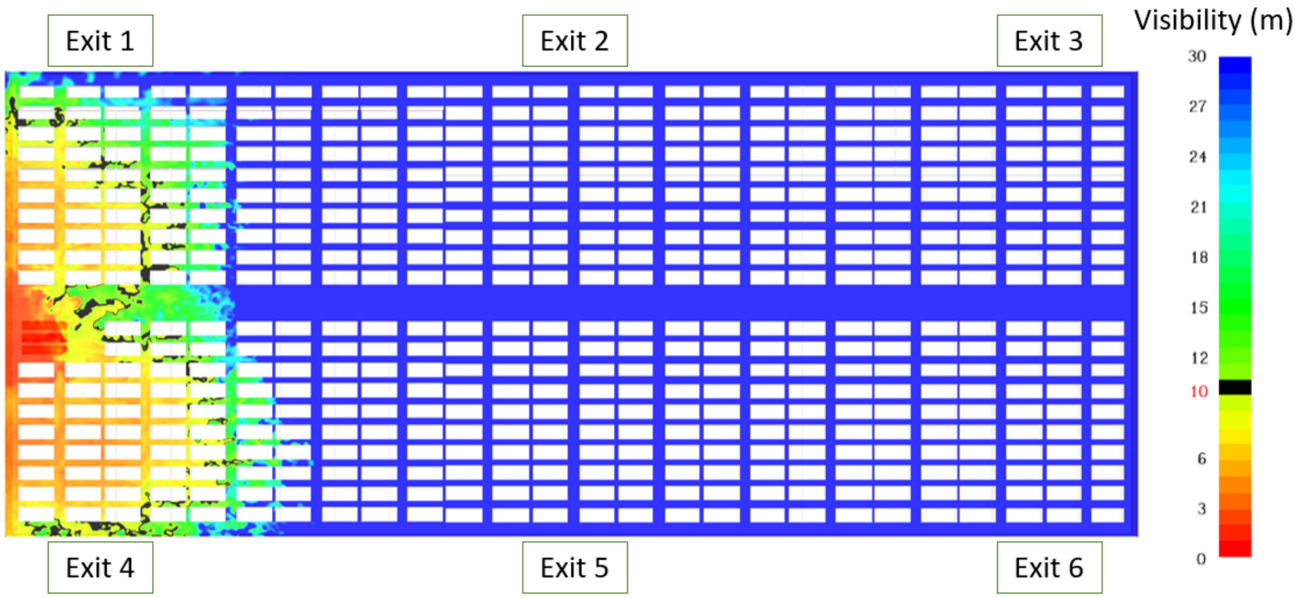

Figure D-18. Visibility conditions 6 ft above the floor at 300 sec (5 min) for west wall fire location

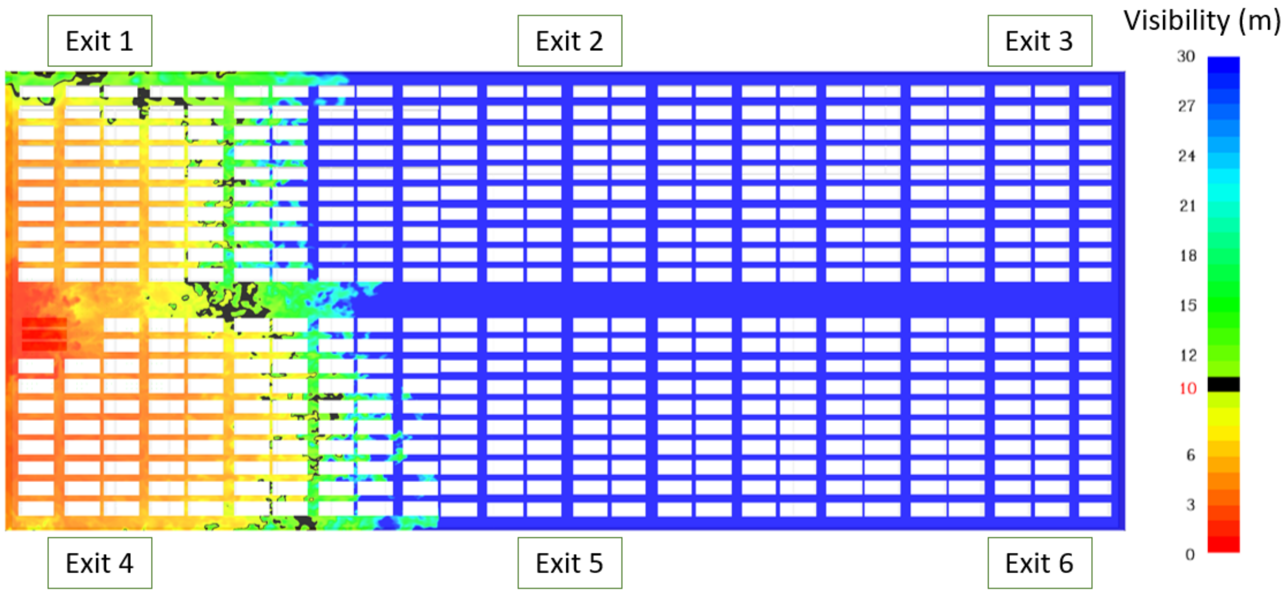

Figure D-19. Visibility conditions 6 ft above the floor at 420 sec (7 min) for west wall fire location

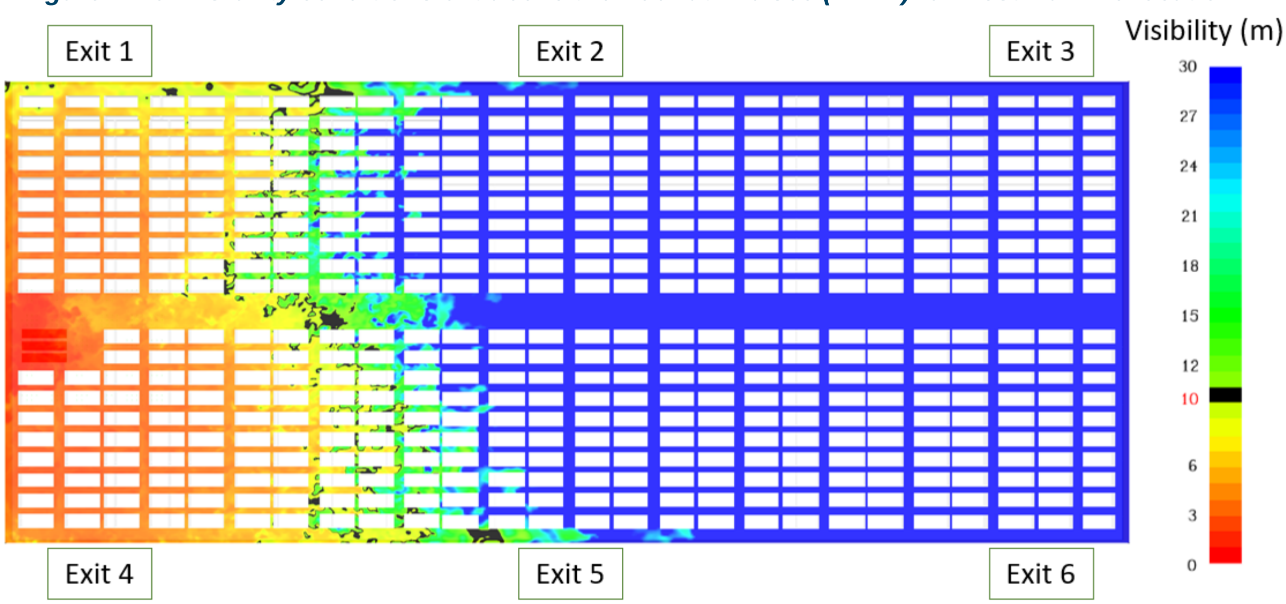

Figure D-20. Visibility conditions 6 ft above the floor at 540 sec (9 min) for west wall fire location

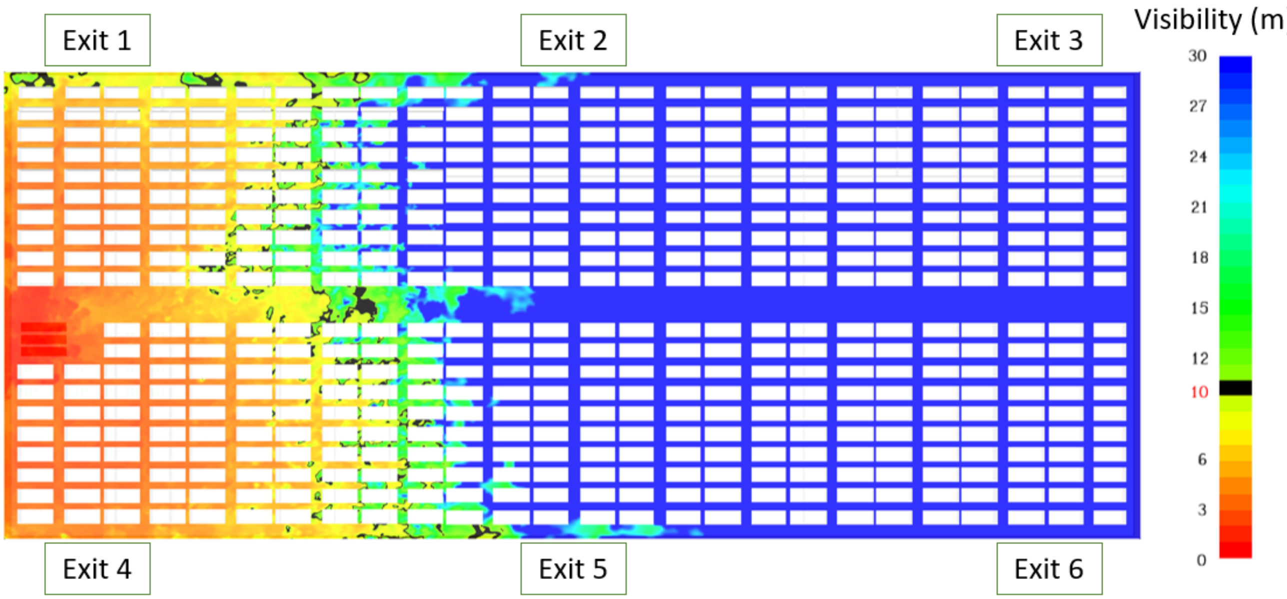

Figure D-21. Visibility conditions 6 ft above the floor at 660 sec (11 min) for west wall fire location

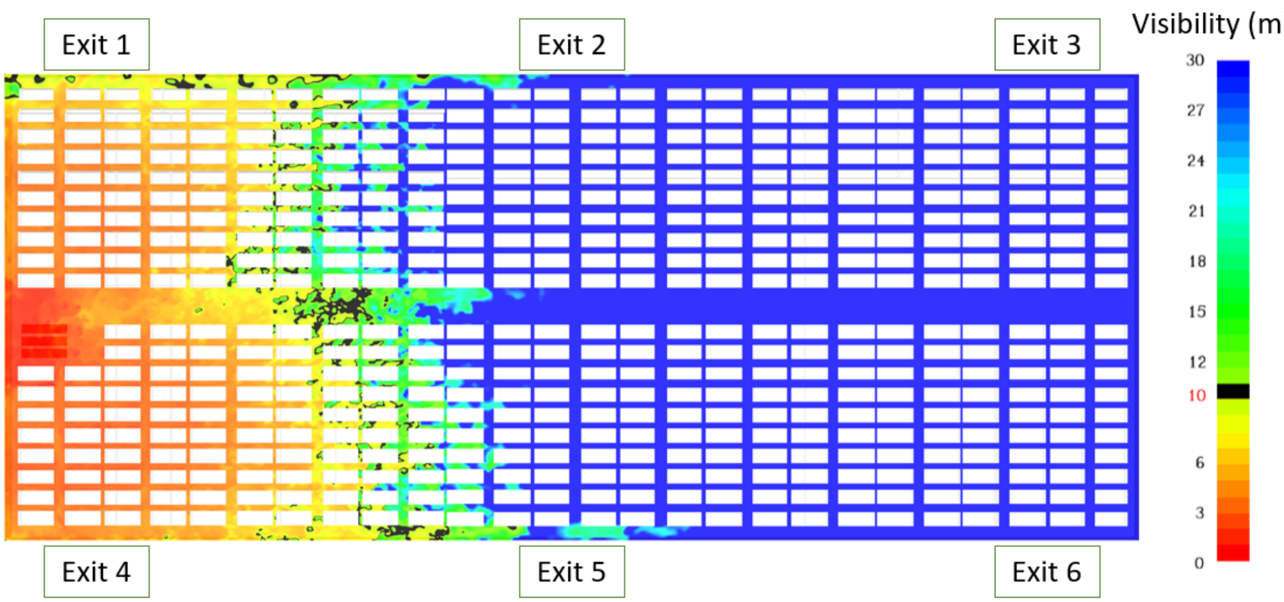

Figure D-22. Visibility conditions 6 ft above the floor at 780 sec (13 min) for west wall fire location

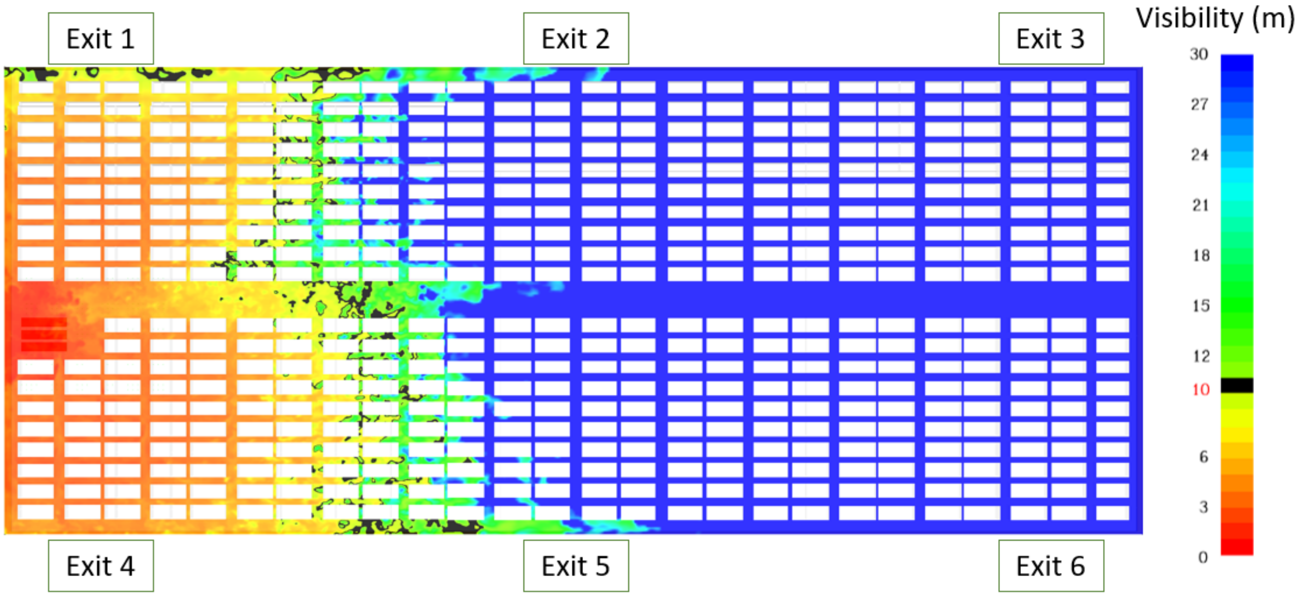

Figure D-23. Visibility conditions 6 ft above the floor at 900 sec (15 min) for west wall fire location